Sensing and control of implements for site-specific field operations

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December 2017

Ph.D. Thesis

Agro Intelligence ApS,
Department of Agroecology & Department of Engineering
Aarhus University, Denmark
DATA SHEET

Ph.D. Title:
Sensing and control of implements for site-specific field operations

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Ph.D. period:
September 2015 to December 2017

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Please cite as:

The Ph.D. Thesis was submitted to the Graduate School of Science and Technology (GSST), Aarhus University and funded by Agro Intelligence ApS and Innovation Fund Denmark, through the societal innovation project ‘Future Cropping’.

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Preface

This Ph.D. thesis is submitted to the Graduate School of Science and Technology, Aarhus University of Denmark. The thesis gathers the studies and patents published in the Ph.D. period from September 2015 to December 2017. The studies have been accomplished as an interdisciplinary industrial-scientific research between Agro Intelligence ApS, the Department of Agroecology and the Department of Engineering, Aarhus University.

The thesis is structured into chapters, where each chapter describes and discusses the core studies from research themes I, II and III listed below. All the study themes focus on integrating sensors and control in agriculture to incorporate the effect of spatial field variability in the application of site-specific field operations to improve operational performances. Theme I describes and discusses novel section control systems for mouldboard ploughing to reduce overlapping in the headlands. Theme II presents a variable mouldboard ploughing depth control system developed by a novel construction integrated with actuators, and novel modelling methodologies to utilise the developed concept plough for site-specific depth control. Theme III describes and evaluates a novel system for site-specific coulter depth measurements and control to maintain a consistent seeding depth. All the studies have been used to describe, discuss and evaluate the performance of the developed systems, as proof-of-concept products.

The industrial work included in this thesis covers the background investigations and the development processes of the novel agricultural products for commercialisation. The products have been IPR (Intellectual Property Rights) protected by the international patents (A-H) listed below, together with the corresponding studies (I-XII). An overview diagram illustrating the interaction between the core studies and core patents in theme (I-III) can be found in Fig. 5. These core publications in the themes are attached as appendices, whereas the supplementary publications are only listed below. The list includes the authors, years, titles, journals and numbers of the publications.

Research theme I: Site-specific section control of mouldboard ploughing

Paper I.
Søren Kirkegaard Nielsen, Lars Juhl Munkholm, Michael Hviid Aarestrup, Martin Hviid Kristensen, Ole Green, 2017. Plough section control for optimised uniformity in primary tillage. Advances in animal biosciences: Precision Agriculture, 8:2, 444-449.

Patent A.
Research theme II: Site-specific depth control of mouldboard ploughing

Study II.

Study III.

Patent B.

Patent C.

Research theme III: Automation for site-specific seeding

Paper IV.

Patent D.

Paper V.

Patent E.

Paper VI.
Supplementary publications

Paper VII.

Paper VIII.

Paper IX.

Paper X.
Michael Nørremark, Peter Kryger Jensen Nielsen, Søren Kirkegaard Nielsen. 2018. Pre-harvest application of glyphosate for thistle (cirsium arvense) and coach grass (elymus repens) control using 3D machine vision. Biosystems Engineering (in prep.)

Paper XI.

Paper XII.

Patent F.

Patent G.

Patent H.
Abstract

Site-specific field operations are one of the key concepts to increasing agricultural plant production. In the last few decades, the industrial automation revolution has introduced a number of new technologies; however, in the agricultural domain optimisation has mainly been targeted towards improving operational efficiencies. This choice of efficiency improvements has led to the upscaling of implements’ operational widths, as well power for as traction, all resulting in heavier implements. The aim of this Ph.D. project was to improve the conditions for crop establishment by studying and developing novel sensing and control technologies for site-specific tillage and seeding operations.

A novel concept system for automatically elevating and lowering individual sections of a mouldboard plough was studied and developed. The system was found applicable for individual section control, which significantly reduced the overlapping area between the headlands and the main working area by up to 80%. When using this concept, a more homogeneous soil reversal, with less random soil mixing, can be expected, which is crucial to eliminate weeds and improve the seedbed conditions for the desired crop establishment. Furthermore, a novel on-the-go ploughing concept was also studied and developed for site-specific depth control. The concept was found to be functional for continuous depth control, independent of communication with the tractor. Multiple novel depth modelling methodologies were studied to utilise the concept plough developed for site-specific depth control. The preferred modelling methodology controlled the operational depth every 10 m in each path, which significantly reducing the ploughed volume by 6,638 m$^3$ in a 24 ha field, corresponding to a volume reduction of 11%.

A novel coulter depth control system for maintaining a consistent drill coulter depth independent of soil conditions was developed and studied. The first investigation was conducted in a soil bin and, finally, a full-scale seed drill was developed and verified in field experiments. The system was found to be functional in measuring the individual coulter depths and dynamically controlling the coulter pressure to maintain the desired coulter depth. Without the control system activated, the seed drill measured a significant spatial coulter depth variation, due to the variability in soil mechanical properties. After smoothing the data using a moving average filter, this variation was calculated as being up to ±8 mm across the experimental blocks; however the variation was significantly reduced to ±2 mm when the coulter depth control system was activated. Overall, the developed seed drill improved the coulter depth accuracy by 15% when comparing to the conventional seed drill.

A uniform seedbed with a consistent seeding depth will generate a more homogenous crop germination, which supports the seedling competitiveness against weed and an improved yield can consequently be expected.
**Resumé (abstract in Danish)**

Områdespecifikke markoperationer er ét af de vigtigste nøglebegreber for optimering af planteproduktionen i landbruget. Gennem de seneste årtier har den industrielle automationsbranche revolutioneret med adskillige nye teknologier; desværre har landbrugets udviklingsfokus primært været rettet mod effektiviteten. Dette valg af effektivitetsforbedringer har medført opskalering af operationsbredder, såvel som øget behov for trækkraft, resulterende i store tunge redskaber. Målet med dette Ph.D. projekt var at forbedre plantetableringsbetingelserne ved at studere og udvikle nye sensorer- og kontrolteknologier for områdespecifikke markoperationer indenfor jordbearbejdning og såning.

Et nyt konceptsystem til automatisk hævnings- og sænkningskontrol af de enkelte sektioner på en muldpladeplov blev studeret og udviklet. Systemet blev fundet anvendeligt til individuel sektionsstyring, hvilket forbedrede grænsefladen mellem for- og hovedager med op til 80 %. Med systemet kan man forvente en mere homogen jordomvendelse med reduceret ukontrolleret jordblanding, hvilket er alfaftørende for at reducere ukrudt og forbedre såbedsforholdene for at opnå den ønskede planteetablering. Derudover blev et nyt dynamisk plovkonceptdesign studeret og udviklet til områdespecifik dybdekontrol. Konceptet blev fundet funktionelt for kontinuerlig dybdekontrol uden kommunikation med traktoren. Forskellige dybdekontrolmodelleringsteknikker blev studeret til at anvende den udviklede plov til områdespecifik dybdekontrol. Den foretrukne modelleringsteknik tilpassede dybden hver 10 m, hvilket signifikant reducerede pløjevolumen med 6638 m³ af en 24 ha mark, svarende til en volumenforbedring på 11 %.

Et nyt sådybdekontrolsystem til opretholdelse af ensartet såskærbryde unavhængigt af jordbundsvariationer blev udviklet og studeret. Det første studie blev foretaget i en jordbænk, efterfulgt af en fuldskala såmaskine udviklet og verificeret i et markforsøg. Systemet blev testet funktionelt i en jordbænk, efterfulgt af en fuldskala såmaskine udviklet og verificeret i et markforsøg. Systemet blev testet funktionelt i at måle de individuelle skærdybder og dynamisk regulere skærtrykket til at opretholde den ønskede skærdybde. Uden kontrolsystemet aktivt, målte den intelligente såmaskine en signifikant rummelig dybdevariation pga. variationer i jordens mekaniske egenskaber. Efter udjævning af data med et glidend gennemsnitsfilter blev denne variation beregnet til at være op til ±8 mm over forsøgsblokkene. Variationen blev signifikant reduceret til ± 2 mm, når sådybdekontrolsystemet blev aktiveret. Ved sammenligning med den konventionelle såmaskine forbedrede den udviklede såmaskine dybdenøjagtigheden med 15 %.

En forbedring af ensartetheden i såbedet og sådybden vil resultere i mere ensartede fremspilinger, hvilket forbedrer planternes modstandsdygtighed over for ukrudt, og i sidste ende kan et forbedret udbytte forventes.
Acknowledgements

A special thank you should be directed towards my main supervisor Lars Juhl Munkholm and my co-supervisors Michael Nørremark, Mathieu Lamandé and Ole Green for their support throughout the Ph.D. project. You have provided guidance in my development as a scientist and shown me how to combine the study with my industrial work on developing novel agricultural machines.

In the industry, I would like to thank my colleagues at Agro Intelligence ApS for personal encouragement and their professional support. You have all been extremely helpful in the progress of product developments and assisting with your experience.

Furthermore, I am grateful to all colleagues in the Department of Agroecology and the Department of Engineering at Aarhus University. You have been helpful along the way with scientific discussions and especially with sharing your scientific experience.

The work was financially supported by Agro Intelligence ApS and Innovation Fund Denmark through the societal innovation project called “Future Cropping”.

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Chapter 1 Introduction

1. Background and motivation

Tillage and seeding are crucial operations for crop establishment to achieve the desired yield of plant production. This has been known for centuries in good agricultural practice. However, the developments in agriculture have mainly introduced time efficiency optimisation (Day, 2011), resulting in larger implement widths and, consequently, heavier machines. Examples of agriculture development initiatives are controlled traffic farming (Bochtis et al., 2010; Gasso et al., 2013; Raper, 2005), fleet management (Sørensen and Bochtis, 2010) and soil workability (Edwards et al., 2016) for planning when to operate with the heavy machines. In general, the focus in agriculture has been on reducing time spent on field operations or only damaging the soil in the headlands and tramlines by utilising similar large operational widths with heavier machines. However, in practice, machine traffic causes considerable yield reductions in the tramlines and headlands (Sparkes et al., 1998a, 1998b), which can make up a sizeable proportion of the cultivated fields in Europe (Petersen et al., 2016). This evolution has been caused by the well-known benefits of economies of scale, providing improved mechanical efficiency and functionality. An example of this is the combine harvester, which has evolved from a weight of 4 Mg in 1958 to 25 Mg in 2009 (Schjønning et al., 2015) and even more today. This trend has accelerated within the last decades (Day, 2011), which might have overridden the good agricultural practice of crop establishment and nursing of individual plants, while maintaining soil fertility (Arvidsson, 2001; Hamza and Anderson, 2005; Raper, 2005; Schjønning et al., 2015). The main adverse effects of the heavy machines are top- and subsoil compaction which reduces pore size, in this way reducing water infiltration, air content and root penetration, which can ultimately reduce plant growth and thereby yields (Chan et al., 2006; Schjønning et al., 2015). An illustrative example of a wheel load creating soil compaction and reducing pore sizes compared to a non-compacted soil with a plant and its root development is shown as a sketch in Fig. 1.

Figure 1: Illustrative sketch of wheel load creating soil compaction and reducing pore sizes compared to a non-compacted soil with a plant and its root development.
The soil is the growth medium in agricultural plant production and due care is important when utilising the soils to obtain the full yield potential today and for yields in the future farming. When comparing agricultural implements with other production industries, a number of new automation technologies have been introduced, especially within the last few decades; however, this development has not completely found its way into modern tillage and seeding implements. Some of these automation technologies might be useful for the development of novel, intelligent, agricultural implements, i.e. for site-specific controlled field operations. Qualitative performances of the heavy implements can be considered as largely neglected, as the majority of modern machines still operate with static settings, manually set by the operator before starting the operations. To optimise the field operations, the static subjective machine settings, targeting the average field condition have to be reconsidered. Manual supervision of wide machines in fast operations is furthermore a challenging task for the operator despite a constant quality evaluation being extremely important to achieve the desired crop potential.

Objective automatic decision support systems to determine the pre-settings or real-time control from sensor input are not convenient to use within operations for crop establishment, even though a number of measurement methods are available to predict soil and crop conditions. Information pertaining to soil and crops can be obtained via multiple methods such as manual samples, on-ground sensors, implement-mounted sensors, drones and satellites, all being, to some degree, descriptive of soil and crop conditions. These methods can provide descriptive site-specific information for decision support of automatic adjustment of pre-settings or provide the dynamic input signals for real-time control, e.g. when operating with tillage and seeding implements. However, this is not routinely used for automatic control of these operations. Furthermore, when travelling at speed with large machines, small surface variations can generate horizontal and vertical vibrations that have significant adverse impacts on, for example, the vibrations or doses when using boom for spreaders or sprayers (Clijmans et al., 2000; Langenakens et al., 1999; Lardoux et al., 2007). Another adverse effect from the increase in size of machines is that fields are being merged, making it even more difficult for the operator to maintain the optimal site-specific performance, as the larger fields cover more variability. If machines can be modified for site-specific controlled operations, not only can it then optimise crop cultivation conditions but it can also reduce the working time, wear and utilised energy (Abbaspour-Gilandeh et al., 2005; Keskin et al., 2011; Natsis et al., 1999; Raper et al., 2005, 2000). Therefore, precision farming using site-specific field operations are generally considered as promising tools for more sustainable, efficient and productive crop cultivation (Jensen et al., 2012; Kaloxylos et al., 2014; Plant, 2001; Wolfert et al., 2017). This thesis focuses on integrating site-specific controlled tillage and seeding operations relative to the spatial variable conditions in agricultural fields in order to enhance the conditions for crop establishment. When cultivating crops, the seedbed quality is crucially important for crop establishment and ultimately crop yield (Braunack and Dexter, 1989a; Glinski and Lipiec, 1990; Guérif et al., 2001;
Håkansson et al., 2011). The overall purpose of the seedbed preparation is to create the optimal seedbed conditions for seed germination with the desired root development (Glinski and Lipiec, 1990). The purpose of primary tillage is to loosen the top soil, apply weed control, and incorporate organic surface material to achieve the desired homogeneous condition (Glinski and Lipiec, 1990; Henriksson and Håkansson, 1993). Deep tillage increases the potential for growth length of both primary and lateral roots (Forbes and Watson, 1992; Glinski and Lipiec, 1990). Secondary tillage controls the aggregates size distribution and creates a firm moist seedbed bottom for the seed to be placed into (Glinski and Lipiec, 1990; Henriksson and Håkansson, 1993). The desired depth and intensity of the tillage operations help to achieve the targeted ratio of temperature and water content needed to accelerate the specific seed’s germination (Forbes and Watson, 1992).

The quality of a seedbed is based on multiple parameters, e.g. bulk density, porosity, particle and aggregate structure, size and distribution (Braunack and Dexter, 1989a; Håkansson et al., 2002). An optimum seedbed porosity was considered to be 0.5 m$^3$ m$^{-3}$, with an aggregates size distribution from 0.5 to 5 mm (Glinski and Lipiec, 1990; Henriksson and Håkansson, 1993); however, this optimum depends on the specific seed and soil composition (Braunack and Dexter, 1989a, 1989b). Unsatisfactory seedbed conditions can be caused by insufficient or too intense tillage treatments. Insufficient tillage intensity creates aggregates that are too large or leaves a compacted seedbed which both can limit seed germination. A too intensely tilled seedbed is more susceptible to soil crusting, wind and water erosion (Braunack and Dexter, 1989b) both from primary and secondary tillage (Van Muysen and Govers, 2002).

Homogeneous field conditions are unlikely due to spatial variability in soil properties vary. Field variations can be measured by electrical conductivity (Corwin and Lesch, 2005), but the measurement is influenced by a number of physico-chemical properties including soluble salts, clay content and mineralogy, soil water content, bulk density, organic matter and soil temperature (Corwin and Lesch, 2005). Many of the seedbed properties can be controlled in the primary and secondary tillage operations, e.g. surface roughness by rollers, tillage depth, degree of loosening, and the aggregate size distribution of the seedbed (Braunack and Dexter, 1989b; Håkansson et al., 2002). The desired site-specific field operations intensity can also reduce wear on machinery and energy, creating a smaller environmental footprint through using less fossil fuel, indirectly helping to create a sustainable plant production. Furthermore, a homogeneous prepared seedbed and crop establishment ensures a uniform natural drainage distribution, which has can significantly reduce the risk of additional pesticide leaching (Petersen et al., 2016).
2. Project perspective

This thesis forms part of a comprehensive societal innovation project called “Future Cropping”. The project has a holistic approach of optimising agricultural plant production. The project includes a number of interdisciplinary elements and integrates a data infrastructure using “big data”. The project generally concentrates on the overall cropping system and the utilisation of the required resources at the right location and at the right time, thereby optimising the chain of the cropping cycle. The disciplines, project scope and infrastructure are illustrated in the Project Model Landscape (Fig. 2). The project is divided into nine work packages (WP) with different sub-focuses to the holistic optimisation of plant production using a platform with big data: WP1: Data acquisition & processing; WP2: Impact assessment; WP3: Certification & test; WP4: Intelligent tillage and crop establishment; WP5: Intelligent fertiliser application; WP6: Microbial inoculants; WP7: Crop monitoring & protection; WP8: Intelligent harvest; WP9: Differentiated N-regulation & drainage filter technology. The project vision is: “to increase turnover of primary plant production and agro-technology by at least 0.6 billion DKK per year and to create new jobs in the sector by 2030, while also decreasing the environmental impact. This will generate enhanced growth and new export opportunities for the Danish food and agro industry clusters. The novelty of Future Cropping is the development of a collaborative ICT platform that integrates vast amounts of data from next generation of agricultural and environmental technologies into intelligent, more efficient and sustainable technologies and solutions for site-specific crop management and environmental regulation.”

Figure 2: The innovation Project Model Landscape from “Future Cropping”, illustrating the scope and the infrastructure activities, divided between the work packages. WP1: Data acquisition & processing; WP2: Impact assessment; WP3: Certification & test; WP4: Intelligent tillage and crop establishment; WP5: Intelligent fertiliser application; WP6: Microbial inoculants; WP7: Crop monitoring & protection; WP8: Intelligent harvest; WP9: Differentiated N-regulation & drainage filter technology.
More specific, this thesis contribute to WP4 entitled “Intelligent tillage and crop establishment”, which focuses on the use of tillage and seeding implements during field operations. The scope of this work package is the integration of site-specific data with the development of novel tillage and seeding equipment for site-specific field operations relative to soil conditions. This thesis has a system approach of optimising crop establishment by improving both tillage and seeding operations. The machines developed are able to measure and control settings site-specifically and potentially provide information for the data platform (WP1), as well as subsequent operations. Overall, WP4 contributes with scientific papers, international patents, and novel products developed, presented at international exhibitions.

2.1. State-of-the-art and research gaps for tillage

In conventional tillage the primary operation is carried out by discs, cultivators or mouldboard ploughs (Hallett and Bengough, 2013). The purpose of choosing mouldboard ploughing in primary tillage is to incorporate organic materials, provide weed control, reduce topsoil compaction, and improve air content and water infiltration (Glinski and Lipiec, 1990; Guul-Simonsen et al., 2002; Henriksson and Håkansson, 1993; Håkansson et al., 2002). The static operational depth and width chosen for the operation depend completely on the experience of the operator, conventionally determined when starting the operation. The static settings do not take into account the on-the-go variability caused by change in surface residues or soil conditions. However, some operators might adjust the static settings a few times, during a field operation. Other well-known cultivation methods are strip tillage, reduced tillage and no tillage (Bertocco et al., 2008; Hallett and Bengough, 2013; Soane et al., 2012). These practices cover different approaches with none using mouldboard ploughing. Tillage without mouldboard ploughs require less energy, reduces the risk of erosion, soil crusting and in some cases can be without risk of major yield reductions (Soane et al., 2012). However, mouldboard ploughing can be needed in some climates and soil types to achieve effective weed control, limit chemical inputs and incorporate large quantities of organic materials (Guul-Simonsen et al., 2002; Soane et al., 2012).

The industrial focus of mouldboard ploughing development has been on improving operational efficiency, starting before tractors were introduced in agriculture. Since the 1950s when tractors became more generally used, the design goal has been greater operational depth, furrow width, number of furrows per plough, more organic material incorporation, higher operational speed, and less mechanical wear (Guul-Simonsen et al., 2002), all to improve efficiency – and sales. However, qualitative ploughing is a complex task which requires an experienced operator with the correct equipment. This complexity tends to be overseen when focusing solely on operational efficiency. This is not new knowledge – Alfred Hall (1914-2011) addressed this issue and established the British Ploughing Association, in which he became General Secretary (1951-1972) as well as founder of the Society of Ploughmen (1973) (Soane, 2009). He was also the inspiration for founding the World Ploughing...
Organisation (WPO) in 1952 and he remained its General Secretary for 40 years (Soane, 2009). Annual mouldboard ploughing competitions were commenced in 1952, organised by WPO (Soane, 2009) and the complexity ensures these competitions are still ongoing.

Scientific research on primary tillage has mainly focused on modelling the effect from soil characteristics properties, geometric plough design parameters, operation speed and depth, combined with draught force (Godwin et al., 2007; Kuczewski, 1981; Mari et al., 2015; Qiong et al., 1986) and how the tillage affects crops establishment and yield (Braunack and Dexter, 1989a; Guérif et al., 2001; Guul-Simonsen et al., 2002; Håkansson et al., 2011). Tillage operations consume a large proportion of total energy compared to the overall cropping cycle. The specific energy demand depends on tillage practice (Bertocco et al., 2008). Different tillage methods are used in the various parts of the world, but tillage dominates the energy consumption in primary production (Shamal et al., 2016). An Italian study found that tillage operations account for around one third of the energy input on average for the overall cropping cycle (Sartori et al., 2005). A similar trend was found in Denmark, where 40 litres of fuel was used for crop establishment out of a total of 83 for conventional and 122 litres in organic crop productions, dominated by mouldboard ploughing (Dalgaard et al., 2002). Therefore, draught and energy consumption have been well studied, as the share, the plough cutting edge and surface, together with timing and depth have significant impacts on the energy requirement (Bertocco et al., 2008). Shallow tillage may, for example, reduce energy consumption by approximately half (Raper et al., 2000). Soil type, water content, and the wear (of the cutting edge) of soil tillage tools impact tillage performance, efficiency, plough pan creation and energy consumption (Guul-Simonsen et al., 2002; Natsis et al., 1999). A small reduction in tillage intensity may have a considerable impact on overall tillage efficiency, due to energy reduction, while still producing the desired seedbed (Guul-Simonsen et al., 2002). Applying site-specific variable tillage depth has shown a considerable reduction in energy used for tillage of 56 % and fuel a saving of 34 % compared to conventional tillage (Keskin et al., 2011). Another study of variable tillage depth found similar energy savings of 50 %, with a fuel reduction of 30 % (Abbaspour-Gilandeh et al., 2005). For subsoiling, a depth reduction from 350 mm to 250 mm reduced the draught force by up to 55 % and reduced the fuel consumption by 45 % when applying site-specific rather than the conventional uniform operational depth (Raper et al., 2005).

Soil compaction mitigation has been studied utilising a variable depth control of a tillage system, based on geo-referenced soil compaction data from a penetrometer and electrical conductivity (Keskin et al., 2011). Site-specific depth control with dynamic Proportional Integral Derivative (PID) control using a hydraulic system has been studied for subsoiling (Anthonis et al., 2004; Mouazen et al., 2004; Saeyes et al., 2004) and precision peat milling (Condon et al., 2001). One of the common site-specific innovations in agricultural is section control which is used for other operations such as mechanic weed control,
fertilisation or spraying (Luck et al., 2010). No research has been found in literature evaluating the potential or utilisation of section control for a mouldboard plough; however, a significant yield reduction in sugar beets and cereals was found in the interface between the main field and headlands, especially on commercial farms (Sparkes et al., 1998a, 1998b), which could be caused by an undesired interface ploughing (i.e. due to overlapping) and traffic from machinery turnings.

A comprehensive review concluded that the greatest potential for optimising mouldboard ploughing would be focus on the operational depth and the characteristics of the shape and surfaces (Guul-Simonsen et al., 2002). Guul-Simonsen et al. (2002) studied the yield effect for different fixed settings of ploughing depths in the review, comparing 14 studies in Northern Europe. A thorough number of sites, locations and durations were compared by measuring the yield response for different ploughing depths. It was concluded that the depth may be reduced to 180-200 mm or less without a significant reduction of crop yields, but with a considerable reduction in energy demand (Guul-Simonsen et al., 2002). However, the studies’ yield responses were still found to be small and uncertain. In another study, the depth was increased from 150 to 220 and 280 mm, where the yield increased marginally by 2 and 3 %, respectively (Håkansson et al., 1998). However, in soils with a high silt content, a shallower ploughing depth resulted in a 10 % higher yield (Håkansson et al., 1998). Henriksson and Håkansson (1993) found that greater ploughing depth down to 300 mm at most sites slightly increased the yield (1-6 %). However, in silty soil the yield was found to increase with reduced depth to 150 mm (Henriksson and Håkansson, 1993), probably because it increased the concentration of organic material near the surface. For sandy soils with limited root development, the ploughing should be deeper to take account of a greater proliferation of perennial weeds, at least periodically (Guul-Simonsen et al., 2002), and when operating at 250 mm instead of 150 mm, weed biomass was reduced by 50 % (Brandsæter et al., 2011). For silty soils a shallower depth can be used where surface layer hardening (crusting) can be an inherent problem. However, other methods than deep ploughing should be used to take account of perennial weeds (Guul-Simonsen et al., 2002). Therefore, a large potential in energy reduction without consequently reducing yield can be expected when applying the correct site-specific ploughing depth within the field boundaries. Therefore, there is a need for a mouldboard ploughing system which automatic control the operation depth. Such a system has not been found in the literature.

Secondary tillage can be conducted using different implements such as discs, spring-tine harrows, power harrows, rotavators, etc. During secondary tillage, the seedbed is slightly compacted after ploughing and the topsoil is loosened to a controlled even depth, defined by the seed of the chosen crop species. The purpose of this operation is to create a homogenous loose seedbed, with a firm moist bottom, containing the required aggregate size distribution (Glinski and Lipiec, 1990; Hallett and Bengough, 2013; Henriksson, 1989; Henriksson and Håkansson, 1993; Håkansson et al., 2002). After
the secondary tillage, the conventional aim is to place the seeds evenly in the transition zone (bottom of the loose seedbed) in order to provide the desired conditions for a quick germination (Håkansson et al., 2002; Håkansson and Polgar, 1985; Karayel, 2008). By this placement, the seeds are able to absorb moisture from the compacted ploughed soil below independent of weather conditions, and heat from above soil transferred through the loose top layer (Chang et al., 2004; Forbes and Watson, 1992). Therefore, the seedbed and the seeding depth have a significant impact on crop establishment, which consequently can influence the yield (Brennan and Leap, 2014; Håkansson et al., 2002; Kinsner et al., 1993; Morrison and Gerik, 1985). Furthermore, a too intense secondary tillage creates a loose seedbed with very small aggregates, which makes the seedbed more susceptible to wind and water erosion (Braunack and Dexter, 1989b; Van Muysen and Govers, 2002) and increase seedbed evaporation and heat transfer to the seeds (Chang et al., 2004; Forbes and Watson, 1992). Finally, the homogeneity of the seedbed and crop establishment are also important for reducing the risk of pesticide leaching (Petersen et al., 2016).

Commercial mouldboard ploughs are generally limited to static settings, which commonly are set manually before starting the operation. The adjustable parameters are the operational depth by adjusting the lift height of the tractor and the mechanical stop of the rear plough wheel, and operational width which can be manually-hydraulically adjusted, i.e. on-the-go by the operator to take account of field wedge. However, a more recent plough system which utilises the Real Time Kinematic (RTK) from Global Navigation Satellite Systems (GNSS) on the tractor and automatically controls the operational width on-the-go has been commercialised. This automatic system ensures a straight furrow while ploughing in variable soil conditions or topography. Such an automatic system has been developed by Geoteam (DK) in collaboration with Trimble (US) and Agrometius (NL), and goes under the name of Geoplough. A similar system has been commercialised by Lemken (DE) and is called Juwel. Very recently (November 2017) Kuhn (FR) has shown a new prototype plough called Smart Ploughing, where they have integrated individual section control. This system is not yet commercially available and it has not been possible to get any detailed description of their system. However, their section control concept has been recognised by the DLG (German Agricultural Society) and been awarded a innovation ‘Silver Medal’ at the Europe's agricultural exhibition, Agritechnica 2017 (DE).

2.2 State-of-the-art and research gaps for seeding

Practice and research have shown that seedbed quality and suboptimal seeding depth can result in poor crop emergence (Brennan and Leap, 2014; Håkansson et al., 2002; Håkansson and Polgar, 1985; Kinsner et al., 1993; Morrison and Gerik, 1985) and can consequently negatively impact the yield potential. In conventional seeding operations, the operational depth is determined by pre-set coulter pressure, solely based on the operator’s experience and may vary in depth depending on variable soil
conditions. The sensitivity to suboptimal seeding depth differs between crop species. General, small seeds with low energy content need a shallow depth, germinate faster, but tend to be more sensitive to depth variations (Håkansson et al., 2011). For instance yellow clover yielded 87 % germination at 20 mm seeding depth but only 4 % germination at 80 mm seeding depth (Ghaderi-Far et al., 2010). Seeding depth has generally a significant impact on the germination rate and emergence delay (Baskin and Baskin, 1998; Håkansson et al., 2011). Håkansson et al. (2002) showed that the time delay for 50 % barley emergence almost increased linearly with increasing seeding depth within the range of 10 to 90 mm at 20°C. The final emergence percentage varied from approximately 85, 100 to 95 % at 10, 39 and 50 mm seeding depth, respectively. Another study also showed that wheat emergence varied with the seeding depth, with an 80 % emergence for 55 mm depth, decreasing to 70 % when the depth was changed to 35 or 80 mm (Kinsner et al., 1993). An example of desired and undesired seeding is illustrated in Fig. 3, where the first seed is at the target depth, the second has too much residue and is not covered by soil, the third has local compacted soil from the euro drill coulter and is not covered by soil, the fourth is at too shallow depth and the fifth too deep. Any delay or reduction in emergence can have considerable negative effects on the seedling’s competitiveness against weeds, plant development and subsequently on the final crop yield and it is therefore crucial to seed uniformly at the desired depth (Durr et al., 1992a; Håkansson et al., 2002; Kinsner et al., 1993).

![Figure 3: An illustrative example of desired and undesired seeding; where the first seed starting from the left is correct in the transition zone, the second has too much residue and is not covered by soil, the third is in compacted soil from the euro coulters and is not covered by soil, the fourth seeding is too shallow and the fifth too deep.](image)

Seed drills with a control system for operating site-specifically are not conventionally used in agriculture; they have mainly been studied at research level. In the last few decades, a few depth control systems have been described (Kiani, 2012; Suomi and Oksanen, 2015; Weatherly and Bowers Jr., 1997). The systems differ in their conceptual approach and evaluation methods. Weatherly and Bowers (1997) developed a hydraulically actuated seeding depth control system that planted the seeds based on the measured soil moisture conditions. The seeding depth was dynamically controlled based on a soil drying front sensor combined with modelling, as water content is an important factor for germination. More recently, Suomi and Oksanen (2015) modified a seed drill for depth control. The seed drill was
with single discs, where each coulter had a wedge roller on the side and a common roller (12 rubber wheels) for compacting and levelling the soil. The system used multiple sensors; the surface was measured with two ultrasonic sensors combined with angle measurements of two implemented soil gauge wheels running on the surface. Rotary sensors were used to measure the angle of three coulters. The system was able to maintain a pre-set seeding depth within ±10 mm at 10 km h⁻¹. However, there is still need for studies to develop a simple active applicable coulter depth control system, as soil resistance varies within fields (Garrido et al., 2011) affecting seeding depth, and no intelligent commercial active seed depth control system is available on the market. Achieving a uniform and adequate seeding depth is a difficult task and depth variations for multiple seeding methods have been observed (Brennan and Leap, 2014; Garrido et al., 2011). Drill seeding depth variations are caused by the variations in soil resistance acting on the coulters during the operation, which generates unwanted coulter vibrations and consequently a non-uniform seed depth placement. Variations in soil penetration resistance depend on different factors such as texture, water content, bulk density and degree of compaction (Dexter et al., 2007; Elaoud et al., 2014), but the soil resistance acting on the seed drill coulter is primarily affected by the secondary tillage operation and the speed of the seeding operation.

To comply with the soil-coulter interaction and depth variations, multiple mechanical coulter designs are commercially available on the market. Some of the well-known seeding methods have been tested and were all found to vary in depth (Heege, 1993). The most common coulters for seed drilling are euro coulters, single- or double-disc coulters, with or without pressure wheels or gliding shoes, e.g. combined with a wedge roller. Seed drills have been found to vary in depth by an standard deviation of 4-11 mm for a ploughed seedbed and a standard deviation of 12-17 mm in direct seeding (Heege, 1993). An more recent evaluation of a modern seed drill has been conducted by DLG (Test Report, 2016), which has shown similar depth variation from 18 to 42 mm, with a mean of 35 mm (SD=5), based on seedling measurements. The experiment was conducted with a Kuhn ESPRO 6000 R at 13 km h⁻¹ in an extensively prepared seedbed classified as a fine crumble soil. The seedbed was prepared by multiple operations: two passing of rotary tillers, one with a disc harrow and one with a deep cultivator, and, finally, the seed-drill-mounted disc cultivator. The seed drill levelled and compress the soil by two sets of wheels and used a disc cultivator, double-disc coulters with individual coulter pressure wheels and a lightweight post-harrow. Such a combination of tillage operations is expected to create a homogenous levelled seedbed which reduces depth variation, and more depth variation may therefore be expected in a conventional practice.

Development of commercial seed drills has mainly focused on mechanical coulter designs and on electronic control metering systems for adjusting seed dosing. All coulter design ensures individually movements, by utilising parallelograms or hinges. Furthermore, combinations of tillage implements
with seed drills are widely used with rollers or wheels to level and compact the soil. The modern commercial seed drill can electronically control the dose and utilise application maps such as the Field IQ from Geoteam (DK) using Trimble (US). More recent technology on the market has been presented by Köckerling (DE), who launched a seed drill with an on-the-go metering and coulter pressure control system at Agritechnica 2017 (DE). The seed drill utilises the Top Soil Mapper from Geoprospectors (AT), to predict the desired coulter pressure and dose of seeds. The operator manually has to decide the control limits. The automatic seed drill depth system developed from this study received a 'Three Star' innovation award at the northern Europe's agricultural exhibition, AgroMek 2016 (DK), as it was able to measure and control coulter pressure, maintaining a consistent coulter depth independent of seedbed variations.

3. Project aim, objectives and hypotheses

The aim of the Ph.D. project was to improve the conditions for crop establishment by studying and developing novel sensing and control technologies for site-specific tillage and seeding operations. An illustrative sketch of the studied operations; a mouldboard plough incorporating soil surface residues and a seed drill operating at a consistent depth are shown in Fig. 4. In this thesis, modelling methodologies, experimental concept models and full-scale proof-of-concept machines were developed and evaluated. The overall hypothesis was that novel technologies and methodologies applying site-specific control will optimise operational performance and enhance the conditions for crop establishment.

![Image of mouldboard ploughing](image)

*Figure 4: Illustrative sketch of mouldboard ploughing incorporating soil surface residues and seeding at a consistent depth to achieve the desired conditions for crop establishment.*

The following objectives were defined with corresponding hypotheses, specifying each study. Each hypothesis generated the foundation for paper developments. A list of the all the studies and patents can be found in the preface and an overview diagram of the core publications are shown in Fig. 5.
3.1. Tillage
The objective for theme I and II was to develop control technologies and methodologies for site-specific tillage operations, in order to improve operational performance in terms of seedbed quality, weed control and energy consumption.

The hypotheses were that:
- With independent section control, the undesirable triangular segments at the interface between the headlands and the main working area will be nearly eliminated, e.g. starting the ploughing operation in an approximately straight line perpendicular to the main working area of the field.
- An automatic ploughing depth control system, installed on an existing mouldboard plough, can dynamically adjust and maintain prescribed operation depths, independent of communication with the tractor.
- It is possible to reduce energy consumption without compromising the purpose of ploughing by utilising spatial data together with a modelling methodology to prepare a site-specific operational ploughing depth map.

3.2. Seeding
The objective for theme III was to develop sensing and site-specific control technologies for optimising the seeding operation for conventional tillage systems, to enhance the conditions for crop establishment.

The hypotheses were that:
- Angle detection of the drill coulter and a known frame height of the seed drill can be used for coulter depth control and thereby obtain an even depth, reducing the low-frequency vibrations independent of soil variability.
- Coulter depths will depend on soil conditions, operational speed and the lateral positioning of the coulter on the seed drill.
- The automated coulter pressure control system will limit the undesired deviations from the target depth and stabilise the coulter depths.

4. Overview of studied themes, papers and patents
To achieve a systematic approach of improving the conditions for crop establishment, both tillage and seeding have been treated as core subjects in this Ph.D. Thesis (themes I-III). An overview diagram, with the interactions between the core studies and core patents are shown in Fig. 5, whereas a list of all the conducted publications can be found in the preface.

In theme I, one paper (I) and one patent (A) have been published. Paper (I) describes and discusses the section control concept of a mouldboard plough, with a field experiment. In theme II, two patents (B, C)
have been published and the corresponding studies of a plough depth control concept (II) and the modelling methodology (III) are presented and discussed throughout this thesis. The studies in theme III describes and discusses an improved seeding operation, published in three papers, initially using a soil bin experiment (IV), then a full-scale coulter depth measurement system (V) and, finally, a full-scale seed drill with an automatic coulter depth sensor-controlled system, verified in a field experiment (VI). In addition, two patents protecting the innovations of the seed drill depth control principle (E) and a system for dynamically controlling the site-specific loosening intensity of track eradicators (D), based on the sensor information from the developed seed drill measurements system is published in paper (V).

Figure 5: Overview diagram of the core studies and core patents, divided into tillage and seeding with the three research themes.
Chapter 2 Materials and methods

1. Section control for mouldboard ploughing

A section control system was developed, presented (Paper I) and IP protected (Patent A). The aim of the research was to investigate, describe and perform a proof-of-concept of a novel innovative plough design with individual section control, to significantly improve the ploughing operation at the interface area between the headlands and the main working area.

Field experiments were carried out to determine the draught forces during a ploughing operation. The experiments were used as input for designing the mechanical construction and dimensioning of the hydraulics system to develop the section control system. The accumulated draught force was determined in the initial field experiment before different hypothetical concepts were analysed (Fig. 2, Paper I). The studied experimental field sandy loam soil consisting of 3.7 % organic matter, 9.6 % clay, 22.3 % silt and 64.5 % sand, with a 25 kg 100 kg\(^{-1}\) gravimetric water content, located close to Vejrumbro (DK, 56.424016E, 9.585012N). The experiment was carried out with force transducers (strain gauges) mounted on the three-point linkage of the tractor, which measured the horizontal draught forces (Fig. 2, Paper I). The soil was ploughed to 250 mm depth at 8 km h\(^{-1}\) with a furrow width of 400 mm. An even distribution of the horizontal forces between each furrow was assumed and the equilibrium equation could therefore be established (Eq. 1, Paper I).

To determine the resulting force position of attack, an additional experiment was conducted where a force transducer was installed on the plough, replacing the shear bolt (Fig. 2, Paper I). With this experimental setup it was possible to measure the moment around the beam rotation point. By combining the measured moment in the furrow beam with the determined horizontal force ($F_{Fx}$), the resulting horizontal force point of attack was found by equilibrium calculations.

The forces from the experiments were used to study and compare different conceptual designs, which allowed individual section control. The studied conceptual designs consisted of different hinge configurations, rail modifications or parallelograms, all allowing the individual sections to be elevated above the soil surface, as illustrated in Computer Aided Design (CAD) drawings (Fig. 6).
Studied ploughing design concepts for the section control analysed by modelling. The blue colour indicates the crucial dynamic parts and the red indicates the conventional frame and beam of the plough.

Of the studied configurations, the “best” mechanical concept was determined after evaluating the stress and designs based on physical constraints (Fig. 6). A physical concept plough was constructed with one section modified. The experimental plough was a fully-mounted, reversible five-furrow plough Agrolux MRWS-P with shear bolts from Kongskilde Industries A/S (DK). The concept plough was used to carry out the force measurement experiment and to validate the performance, based on a surface evaluation, when using the modified plough (Fig. 7, Paper I).

2. Depth control for mouldboard ploughing

A concept for automatic ploughing depth control was studied (Study II) and IP protected (Patent B). The aim of the research was to investigate and develop a proof-of-concept of a novel innovative plough solution, applicable for site-specific automatic depth control. The hypothesis was that an automatic ploughing depth control system, installed on an existing mouldboard plough, can dynamically adjust and maintain prescribed operation depths, independent of communication with the tractor. The second hypothesis was that it was possible to reduce energy consumption without compromising the purpose of ploughing by utilising spatial data together with a modelling methodology to prepare a site-specific operational ploughing depth map.
The overall requirements for the mechanical concept were that the plough should not have any significant increment in weight or maintenance and the weight transfer from the soil/plough to the tractor wheels should be retained, ensuring the traction force required for the operation. In addition, the plough should be able to adjust and maintain the desired operational depth without communicating with the tractor and it should not require input from the operator during the automatic depth controlled operation. Different actuating concepts were studied to find the desired solution. The desired solution was further analysed and optimised by the Finite Element Method (FEM) with respect to deformation and deflection. Finally, the system was constructed and installed on the reversible five-furrow plough Agrolux MRWS-P from Kongskilde Industries A/S (DK).

After determine the conceptual solution, the next step of developing an automatic ploughing depth control system was to study applicable methodologies, utilising spatially variable input data to control the site-specific operational depth (Study III). A literature search revealed that no previous studies had examined how to apply measurable physical input parameters, with weighting, to model the in-field optimal site-specific mouldboard ploughing depth. However, the review study of 165 publications by Guul-Simonsen et al. (2002) found that soil conditions such as texture, structure, compaction and wetness as well as strength, plasticity and workability are important parameters to take into account when determining the static ploughing depth. Other parameters to consider could be crops, soil surface residue, bulk density, weed species/quantity, crop rotation, spring/autumn season, weather conditions, pesticide leaching potential, nutrient losses, wind/water erosion, choice of secondary tillage, or descriptive prediction parameters using different sensing methods such as implement-mounted, hand-held, in-soil, drone or satellite sensors. However, to ensure useful data, it needs to be measured with a fairly high resolution, i.e. <2 m, which is a comprehensive task if the information is to be based on manual measurements. The measured input data needs to be analysed and structured with weighted parameters describing their significance (model calibration) for the operational depth if the information is to be used to determine the agronomically desired site-specific ploughing depth. On the other hand, the information needs to be easily accessible if it is to be applicable in practice purpose. Regarding energy consumption, even if a small reduction in ploughing depth can be achieved, this will result in a considerable energy saving (Abbaspour-Gilandeh et al., 2005; Guul-Simonsen et al., 2002; Keskin et al., 2011; Raper et al., 2005; Sartori et al., 2005; Shamal et al., 2016), and a reduced depth does not necessarily compromise operational quality (Guul-Simonsen et al., 2002; Håkansson et al., 1998).

An ideal modelling system for finding the agronomic desired ploughing depth should include many or all the listed parameters above. The most essential parameters to consider are the site-specific root weed intensity, soil compaction and quantity of surface residue; however, to initialise the study, it was decided to include just one measureable key input parameter. In this way, the focus could be kept on
studying multiple applicable methodologies to utilise spatial data for modelling operational site-specific ploughing depth maps. MOG (Material Other than Grain) was chosen to be the input parameter as it is measureable and one of the three main spatial inputs parameters that need to be considered when determining the site-specific ploughing depth. The ploughing depth correlation to other input parameters in the model was not further studied in this thesis; however, the developed plough is prepared to measure and on-the-go estimate soil compaction, as this information need to be considered in the future depth model. The following two assumptions were used to simplify this complexity, allowing the study to focus on the operational depth modelling methodologies: A linear correlation between MOG and ploughing depth within a defined range, and that grain yield mass was equal to MOG (a harvest index of 50 %). Model calibration needs subsequent agronomic research for including the additional parameters. This simplification allowed the research to focus on studying operational modelling methodologies, applicable for the developed depth controllable plough.

An experimental field of 23.8 ha was used in the study, where the previous year’s grain yield measurements were used as an input to determine the MOG and ultimately the site-specific targeted ploughing depth at a 10x10 m resolution. From this map, multiple site-specific operational depth control maps for a real field application situation were modelled and discussed. The experimental field was located in Bjerringbro (DK, 56.374499E, 9.566601N). The soil was classified as a combination of loam and clay till, glaciofluvial sand and peat with a clay content varying from 3 to 35 %. Previous year’s cultivation was winter wheat, harvested by a Massey Ferguson 9280 (US) auto-level 30 feet combiner, where the grain yield was measured.

3. Coulter depth sensing and control

The seed drill coulter depth measurement and control studies, consisted of two patents (Patents D, E) and three papers (Papers IV, V, VI), as illustrated in Fig. 5. In the initial study, a proof-of-concept for a low-cost coulter depth sensing and control system for a seed drill was developed and evaluated in a soil bin (Paper IV). The first objective was to examine and analyse the depth variations and vibrations by detecting the angle of the drill coulter in the soil bin. The second objective was to design and implement a control system to manage coulter depth adjustments, to be tested at two extreme soil conditions. The hypothesis was that angle detection of the drill coulter and a known frame height of the seed drill can be used for coulter depth control and thereby obtain an even depth, reducing the low-frequency vibrations independent of soil variability.

This study was carried out in a rotating soil bin (Fig. 2, Paper IV), with the developed concept seed drill using an angle sensor, a hydraulic valve with a hydraulic cylinder for coulter pressure control and an embedded control unit connected to a laptop. A sub-millimetre, accurate reference system Indoor
Global Positioning System (iGPS) was used with a Graphical User Interface (GUI) on a laptop, connected by wi-fi to the positioning sensors. The study covered three different types of experiments: static measurements, dynamic sensing and testing of multiple control algorithms for maintaining the desired coulter pressure, due to change in seedbed conditions.

To evaluate the developed sensing system, an experiment was conducted under dynamic conditions with rapid coulter depth variations. The system was dynamically verified with the iGPS reference system using cross-correlation (Fig. 3, Paper IV), followed by power spectral analyses using Fourier Transform (Figs. 5, 6 & 8, Paper IV). For the control experiments, three different control systems (Proportional (P), Proportional Integral Derivative (PID) and three-position control) were examined. First the conventional coulter depth precision and accuracy were determined with the dynamic measurement system. The measurement system was used to evaluate the performance of different control algorithms for minimising coulter depth variations. Afterwards, set-point step experiments were conducted to simulate change in soil resistance, evaluating the response and settling time of the control systems. The step was changed from 55 to 44 mm in depth (Fig. 9, Paper IV). Both experiments were carried out in sand and gravel to simulate significant coulter-soil resistance variation in the seedbed. To ensure the utilised sand and gravel generate the desired significant coulter depth resistance variation, an experiment with a fixed actuator was first carried out to measure the impact from the seedbed on the coulter depth.

The developed conceptual seed drill tested in the soil bin by in paper (IV) needed additional work to be applicable for full-scale seed drill to operate in a real seedbed. Therefore, the aim of the subsequent study (Paper V) was to evaluate the performance of the novel coulter depth sensing system developed in paper (IV) after further development and implementation on a low-cost, lightweight, three-meter single-disc seed drill, operating under real field conditions. Under real conditions the seed drill is carried by wheels and the machine frame height can therefore be unsteady compared to the soil bin. The developed coulter depth sensing system in the study (Paper IV) was designed to measure the coulters spatial depth distribution and the effect of operational speed. The hypothesis was that coulter depths depends on soil conditions, operational speed and the lateral positioning of the coulter on the seed drill.

The experimental concept consisted of a three-meter wide Ecoline Kongskilde, single-disc seed drill (Fig 1, Paper V), modified with a sensing system to obtain the individual coulter depths. For sensing the coulter positions, linear position sensors were installed on every second coulter (11 in total). The linear position sensors (“TX2” from Novotechnik, U.S., IP67, resolution at 0.01 mm and linearity up to 0.05 %) measured the coulters’ positions in relation to the machine lateral frame (Fig. 7). Two ultrasonic height sensors (“P43” from PIL Sensoren, IP65, linearity error <0.5 %, Germany) were installed perpendicular to the lateral machine frame to measure the distance to the soil surface (Fig. 7). These
sensors allowed the seed drill to account for any wheel-soil penetration caused by variations in seed quantity (machine weight) and variations in soil resistance to penetration. Wheel track eradicators (spring tines from Kongskilde) were installed to one side only of the seed drill, in front of coulter 10, to test the impact of the wheel track on coulter depth. For data processing a “B&RX20” controller was used (B&R Industrial Automation, 12 bit A/D converter, AUT). The system was able to measure and log individual coulter depths with a frequency of 100 Hz. The controller was also connected to a Global Navigation Satellite Systems (GNSS) unit (“BT-Q1000XT”, Qstarz, TWN) to record the global position of the coulter depth measurements.

![Figure 7: Modified single disc coulter with the linear position sensor and the ultrasonic soil surface distance sensor, to measure the coulter depth.](image)

The field experiment was conducted in Tokkerup, (DK, 55.290629E, 12.139126N) on the 11 of April 2016, in a sandy loam soil. The topsoil texture of the field was determined to be relatively homogenous based on 13 composite samples taken in different areas of the field. The soil organic matter content was 2.9 g 100 g⁻¹ (SD=0.5) and contents of clay, silt and sand were 12.1 (SD=2.2), 16.7 (SD=2.3) and 68.4 g 100 g⁻¹ (SD=2.9), respectively. The field was relatively flat with a difference in elevation of 4 m across the 5.7 ha experimental field. The mean gravimetric water content in the seedbed was 14.6 kg 100 kg⁻¹ at the time of seeding. Spring barley (*Hordeum vulgare* L.) was grown as it is a dominant cereal crop in Denmark. The experiment was organised as a randomised block experiment with six replicates. Each strip trial was 3 m wide and 350 m long. Eleven individual coulter sensors were installed on the Kongskilde EcoLine seed drill at a lateral distance of 250 mm between each coulter. The tested operational speeds were 4, 8 and 12 km h⁻¹ in each block. A speed between 5 and 8 km h⁻¹ is recommended for Kongskilde EcoLine seed drill, but higher speeds are common in practice. The tractor used for the experiment was a Fendt 710 with a front wheel load of 1550 kg and a rear wheel load of 2050 kg. The front tyres were size 600/60R28 and the rear tyres were 710/60R38. The load-rated inflation pressure was adjusted to the required 40 kPa for all tyres to ensure a minimum impact from the wheel tracks. The tyres on the seed drill were a size 7.00-12 and loaded with 450 kg (±150 kg,
depending on the seed quantity), and an inflation pressure of 120 kPa was used, as recommended to get a constant loaded radius independent of seed quantity. The seeding rate was set at 155 kg ha\(^{-1}\) which was verified by three repetition tests. This corresponds to 290 seeds per m\(^2\) at 95 % emergence. Based on the soil and the weather conditions at seeding, a targeted seeding depth of 30 mm was selected. Before starting the experiment, the farmer manually adjusted the coulter down pressure based on his experience and observations from the actual seeding depth of the first trial. After this conventional practice for adjusting the coulter pressure, additional seed depth check samples were used to calibrate the coulter depth measurement system to the actual seeding depth. An example of a seed depth measurement is shown in Fig. 8.

![Figure 8: An example of a seed depth measurement in the experimental seedbed using a vernier caliper.](image)

Evaluation of the raw data was done by depth measurement subdivision to ensure valid data was obtained and to get an overview of the data before a more advanced and detailed data analysis. The differences in coulter depth according to the coulter’s position, block, the operational speed and the effects of operational speed on each coulter (interaction Coulter:Speed) were tested in a linear mixed model where Coulter, Speed, and their interaction, were treated as fixed factors. Block, as well as the interaction effects between Block:Speed, Block:Coulter and Block:Speed:Coulter were treated as random factors. Likelihood ratio tests were used to evaluate the significance of the fixed factors. Tukey’s range test was used to group and compare coulter depths from A (deep) to G (shallow), as the method divided treatments into distinguishable groups with significant differences (Tukey, 1949).

Finally, the full-scale coulter depth control system was developed and installed on the simple, lightweight, three-meter wide EcoLine seed drill and evaluated in a real field application (Paper VI). The control system utilised the sensing system developed and studied in a real field experiment (Paper V), with different operational speeds. In addition, the findings from the soil bin experiments (Paper IV)
were used to determine the approach for developing the actuator system and control algorithm. The hypothesis was that the automated coulter pressure control system would limit the undesired deviations from the target depth and stabilise the coulter depths. When using the instrumentation from the coulter depth measurement system, verified by the previous study (Paper V), the focus could therefore shift to developing the actuator and the control system. To apply the coulter pressure control, the seed drill was modified with a control unit and actuator, replacing the manually adjustable spindle. The actuator was a hydraulic cylinder controlled by an electro-hydraulic 4/3 directional oil valve SV08-47B (HydraForce, USA) and a pilot-controlled, leak-proof one-way valve. A field experiment was conducted with blocks, using four replicates. The different treatments were active or non-active coulter depth control and the control system performance was evaluated at the three different speeds of 4, 8 and 12 km h\(^{-1}\). The four blocks were used as replicates for the field experiment in a randomised order. The blocks were 350 m long and the crop was spring barley (\textit{Hordeum vulgare} L.).

Heat-intensity-depth maps were generated and probability density functions were fitted to the data from the different treatments to compare the distribution of the coulter depth around the target depth. Two linear mixed models were created for modelling coulter depth in order to analyse the performance of activating the coulter depth control system and test the impact of the different treatments on the coulter depths. Two mixed linear models, one with control and one without, were created with the terms and random factors as in the previous coulter depth sensing study (Paper V), to evaluate the control system. The three-sigma rule was used to examine the normality of the residuals distribution of the mixed linear models. Likelihood ratio tests were used to evaluate the significance of the fixed and random factors of the models. The block effect caused by the soil’s mechanical properties variations was studied for both models, to compare system performance. Finally, to compare the seeding operations in the statistical evaluation, the resultant deviations (calculated from the random effects of the models) were compared to determine the performance of the coulter depth control system. The confidence intervals (CI) of the standard deviations (SD) were found to indicate the significance. In addition, Monte Carlo simulations were applied based on the linear mixed models to test for reduction improvement of the undesired coulter depth deviations when activating the control system. The simulations were done by calculating 1000 datasets for each of the two models. The datasets were the same size and structure as the measured datasets for the models, and from these models 1000 deviations were estimated. The difference between the two systems resultant deviations was found, with a confidence interval to compare the system performance. The data analysis and statistical calculations were carried out in R-studio (Rstudio, USA) and MatLab (Mathworks, USA).

For additional examination of the coulter depth measurements and control system, two independent methods were used to estimate the seeding depth variations. Manual mesocotyl length measurements of
the seedlings as well as drone images were used to calculate Normalised Difference Vegetation Index (NDVI) and seedling measurements were taken randomly in selected trials both with and without using the developed depth control system. The mesocotyl in cereal is the growth of a seedling between the seed and the plumule, which indicates the approximate seeding depth (Weintraub and McAlister, 1942). A small difference between the real seeding depth and the mesocotyl length was expected due to soil erosion and natural soil compaction caused by environmental influences. Mesocotyl length measurements were obtained for 4 and 8 km h\(^{-1}\). Between 106 and 318 seedlings were measured for each of the speeds and trials with the depth control system and without it, giving a total of 726 manual measurements. An example of the mesocotyl length measurement methods is shown in Fig. 9.

The multispectral images for the NDVI were captured by a SenseFly eBee Ag (CHE) fixed-wing drone with an Airinov MultiSPEC 4C (FR) camera and the data were subsequently processed with Pix4D (CHE) drone mapping software. The NDVI uses the spectral reflectance of plants in the visible red and the near-infrared regions of the light spectrum to assess vegetation evidence. The NDVI value indicates the Photosynthetically Active Radiation (PAR), which is proportional to the dry matter production and consequently can be used to predict yield variations based on the stage of the crop (Christensen, 1992; Christensen and Goudriaan, 1993). Therefore, the differences in dry matter production were evaluated both with the depth control system and without it. In total, between 1 and 1.5 million pixels for each speed with depth control and without depth control trials were captured. The entire experimental field was recorded under one flight to reduce potential misleading climatic impacts, such as changes in sunlight and cloud cover.
Chapter 3 Results and discussion

1. Section control for mouldboard ploughing

1.1. Concept selection

The measured accumulated horizontal draught force was approx. 32 kN in the field experiment in which each section draught force ($F_{dx}$) could be estimated to 6.4 kN by the equilibrium calculations (Eq. 1, Paper I).

Of the six concepts evaluated in the study (Fig. 6), the selected “best” functional concept was further studied to determine the desired dimensioning and actuating system, as shown in the CAD drawing (Fig. 10). Finally, the concept was constructed and implemented on a conventional reversible five-furrow plough Agrolux for testing and demonstrating the novel section control concept, under real field conditions (Fig. 7, Paper I).

![Figure 10: Final model of the selected concept for controlling the individual sections, consisting of the rotational construction of the section, controlled by a hydraulic cylinder.](image)

The best concept used a hydraulic cylinder that formed a robust construction with the rotating mechanism, restricting maintenance to grease lubrication (Fig. 10). The chosen mechanical concept dimensions was optimised regarding deflection and deformation, using FEM based analysis on the forces determined in the ploughing experiments. The plough sections were hydraulically controlled via a control unit and a hydraulic 4/3 directional valve. In addition, a new hydraulically adjustable stone release system was integrated which also protecting the construction for sudden impacts (Fig. 5, Paper I).
1.2. System evaluation

A visual soil surface evaluation showed that the operation started nearly perpendicularly to the main working direction, which optimised the tillage interface between the main working area and the headlands (Fig. 7, Paper I), leading to a more homogeneous soil inversion and less random soil mixing in this area (Figs. 6 & 7, Paper I). Theoretically, the overlapped area for a five-furrow plough will be reduced by 80 %, as calculated by Eqs. 3, 4 & 5, Paper I and illustrated in Fig. 11. This significant improvement will increase with the number of plough sections.

![Figure 11: Overlapped area for conventional ploughing (left) and ploughing with section control (right). The overlapping area can be calculated with section control, $A_{sc}$ (Eq. 4, Paper I), and without section control, $A_{nc}$, (Eq. 3, Paper I).](image)

The system showed the desired performance in controlling the individual sections, both tested by modelling and demonstrated in real field operations. A more homogeneous soil reversal and less uncontrolled soil mixing can therefore be expected in the interface area, improving the conditions for crop establishment. Furthermore, the system can be used for choosing how many working sections are in active ploughing operation. An additional benefit of the system is that irregularly shaped fields can be ploughed at a constant furrow width by activating/deactivating the individual sections i.e. during wedge operations in the main working area when finalising fields. Furthermore, when reducing the number of sections operating in the soil it will lead to a considerable reduction in the traction force needed for powering the plough. This feature is especially useable when ploughing in areas with variable conditions i.e. due to soil strength or heavy topography. In practice, one section could be elevated when ploughing uphill or in heavy and wet soil, preferably determine in the headlands, otherwise, on-the-go when more traction is needed, and when ploughing downhill in the other direction, or in loose soil, all sections could then be utilised as less traction force is required.
1.3. Section control for mouldboard plough patent
In addition to paper (I), a patent was developed with a background study and a detailed description of the invention principle (Patent A). A conceptual sketch of the invention is shown in Fig. 12, with corresponding abstract.

![Conceptual sketch of the plough section control invention](image)

**Figure 12:** Conceptual sketch of the plough section control invention. The present invention relates to a plough system comprising: i) a plough frame, said plough frame comprising coupling means (4) for coupling said plough frame to a towing vehicle; wherein said plough frame having an extension in a lengthwise direction, and an extension in a transverse direction; wherein said plough frame comprising two or more lifting means (6,6'); said lifting means comprising a fixed part (8) being mounted on said plough frame, and a moving part (10) carrying a plough shear (12, 12'); wherein each said lifting means (6,6') comprising an actuator (14, 14'); wherein said actuator being configured to allow altering of said plough shears (12,12') from a lowered position to a raised position, and vice versa; wherein said plough shears (12,12') being arranged on said frame in mutual staggered orientation in relation to a lengthwise direction as well as to a transverse direction; ii) a control unit configured to receive controlling input, and in response thereto independently activate one or more actuators (14, 14') associated with said lifting means; thereby enabling independent raising and/or lowering of one or more of said plough shears (12,12'). The plough system provides improved ploughing quality of fields of soil comprising a mainland and a headland.

2. Depth control for mouldboard ploughing

2.1. Concept investigation
Multiple configurations of actuating the ploughing depth independently, without tractor communication or interaction with the operator were studied (II). Different solutions of extending the three-point linkage with height-adjustable arrangements (elevators), inspired from forklift loaders, were also evaluated. These solutions were rejected due to adverse major material stress on the lift wheels from the moment of the heavy lift-mounted implement and due to the additional need for maintenance of bearings, wheels and grease lubrication. Other configurations with parallelograms in the three-point linkage were also studied; however, all of them were rejected due to the length extension, which introduced considerably more weight to be carried by the tractor lift. Even a small weight or length extension is undesirable for lift-mounted implements, e.g. ploughs, as they already stress the lift significantly when elevated, especially during transport which can generate vibrations and oscillations. A solution of mounting an additional depth control wheel in front of the plough was likewise studied as it would be a generic depth control solution applicable for most plough producers. This solution needed
a considerable extra effort of maintenance, but was mainly rejected due to the adverse effect of inhibiting the desired vertical weight transfer from the plough to the tractor rear wheels, ensuring traction. If the weight transfer was not required to achieve the needed traction force, a solution with height-adjustable wheels running at both ends of the plough would be a generic solution for accurate depth control.

The chosen conceptual solution was a combination of the existing three-point linkage, which is functional as a parallelogram, with an extra external cylinder for elevation. This solution required no additional maintenance as it did not utilise any bearings or wheels. Furthermore, the solution did not apply any considerable extra weight and the desired weight transfer was retained, ensuring traction force. As most tractor lifts use single-acting lift cylinders and are able to operate in a floating position, an external cylinder implemented from the drawbar of the tractor to the top point of the plough headstock made it possible to dynamically control the frame height of the plough. This solution ensured all forces were controlled, e.g. draught and lateral forces were handled by the existing lift, roll and yaw by the mechanical fixed connection of the lift arms, and the existing top linkage took care of the pitch forces. The resulting vertical force could be controlled by the externally implemented cylinder. The vertical displacement could then control the height of the existing tractor lift, corresponding to the operational depth of the plough, as shown in the CAD drawing (Fig. 13). A telescopic cylinder was chosen to obtain the stroke length needed when the conventional tractor lift elevates the plough in the headlands. This new concept takes over and controls the tractor lift during the ploughing operation independently of communication with the control system of the tractor. When elevating the plough in the headlands, the installed cylinder follows the lift position using a refilling circuit, and when resetting the lift into floating position the external cylinder takes over and controls the headstock height of the three-point linkage, corresponding to operational ploughing depth (Fig. 13).

Figure 13: Existing tractor-plough three-point linkage with the novel control concept, using an external hydraulic cylinder to adjust the height of the plough headstock and controlling the operational depth.
To control the external installed cylinders a hydraulic system was developed. The height actuator in the three-point linkage consisted of the single-acting telescoping cylinder C1 at the front end of the plough (Figs. 13 & 14) and the double-acting cylinder C2 for the plough’s rear wheel (Fig. 14), which acted together to adjust the frame height of the plough. The cylinder C3 adjusts the common ploughing width, leakage protected by the one-way pilot valves (Fig. 14). The final cylinder, C4 (Fig. 14), is used for the section control system and is equipped with hydraulic pressure transmitters, in order to estimate soil compaction, during ploughing operations. This instrumentation can potentially map soil compaction or be used as additional dynamic input for on-the-go decision support, when modelling the desired site-specific ploughing depth, or as input for the traction control system, using the section control. All cylinders are speed-controlled by the one-way flow-adjustable valves. The relief valves for the section control cylinder C4 (Fig. 14), were functional as the stone release system and for additional protection of the mechanical construction. The 4/3 directional flow-control valves V3-V6 (Fig. 14) are used to control the movements of the cylinders (C1-C4). To avoid oil cavitation due to external forces, i.e. in stone release or when elevating the tractor lift in the headlands, the low-pressure refilling circuit was developed with oil supplied by V2 (Fig. 14). Lastly, a bypass valve V1 (Fig. 14) was installed allowing oil to circulate unhampered when no functions are activated.

Figure 14: Hydraulic diagram for the plough section and the plough depth control system.
2.2. Plough depth modelling map

Descriptive field information can always be used to calibrate and improve the accuracy of the site-specific depth control model (Eq. 1). A reduced ploughing depth does not necessarily compromise operational quality (Guul-Simonsen et al., 2002; Håkansson et al., 1998), but always reduces energy consumption (Abbaspour-Gilandeh et al., 2005; Guul-Simonsen et al., 2002; Keskin et al., 2011; Raper et al., 2005; Sartori et al., 2005; Shamal et al., 2016). Therefore, the site-specific depth relative to soil condition is likely to give promising results in respect to energy consumption, but it might also improve the seedbed conditions for crop establishment. To initialise the study (III) and keep the focus on the operational methodology, it was decided to base the site-specific ploughing depth solely on MOG, modelled to ploughing depth, as MOG has to be incorporated correctly to gain from the ploughing operation (Henriksson and Håkansson, 1993). The next step would be to include root weed intensity and the on-the-go estimation of soil compaction in the model, which is measured in the hydraulic system.

The motivation for adjusting the depth based on the MOG quantity was to keep a homogeneous proportion of organic material mixture incorporated in the soil, i.e. a partly decomposed or small MOG quantity requires shallower ploughing. Andersen (1993) found a positive yield response when increasing the mouldboard ploughing depth to 300 mm when incorporating residue, but that a reduced depth to 150 mm was sufficient when the field was harrowed before ploughing, probably because the residue was partly decomposed. The MOG quantity forms the main part of the surface residue, if no external material has been added, and the incorporation process is directly controlled by the ploughing depth. In this study the MOG was predicted solely from grain yield data, measured by the harvester from the previous year, but MOG can also be predicted from other measurement sources, e.g. implement-mounted sensor, satellites or drones i.e. with multispectral cameras. The developed concept plough was designed to be controllable in the estimated required depth range from 150 mm to 250 mm.

It has not been possible to find a detailed model in the literature describing a relationship between the optimal ploughing depth and MOG, therefore the following simplified linear depth model was created as an example of utilising spatially variable data (Eq. 1). The model coefficients and thresholds were calibrated from a practical approach, correlating MOG (x) to site-specific ploughing depth f(x):

\[
f(x) = \begin{cases} 
150 \text{ mm} & \text{if } x < 4 \text{ Mg} \\
x \cdot \frac{16.7 \text{ mm}}{\text{Mg}} + 83.3 \text{ mm} & \text{if } 4 \text{ Mg} \leq x \leq 10 \text{ Mg} \\
250 \text{ mm} & \text{if } x > 10 \text{ Mg}
\end{cases} \quad \text{Eq. 1}
\]

The site-specific ploughing depth maps were generated using the linear model (Eq. 1), with a resolution of 10x10 m. When using this resolution, each ploughing depth was based on the average of 4 to 6 grain yield measurement values. For visualisation of the modelled site-specific ploughing depth target, a raster heat-intensity map was created, varying the desired ploughing depth continuous from 150 mm
(green) to 200 mm (yellow), and from 200 mm (yellow) to 250 mm (red), displayed in Google Earth (Fig. 15).

![Image](image.jpg)

**Figure 15:** Site-specific ploughing depth map modelled from MOG data with a resolution of 10x10 m, where the colour mixing represent a continuous depth variation from 150 mm (green), to 200 mm (yellow) and to 250 mm (red).

The heat-intensity-depth map (Fig. 15) revealed a shallower modelled ploughing depth in the headlands due to having less MOG. One path and a few areas in the field were lacking depth values, illustrated with transparent squares (Fig. 15) as no data were found in the grain yield map. This could have multiple explanations such as no yield harvested (as in the line without data), very low resolution of the harvester, problems with the measurement system or incorrect management when the grain yield data were obtained and processed. Furthermore, some unexpected consistent lines with a reduced ploughing depth in the middle of field were found. Most likely these were caused by the harvester operating in wedges when finalising the field or some unexpected management in the operation. Conventional harvesters assume a full header during yield mapping, therefore wedges (i.e. area where the header is only partially utilised) can significantly impact the quality of grain yield maps. Even though modern harvesters can calculate the utilised operational width of the header from the traffic pattern using the auto steering, this information tends not to be included during grain yield mapping. Grain yield maps have until now mainly been used for field operation management and not as data input for further modelling. At least one harvester path in wedge or with only a partially full header cannot be avoided when finalising the main field operation, as fields are not an ideal rectangular shape. These considerations can explain some of the yellow lines (Fig. 15). Neither can accurate geo-referenced grain yield maps be assumed from harvesters. Another reason for possible inaccuracy is incorrect or missing calibrations of the yield sensors, which are required every year, and some systems even have to be calibrated relative to each crop species (Grzegorz et al., 2010). This is inconvenient in practice,
especially due to the short time period suitable for harvesting. There is also adverse risk of inaccuracy in geo-reference systems caused by the notable dead time of between 8-12 s when the straw and grain are cut, processed and transported from the header to the measurement equipment in the elevator (Grzegorz et al., 2010). This dead time is included in some of the software systems; however, this cannot be assumed for all grain yield maps. This error can cause grain yield maps to show considerable offsets, i.e. from 10 to 20 m, depending on the speed. An additional dead time often not considered in grain yield maps is the transportation time from the sides to the middle of the modern wide headers, which significantly impacts the accuracy of the global positioning during the grain yield measurements. Furthermore, when changing driving direction this positioning inaccuracy can increase considerably (potentially twofold), as the driving direction is unlikely to be taken into account in the grain yield measurement versus positioning systems. Resolution, accuracy and precision differ between measurement systems and measurement methods and data quality (uncertainty) has to be given with the data, for knowing the usefulness for further applications of the data. However, in this study it was assumed that the accuracy of the grain yield data was sufficient for ploughing depth modelling to study different operational modelling methodologies. For any subsequent use of the grain yield maps, data quality might become more relevant to improve in the future, for example when it is used as input for site-specific controlled operations. Future harvesters might already be in a development process that may take into account of some of these issues in more sophisticated measurement systems, as most of the inaccuracies can be predicted or measured. The constructed concept plough was designed to adjust the depth continuously; however, since one of the assumptions in the methodology was to use the harvester grain yield data, continuous depth control was not possible due to the discussed inaccuracies in the input data.

Another parameter which should be considered in MOG data impacting the operational depth is the applied soil compaction from traffic. Turnings and additional traffic in the headlands generate undesired top- and subsoil compaction (Schjønning et al., 2015). This traffic lowers the yield response (Sparkes et al., 1998a, 1998b), which in this modelling approach will result in a reduced ploughing depth (Eq. 1 & Fig. 15). Soil compaction in the headlands requires a more intense ploughing operation, instead of a reduced depth, for loosening the topsoil. A greater downforce may also be needed in extremely compacted soils to maintain the desired operational depth. Loosening the topsoil is also one of the reasons for choosing a ploughing operation, which may particularly important in the headlands. This headlands issue can be solved by adding an additional depth bias, when operating in the headlands, either in the modelling of the operational depth map or manually by the HMI (Human Machine Interface).
2.3. Operational modelling methods

Three different operational modelling methodologies were studied to find the preferred solution. The first solution was chosen conservative and used a consistent depth for each operational path, based solely on the greatest modelled depth from Eq. 1, for each specific path. An operational map was modelled, maintaining a consistent depth and width for each path, adjusting the ploughing settings in the headlands. The operational depth was plotted as an operational depth map, varying between 150 mm (green), 200 mm (yellow) and 250 mm (red) and illustrated in Google Earth (Fig. 16). When comparing to the static reference depth of 250 mm, this method will entail slightly less deep ploughing with a mean depth of 244 mm. By this conservative approach, all the input data for each path have to be inaccurate, which is mostly unlikely, to compromise operational quality, when comparing to the reference depth. However, if one or more data point in each path is extreme, it will calculate the maximum depth for the entire path, giving a solution almost similar to the static reference ploughing depth. The map is dominated by deep ploughing (Fig. 16), and it only reduced the ploughed soil volume turned by 0.6 %. However, this was still a considerable absolute reduction in ploughed soil volume of 255 m$^3$ when compared to the consistent reference depth of the 23.8 ha field. As discussed, this method is sensitive to incorrect yield measurements out of the normal range, e.g. as a result of incorrect management of crop establishment or nursing, poorly calibrated sensors, unexpected traffic (tramlines) in field areas or other extreme values for each path, as this will affect the fixed ploughing depth setting for the path.

![Figure 16: Operation map with fixed ploughing depth for each row, calculated as the greatest depth, where the colour represent a depth variation from 150 mm (green), to 200 mm (yellow) and to 250 mm (red).](image)

Another less intensive tillage method could be to use a quantile fraction of the yield measurements, targeting the majority of data in the paths, e.g. 75 % or 90 %, and thereby excluding the extremes that could be caused by values out of normal range. This method will achieve a significant reduction in depth; for the experimental field it was, for example, 6.4 % and 3.4 %, respectively. However, this method can be sensitive to a consistently low data quality for the specific path, which potentially could
compromise the operational performance. On the other hand, when excluding extremes it could also increase the operational quality, as it is the majority of data in the path that determines the consistent ploughing depth, as deep ploughing does not in all cases increase the yield potential (Gronle et al., 2015; Guul-Simonsen et al., 2002; Håkansson et al., 1998).

The preferred method from a control perspective is to adjust the operational depth on-the-go, either continuously or for field sections i.e. 10 m along each the path. Each path should operate within a defined depth range, determine to 33 mm (1/3 of the 100 mm depth adjustable range) while keeping a fixed operational width in each range for the path (Fig. 17). There is limited information in the literature with respect to the exact width/depth ratio, as multiple factors such as speed, mouldboard size, shape, angle, soil composition, etc., impact this correlation, but some recommendations have been found. The review by Guul-Simonsen et al. (2002) found 1.4 (\(\sqrt{2}\)) and 2 as width/depth ratios. Plouffe et al. (1995) found a ratio of 3 as the best compromise and that ploughing depth can usually be varied within fairly wide limits without major problems with ploughing quality (Guul-Simonsen et al., 2002). Therefore, depth and width might not need to be proportionally correlated, supporting utilisation of this site-specific method, whereby depth is controlled within a small range of 33 mm in each path without adjusting the operational width (Fig. 17). These ranges of depth control should not exceed a limit where it compromises the operational quality, e.g. by poor incorporation of weed and MOG or unevenness in the resulting soil surface, which require more energy in the secondary tillage operation (Guul-Simonsen et al., 2002). This site-specific method utilises more potential of the developed depth controlled concept plough and operates with a significantly higher control resolution of the field, when adjusting the depth every 10 m rather than keeping it consistent for a full path length of 500 m. This method significantly reduced the ploughed soil volume by 11.2 %, corresponding to an absolute reduction of 6,638 m³.

![Figure 17: Operation map with on-the-go depth control every 10 m, where the colour mixing represent a continuous depth variation from 150 mm (green), to 200 mm (yellow) and to 250 mm (red).](image)
A comparison of the operational methodologies with the reference ploughing to a consistent depth of 250 mm was carried out. The reference method ploughed and turned a soil volume of 59,518 m$^3$ of the 23.8 ha experimental field. The depth distribution of each operational ploughing method was plotted in weighted histograms (Fig. 18). The different histograms refer to: (A) the deepest depth of each path, (B) the 75 % quantile depth, (C) the 90 % quantile depth and (D) the site-specific control for every 10 m in each path (Fig. 18). The mean depth of method (A) was conservative and reduced the mean depth slightly to 244 mm from the reference of 250 mm, as one or more data points for each path required deep ploughing (Figs. 16 & 18). For method (B), maintaining a consistent depth for each path targeting the 75 % quantile resulted in a smooth distribution around the mean of 231 mm (Fig. 18). For (C), a slightly deeper ploughing depth was achieved, with a mean of 239 mm (Fig. 18). Finally, a very smooth depth distribution around the mean of 222 mm was found for the control preferred site-specific method (D), when adjusting the depth on-the-go for every 10 m (Fig. 17 & 18).

![Figure 18: Weighted normalised histograms for each of the methods: (A) deepest depth, (B) 75 % quantile, (C) 90 % quantile and (D) site-specific within every 10 m.](image)

The different key indicators of the ploughing settings i.e. mean ploughing depths, total soil volume ploughed, reduced soil volume ploughed and percentage of soil volume reduced, were collected and listed for each method of the experimental field (Table 1). The conservative method (A) reduced the ploughing volume by 355 m$^3$, corresponding to a 0.6 % volume reduction. For the 75 % (B) and 90 % (C) quantile depths for each path, the volumes were reduced by 3,787 m$^3$ and 1,991 m$^3$, corresponding to 6.4 % and 3.4 %, respectively. Finally, the site-specific control for every 10 m (D) considerably reduced the soil volume by 6,638 m$^3$, corresponding to a volume of 11.2 %. Guul-Simonsen et al. (2002) found that penetration resistance, and thereby the draught force, increases approximately proportionally to the ploughing depth at the normal depth range and hereafter increases significantly due to the untilled soil plough pan. Therefore, the reduced volume percentage in Table 1 is approximately proportional to the reduction in ploughing energy, and the reductions can therefore be
considered substantial energy savings since tillage generally is the largest consumer of energy in primary plant production (Dalgaard et al., 2002; Sartori et al., 2005; Shamal et al., 2016). For the site-specific control method, reducing the soil volume by 11.2 % will result in a calculated fuel saving of between 6.2 % and 9.2 % when using the correlation between energy and fuel savings from the literature, where depth reductions and fuel consumption have been studied for other tillage systems (Abbaspour-Gilandeh et al., 2005; Keskin et al., 2011; Raper et al., 2005). However, this linear correlation between depth and energy is thought to be conservative, as soil at the bottom of the plough layer tends to be denser and require more energy to loosen and lift, which both require more tillage energy applied. Therefore, even greater energy reductions for all methodologies may be achievable.

*Table 1:* Key indicators for comparing of the operational ploughing methods of site-specific depth control.

<table>
<thead>
<tr>
<th>Ploughing Method</th>
<th>Mean ploughing depth [mm]</th>
<th>Total soil volume ploughed [m$^3$]</th>
<th>Reduced soil volume ploughed [m$^3$]</th>
<th>Percentage of soil volume reduced [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional in 250 mm</td>
<td>250</td>
<td>59,518</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Deepest depth per path (A)</td>
<td>244</td>
<td>59,163</td>
<td>355</td>
<td>0.6</td>
</tr>
<tr>
<td>75 % quantile depth (B)</td>
<td>231</td>
<td>55,731</td>
<td>3,787</td>
<td>6.4</td>
</tr>
<tr>
<td>90 % quantile depth (C)</td>
<td>239</td>
<td>57,527</td>
<td>1,991</td>
<td>3.4</td>
</tr>
<tr>
<td>Site-specific every 10 m (D)</td>
<td>222</td>
<td>52,880</td>
<td>6,638</td>
<td>11.2</td>
</tr>
</tbody>
</table>

Additional studies are needed to independently validate the discussed methodologies, focusing on ploughing performance and, ultimately, yield response. In addition, interaction between depth, skimmers and width with different plough designs and soil interaction needs to be studied in relation to operational performance, focusing on the incorporation of MOG, weed control, surface evenness, energy consumption and, ultimately, yield response. Furthermore, additional model input parameters and their significance needs to be studied, staring with focusing on weeds and soil compaction, calibrated to determine the desired agronomic site-specific depth. A compacted or wet area need deep ploughing, even though low MOG has been estimate, due to a low yield. However, the novel concept plough described, with the discussed operational methodologies, paves the way for further agronomic studies, which together with an updated model, will result in a fully automatic site-specific, depth controlled mouldboard ploughing system for real field applications.

### 2.4. Plough depth control patent

A patent was developed describing the background investigation and the concept invention was IP protected (Patent B), of automatically controlling the mouldboard ploughing depth. A conceptual sketch is shown in Fig. 19, with corresponding abstract.
Figure 19: Conceptual sketch of the plough depth control invention. The invention relates to a coupling mechanism for coupling an agricultural implement (200) to a tractor (300); said coupling mechanism comprising: a top link (2), said top link is having a front end (4) configured to be pivotally mounted on a rear end (6) of a tractor; and said top link is having an opposite rear end (8) configured to be pivotally mounted on a three point linkage (10) of an agricultural implement; a first lift arm (12) and a second lift arm (14); said first lift arm and said second lift arm each having a front end (16) configured to be pivotally mounted on a three point linkage of an agricultural implement; said two front ends of the first and second lift arm, at their points of mounting, are configured to share a common pivot axis (20); wherein said first and second lift arms being adapted to be arranged below the top link; a first hydraulic actuator (22); said hydraulic actuator is having a first end (24) configured to be pivotally mounted at a rear end of a tractor; and a second end (26) configured to be pivotally connected to a three point linkage of an agricultural implement; a hydraulic control valve (28) comprising an inlet (30) and an outlet (30') for pressurized hydraulic fluid; one or more primary outlets (32) for supplying pressurized hydraulic fluid to said first hydraulic actuator (22); and one or more secondary outlets (34) for supplying pressurized hydraulic fluid to a second hydraulic actuator (36) being located on said implement (200) to be moved by said tractor (300); wherein said hydraulic control valve (28) comprising one or more individual valves for controlling the flow of hydraulic fluid from the inlet (30) for pressurized hydraulic fluid to the first hydraulic actuator (22) and the second hydraulic actuator, respectively.

2.5. Top linkage control patent

During the study of the plough depth control system and the development of the hydraulic system, a new invention for controlling the top linkage active was studied and IP protected (Patent C). This system can be used in combination with the active depth control system to adjust the load on the rear end of the plough to apply more downforce to the rearmost plough sections. Furthermore, it can be used to transfer more downforce to the front wheels of the tractor to increasing the traction force, or distribute front-rear wheel load to comply with soil compaction. Finally, the invention can be used to minimise implement oscillations when elevated during transport. When transporting heavy lift-mounted implements such as ploughs, cultivators, seed drills, etc., oscillations often occur; this can be controlled with the principle IP protected by the invention (Patent C). A conceptual sketch is shown in Fig. 20, with corresponding abstract.
Figure 20: Conceptual sketch of the dampening invention (100). The invention relates to a coupling mechanism for damping oscillations between a tractor and an agricultural implement during transport thereof; said coupling mechanism comprising: a top link, said top link is having a front end (4) configured to be pivotally mounted on a rear end (6) of a tractor; and said top link is having an opposite rear end configured to be pivotally mounted on three point linkage of an agricultural implement; wherein said top link is comprising a hydraulic actuator (38), said hydraulic actuator is having a front end (40) and a rear end (42); said hydraulic actuator is being arranged between the front end and the rear end of said top link so as to allow altering the effective distance between the front end and the rear end of said top link; a first lift arm (12) and a second lift arm (14); said first lift arm and said second lift arm (12,14) each having a front end (16) configured to be pivotally mounted on a rear side of a tractor and an opposite rear end (18) configured to be pivotally mounted on a three point linkage of an agricultural implement; said two rear ends of the first and second lift arm, at their points of mounting, are configured to share a common pivot axis (20); wherein said first and second lift arms (12,14) being adapted to be arranged below the top link (2); a transducer (44); said transducer being configured to sense the load exerted between the front end (40) and the rear end (42) of said hydraulic actuator; a hydraulic valve comprising one or more outlets and being configured to supply pressurized hydraulic fluid to said hydraulic actuator in response to instructions received by said hydraulic valve; a control unit configured to receive a signal (54) provided by said transducer, and being configured to translate this signal into instructions to be supplied to said hydraulic valve according to a predetermined protocol in order to suppress any oscillations encountered between a tractor and an agricultural implement during transport thereof.

3. Coulter depth sensing and control for seeding

3.1. Concept investigation

The novel coulter depth measurement and control system, developed and tested in the soil bin, was found capable of sensing and maintaining a consistent drill coulter depth independent of coulter-soil resistance variations (Paper IV). The rotational soil bin was found beneficial for evaluating the coulter depth control system (Fig. 2, Paper IV).

In the static experiment the coulter angle was accurately calibrated to the coulter depth. The dynamic experiment verified the accuracy for dynamic conditions by coulter depth cross-correlation to the sub-millimetre iGPS reference system, calculated to be 0.99, tested with six rotational repetitions in the soil bin (Fig. 3, Paper IV). In addition, the dynamic experiments concluded that the system was able to
detect rapid coulter depth variations generated from rigid stone simulators. When examining the soil variation with the conventional fixed downforce spring, the mean coulter depth decreased by 23 mm due to changes in soil-coulter resistance when the seedbed was changed from sand to gravel. This depth change generated the anticipated condition for testing the control systems, adjusting the coulter pressure according to the change in soil resistance.

The dynamic coulter pressure control system showed significant improvements, in achieving and maintaining the desired coulter depth independently of variations in soil resistance. It could be concluded that all three studied control algorithms minimised the depth variations and were able to find, with slightly different levels of accuracy, the desired depth despite the significant change in seedbed resistance from sand to gravel. The small differences between the control system’s inaccuracies were found to be inconsiderable and mainly related to randomness from the soil. The power spectral analysis identified the frequencies to have the greatest magnitudes below 1 Hz, which meant that coulter depth variations tended to have slow depth variations (Figs. 5 & 6, Paper IV). This finding was as anticipated and essential for the system, since none of the control systems reacted fast enough to minimise vibrations greater than 1 Hz. To minimise more rapid depth vibrations, the system’s dead time and response time have to be improved, which are mainly related to hardware constraints of the hydraulic actuating system. However, a too fast response is not desirable for the mechanical construction, as the coulters have to be able to handle stones, without damaging the construction.

The PID control system was the most stable and accurate control system, but it was important that the D control part was inhibited with the filter because it tended to generate instability caused by the depth vibration.

![Figure 21: Measured coulter depth and control output for a step in the set-point coulter depth from 55 mm to 44 mm for sand using three-position control (a), P-control (c), and PID-control (e) and for gravel using three-position control (b), P-control (d), and PID-control (f).]
From the step in the set-point, the PID control had a faster response than the P control, but considerably slower than the three-position control; however, the PID and P controls were more accurate than the three-position control, due to the nearly elimination of the undesired static error (Fig. 21). For greater depth variations, all controls system would momentarily adjust the output to the maximum, making them equally fast until the P and afterwards the PID control reduced the actuator output level, due to the proportional control action. The three-position coulter depth control system was found to be the most cost-efficient solution for a proof-of-concept of the studied technologies. The three-position system provided a mean depth deviation from the desired coulter depth of -0.89 mm (SD=1.08) and -1.18 mm (SD=1.55) for sand and gravel, respectively.

3.2. Individual coulter depth sensing

The novel instrumentation from the soil bin was further developed and implemented on the full-scale, three-meter wide seed drill. The system was found to be functional for static and dynamic conditions for high-resolution, on-the-go measurements of the individual coulter operational depths (Paper V). The field experiment generated the data to verify the concept and study coulter depth variations in a real field application.

Heege (1993) found seed depth variations for drill seeding (with disc, shoe and packer-ring) to vary with a SD between 6 and 11 mm. In this study, testing the single-disc drill, greater magnitudes of coulter depth variations were found (SD from 16.5 to 18.0 mm). Table 2 presents the distribution of the mean coulter depth measurements in percentages for specific depth intervals at the three operational speeds (depths are given as negative values since positive coulter values indicated that the coulter released the seed above the soil surface). The magnitude of the coulter depth variations tended to increase with speed (Table 2); however, this was not tested significant. Less than 25 % of the mean coulter depth measurements were within ±5 mm of the targeted -30 mm depth and the percentage decreased when increasing speeds (22.2, 20.7 and 19.0 %, for 4, 8 and 12 km h\(^{-1}\), respectively). The same trend of deviation was observed for -60 to 0 mm interval (90.3, 88.5 and 85.5 % for 4, 8 and 12 km h\(^{-1}\), respectively). Therefore, a higher percentage of the mean coulter depth measurements closer to the targeted depth of -30 mm were achieved when lowering the speed (Table 2). This means that the depth distribution increased with speed due to higher coulter resistance, which was also shown by the probability density functions (Fig. 5, Paper V). The mean of the coulter depths tended to decrease slightly with increasing operational speed. Mean coulter depths for speeds of 4, 8 and 12 km h\(^{-1}\) were -22.1, -20.9 and -19.0 mm, respectively. These small variations in coulter depth means and variations can be related to the speed relative to soil mechanical properties: soil deformation can occur at a given rate and increasing the operational speed will prevent coulter penetration.
Table 2: Mean coulter depth measurements in percentage disturbed between six chosen coulter depth intervals, for each of the three tested operational speeds.

<table>
<thead>
<tr>
<th>Interval</th>
<th>4 km h(^{-1})</th>
<th>8 km h(^{-1})</th>
<th>12 km h(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>-35 to -25 mm</td>
<td>22.2 %</td>
<td>20.7 %</td>
<td>19.0 %</td>
</tr>
<tr>
<td>-40 to -20 mm</td>
<td>42.5 %</td>
<td>40.0 %</td>
<td>37.0 %</td>
</tr>
<tr>
<td>-50 to -10 mm</td>
<td>73.7 %</td>
<td>71.0 %</td>
<td>66.8 %</td>
</tr>
<tr>
<td>-60 to 00 mm</td>
<td>90.3 %</td>
<td>88.5 %</td>
<td>85.5 %</td>
</tr>
<tr>
<td>On soil surface</td>
<td>8.9 %</td>
<td>10.6 %</td>
<td>13.5 %</td>
</tr>
<tr>
<td>Below -60 mm</td>
<td>0.9 %</td>
<td>1.0 %</td>
<td>1.1 %</td>
</tr>
</tbody>
</table>

The targeted mean coulter depth of -30 mm was not reached at any of the tested speeds (Fig. 5, Paper V). A few seeds were released above the soil surface, but they might still be partly covered due to the light post-seeding harrowing carried out by the seeder. The significance of the fixed terms in the mixed linear model: Coulter, Speed, and their interaction were tested using Likelihood ratio tests. Only the coulter position had significant effects on coulter depth. According to this model analysis, operational speed had no significant effect on coulter depth, which means that all the coulters reacted approximately similarly when increasing operational speed. However, when considering speed as a continuous variable in the mixed linear model, a decrease of mean coulter depth of 1.5 mm for a 4 km h\(^{-1}\) speed increment was found, although not tested significantly. The random effect factors could not be eliminated by the Likelihood ratio test and a significant random block effect on coulter depth was found (P<0.0001). The model residuals of the whole measuring system describing the variance of the coulter depth can be represented by the standard deviation (SD=15.7 mm). The SD from the model representing the random effect, Block:Speed:Coulter, was found to be 2.6 mm (block effect for the individual coulter depth means in one trial compared to the modelled mean). The mean coulter depth for all coulter positions differed significantly between trials, with a SD of 5.1 mm, as determined by the random effect Block:Speed (block effect for the individual trial depth means compared to the modelled mean).

Bias of the mean coulter depth in the driving direction across the entire experimental field was calculated for each coulter and for visualisation; it was smoothened by a moving average filter using ±10 data points. Bias of the mean coulter depth ranged from ±5 mm from the target depth across the driving direction (Fig. 22). This inconsistent coulter depth was caused by variations in soil mechanical properties between the blocks, as the seeding operation was performed with a fixed coulter pressure. The depth depends on the soil-coulter resistance to penetrate. Penetration resistance can be measured by a penetrometer (Garrido et al., 2011). Field variations can also be measured and mapped by electromagnetic resistance measurements (Godwin and Miller, 2003). No relationship was found between the EM38 map for the experimental field when comparing with the measured coulter depth variations. This coulter depth variability across the field highlights the need for coulter pressure
adjustments to the variable soil conditions to achieve and maintain the desired coulter depth. The results also illustrate the potential of using the coulter depth measurement system for mapping variations in soil mechanical properties.

![Bias of coulter depth means in the driving direction for each coulter across the field.](image1)

*Figure 22:* Bias of coulter depth means in the driving direction for each coulter across the field.

The determined coulter pressure was not sufficient to secure the targeted mean depth of -30 mm for any of the coulters (Fig. 23). Mean depths differed significantly between individual coulters, whereas the interaction between the coulters across speeds was not significant. The least squares mean of coulter depths varied from -14.2 to -25.9 mm for coulter 2 and 10, respectively. These two coulters were located in the wheel tracks of the tractor. Using Tukey’s range test, the coulters were grouped according to their significantly different mean depths (P<0.05) by non-identical letters, labelled A (deep) to G (shallow) (Fig. 23). No similar study of coulter depth variation within the operational width of a seed drill has been found in the literature.

![Modelled mean depth for each coulter of the seed drill in the driving direction. Different letters indicate significant differences between coulters (P<0.05).](image2)

*Figure 23:* Modelled mean depth for each coulter of the seed drill in the driving direction. Different letters indicate significant differences between coulters (P<0.05).

Coulter 10 seeded in the loosened wheel track and coulter 2 in the unloosened track, as no track eradicators were mounted in that side. Shallow coulter depth in wheel tracks can be mitigated by the use of track eradicators, as shown in this study, although it is important to avoid too intensive a loosening
and thus risking a deeper coulter depth compared to the remaining coulters (Fig. 23). This finding shows the importance of seeding in soil with an even soil-coulter resistance, i.e. by uniformly prepared seedbeds by correct setting of track eradicators or using a common front roller to evenly compact the soil in the full operational width. Alternatively, individual coulter pressure adjustment for the coulters operation in the wheel tracks could be installed.

Traces of the Power Spectral Densities (PSD) for the coulter depth at the three tested operational speeds of 4, 8 and 12 km h$^{-1}$ were analysed from the raw sensor data of coulters 2, 6 and 10. The only other PSD analysis of coulter depth variations found in the literature was by the previous soil bin study (Paper IV). To evaluate the remaining combination of coulters versus speeds, a function was applied extracting the 15 greatest peak values for each PSD function and plotting the values in a common graph (Fig. 9, Paper V). These values represent the majority of the power magnitudes (peaks) with their respective frequency, in a method similar to that used by Jeon et al. (2004). With this method the evaluation included and represented in one plot the nine combinations of all the different speeds for coulter 2, 6 and 10. The majority of coulter depth variations fell within the frequency band from 0 Hz to approximately 0.5 Hz, independent of speed (Fig. 9, Paper V) which is consistent with soil bin experiment (Paper IV). A few coulter depth oscillations with frequencies greater than 0.5 Hz were also observed, but only with low power spectral density (Fig. 9, Paper V). The frequency band of coulter depth oscillations widened slightly when increasing the operational speed, but without any considerable change in power magnitude. No clear natural frequencies were identified by the discrete Fourier transformations of the coulter depth measurements.

The developed coulter depth measurement system was found to work well and can be utilised to provide important field management information such as on-the-go monitoring or mapping of individual coulter-soil resistance measured by the coulter depths, to adjust setting of operation speed, coulter pressure, observe stones stock to a coulter or adjusting the intensity of the track eradicators. However, the full potential of the measurement system can be achieved if the sensor signal is used for a full-scale, dynamic, on-the-go automatic coulter pressure control system. Such a system should be able to operate site-specifically and maintain the coulter pressure, irrespective of variable seedbed conditions.

3.3. Full-scale, on-the-go coulter depth control
The full-scale seed drill with the automatic, on-the-go coulter depth control system was developed and evaluated (Paper VI). The signals from the 11 coulter depth measurement instrumentation, studied in paper (V) were used to analyse the performance of the treatments: “No Control” and “Control”, tested at the same three operational speeds, 4, 8 and 12 km h$^{-1}$. The raw coulter depth data produced in the experiment are depicted as heat-intensity-depth maps in Fig. 24.
Figure 24: The coulter depth measurements shown for all four blocks and the three different operational speeds of 4 (A), 8 (B) and 12 km h\(^{-1}\) (C). Target depth is in green, blue is deeper than target depth, yellow is closer to the surface than the target and red is on top of the soil surface.

The heat-intensity-depth maps show all the measurements registered for the four blocks and the six trials. As the distance from the frame to the soil surface was estimated using two ultrasonic sensors and linear interpolation, some of the measurements might not represent the actual coulter depth relative to the respective soil surface in the coulter row. Any stone, soil lump, or curvature generating micro-topography in between the surface sensors will not be registered due to the linear interpolation from the frame height sensors. On the other hand, micro-topography in the measured row will influence the frame height measurement adversely. This explains the lateral lines (Fig. 24), with unanticipated rapid colour changes. This can potentially lead to small inaccuracies in the coulter depth measurement system. However, due to the brevity of the changes, the coulter pressure settings were not affected by the control system and the same measurement system was used to examine both treatments (no control and control). Therefore, this was not considered to impact the evaluation of the system. In the longitudinal direction there were, however, some unanticipated coulter depth variations, e.g. in Fig. 24B, block 1 of the control with 8 km h\(^{-1}\), where one coulter was seeding on top of the seedbed. This was most likely due to soil containing stones or a lump of residues, been picked up or accumulated on the coulter. The data affected represented 1.5 % of the treatment data and removing it did not impact the evaluation of the control system for the treatment. When visually assessing the heat-intensity-depth...
maps, the seed drill with the active coulter depth control system had, overall, a more consistent
dominating green colour (i.e. closer to the target depth) than without the control system, as the coulters
operated more consistently at the targeted depth (Fig. 24).

A graph displaying the cumulative displacement percentages vs. the confidence interval of coulter depth
measurements around the -30 mm target coulter depth for the three operational speeds with and without
depth control is shown in Fig. 25. For example, at a confidence level of 90 %, the confidence intervals
were 24, 26 and 26 mm for the control system and 30, 32 and 34 mm for the standard seed drill, at 4, 8
and 12 km h\(^{-1}\), respectively. The graph clearly demonstrates the improvement achieved by the depth
control system compared to the standard seed drill for all working speeds. The graph also illustrates the
almost non-visible difference between 8 (red) and 12 km h\(^{-1}\) (blue) with the depth control system active,
which means that the system brought about a considerable improvement, allowing the operator to work
at 12 km h\(^{-1}\) almost without compromising performance (Fig. 25).

![Figure 25: The cumulative measurement percentages against confidence intervals of depth measurements
with and without the depth control system, for the different operational speeds. Note that the 8 km h\(^{-1}\)
line (red) for the depth control system coincides with the 12 km h\(^{-1}\) (blue), and is thus hidden behind it.]

Probability density functions, illustrating the mean coulter depth distributions for the three operational
speeds with and without the depth control system, are shown in the histograms in (Fig. 4, Paper VI). All
six plots have approximately symmetric and unimodal forms. Nevertheless, the histograms for the depth
control system show a higher relative frequency at the targeted depth and a narrower distribution around
the mean depths than the histograms for the standard seed drill without control. Coulter mean depths
and standard deviations for the different speeds and systems registered the following values at
respectively 4, 8 and 12 km h\(^{-1}\) with the coulter depth control system -26.5 (SD=14.3), -24.7 (SD=15.5)
and -23.7 mm (SD=15.2 mm), and without the coulter depth control system -22.0 (SD=16.4), -20.9
(SD=17.0) and -19.0 mm (SD=18.0 mm). The mean depths were shallower than the targeted depth for
both systems. This was caused by the hydraulic actuating system design, operating with a one-
directional cylinder and the actuator’s release speed therefore depended on the soil resistance (counterforce) acting on the coulters. However, the mean coulter depths for the different speeds were consistently closer to the targeted depth with the control system activated. The mean coulter depth offsets from the targeted depth were 3.5, 5.3 and 6.3 mm for the depth control system at 4, 8 and 12 km h\(^{-1}\), respectively, compared to 8.0, 9.1 and 11.0 mm without the depth control system. The offsets were calculated as the distance relative to the targeted depth of -30 mm, defined from the measured and interpolated soil surface. Therefore, the presented coulter depth measurement might show more variation than the actual seeding depth in the specific rows, as the individual coulters were spring-loaded, allowing them to follow some of the individually micro-topography, due to the soil-coulter resistance. However, this did not influence the evaluation of the system performance as the analyses were conducted with the same coulter depth sensing system for both evaluations.

3.4. Independent examination of the coulter depth control system

The seeding depth evaluation based on manual seedling mesocotyl measurements gave mean seeding depths of -33.7 mm (SD=7 mm) and -34.5 mm (SD=9.4 mm) at 4 and 8 km h\(^{-1}\), respectively, with the depth control system activated, and -34.9 mm (SD=10.7 mm) and -34.3 mm (SD=9.8 mm) without it, as shown in Table 3. Even through the coulter depth control system presented values closer to the target depth for a speed of 4 km h\(^{-1}\), no significant difference between the mean values was found between the treatments, with the number of samples registered. At least 106 measurements were taken for each trial, but these measurements were not sufficient to conclude on significance on their means or variances using a \( t \)-test and \( F \)-test. An exception was for a speed of 4 km h\(^{-1}\), where the samples showed a significant difference for the standard deviation between the seed drill with the depth control system and without it. However, a more uniform depth distribution for the depth control system was generally found when analysing the raw data. This evaluation method was limited by the fact that the seedlings measured were exclusively the seeds that had emerged at the time of sampling, leaving potentially relevant data unregistered, e.g. seeds that did not germinate and become plants. This could be caused by seeds placed on the surface or being planted too deep, resulting in no or extremely delayed emergence. This reveals the relative complexity of comparing the mesocotyl and the coulter depth measurements (Table 3), as the extreme values, e.g. non-emerged seeds, were not considered in this evaluation method.

The second independent evaluation method employed was the multispectral images used for calculating the NDVI. The NDVI mean values (Table 3) were slightly lower for the trials with the depth control system than without it, due to environmental conditions. A very wet period experienced during the field experiment allowed seeds close to the surface to emerge and establish faster than the seeds at target depth. Between 34 mm and 51 mm of rain was registered in the area from the seeding date on 11 April.
until the NDVI data collection on 30 April, which was substantially above the mean for that period of 25 mm (DMI, 2016). Therefore, coulter depth measurements for the seed drill without the depth control system had slightly higher mean values, due to more developed seedlings, than the seedling with the depth control system (Table 3), causing the insignificantly higher NDVI values. However, F-test showed that the NDVI variances for the trials with the depth control system and without it differed significantly for all working speeds (Table 3). Consequently, the NDVI for the seed drill with the depth control system was significantly more uniform than without it, thus showing that the seedling developed more consistently, most likely as a result of the more uniform seeding depth. The NDVI variances obtained imply therefore that the method used for depth control system validation confirms the uniformity of the seeding depth, as found by seed drill coulter depth measurement system.

Table 3: The results from the three evaluation methods showing the means and standard deviations for the different treatments and operation speeds.

<table>
<thead>
<tr>
<th></th>
<th>4 km h⁻¹</th>
<th>8 km h⁻¹</th>
<th>12 km h⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Depth control</td>
<td>No control</td>
<td>Depth control</td>
</tr>
<tr>
<td>Mean</td>
<td>-26.5</td>
<td>14.3</td>
<td>-24.7</td>
</tr>
<tr>
<td>SD</td>
<td>-33.7</td>
<td>7.0</td>
<td>-34.9</td>
</tr>
<tr>
<td>Mesocotyl length measurement [mm]</td>
<td>-34.5</td>
<td>9.4</td>
<td>-34.3</td>
</tr>
<tr>
<td>NDVI calculations</td>
<td>0.236</td>
<td>2.3 10⁻²</td>
<td>0.241</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.242</td>
</tr>
<tr>
<td></td>
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</tr>
</tbody>
</table>

The overall results exposed in Table 3 agreed with previously discussed data and graphical representations (Fig. 24, 25) that the low-cost coulter depth control system effectively improves the uniformity performance of the seed drill and being able to control of the coulter pressure on-the-go, maintaining a more consistent coulter depth, despite changes in soil-coulter resistance.

3.5. Mixed linear modelling examining the coulter depth control system

The residuals from the mixed linear models created from the coulter depth measurement followed approximately a normal distribution, as shown by the values of 0.695, 0.954 and 0.995 for the conventional system and 0.700, 0.954 and 0.994 for the control system, for one, two and three standard deviations, respectively. The mixed linear models found that only Coulter was significant for the fixed terms when testing Coulter, Speed and their interaction for both models (conventional seed drill system and with the control system), as found in the coulter depth measurement study (Paper V). It was not possible to reduce any of the random effects from the initial models, similar to the coulter depth measurement study (Paper V). Therefore, both models included the same factors of fixed terms and random effects. In the final mixed linear models of the conventional system and the control system different standard deviations of the random effects for the models were found. The standard deviations express the variation of coulter depths relative to the estimated mean depths from the models.
For the system without the active control, a resultant standard deviation of 17.1 mm was found for the linear mixed model residuals. When activating the coulter depth control system, the resultant standard deviation was significantly reduced to 14.5 mm. These resultant standard deviations describe the residuals for the modelled coulter depth and were probably mainly caused by the spatial variation in soil mechanical properties. To evaluate the variation and the performance of the active control system, the lateral block effect of the field was calculated based on the coulter depth with the static coulter pressure and active coulter pressure control system. The block effect was calculated as the longitudinal mean coulter depth for each coulter across the experimental field for “No control” and “Control” (Fig. 26). These block effects illustrated in Fig. 26 were found by smoothing the individual coulter depths by a laterally moving average filter using ±10 data points. In the coulter depth measurement study (Paper V) a block effect was found with a bias variation of up to ±5 mm from the mean coulter depth. A similar block effect was found in this study, although it was up to ±8 mm without the control system activated. When activating the coulter depth control system, it was significantly reduced to ±2 mm (Fig. 26).

The reduction in the standard deviations in the mixed models when activating the control system was calculated to be 15.2 %. This improvement was found by the resultant coulter depth deviation reduction, when comparing the linear mixed models of the standard seed drill and the developed seed drill with the active control system. When calculating at the 95 % confidence interval, a considerable absolute reduction in the coulter depth confidence span of 10.4 mm was achieved when activating the control system. When analysing the coulter depth deviations using Monte Carlo simulations, the difference was found to be significantly reduced (p<0.005). At the 95 % confidence interval, the span reduction ranged from 7.2 mm to 13.3 mm when the mixed models’ confidence span was calculated with the simulated deviations. In conclusion, the developed seed drill significantly reduced the undesired coulter depth variations, maintaining a more consistent coulter depth when activating the developed coulter depth control system, independent of soil-coulter resistance variations.
3.6. Seed drill depth control patent

In addition to the three papers (IV, V, VI), patent (D) was developed for IP protection with a background study and description of the seed drill depth control invention. A principle illustration of the invention is presented in Fig. 27, with corresponding abstract.

Figure 27: Conceptual sketch of the coulter depth control invention. The apparatus relates to a sowing apparatus (200), said sowing apparatus comprises: a frame (2) comprising a front end and a rear end, as seen in relation of the intended direction of movement; said intended direction of movement defining a longitudinal direction (X) of the apparatus; wherein said frame is having an extension in a vertical direction, said vertical direction being perpendicular to the longitudinal direction (X); wherein said frame comprising one or more shear carriers (8), said shear carriers each having a first end and a second end; wherein said one or more shear carriers (8) at its first end being pivotally suspended onto said frame in a suspension (202); wherein said shear carrier at its second end (12) comprising one or more shears (16) adapted to be at least partially submerged into the soil (18); wherein in respect of one or more of said one or more shear carriers (8), said frame comprising seed conveying means (20) for conveying seeds into the soil at a position corresponding to one or more of said one or more shears; wherein in respect of one or more of said one or more shear carriers (8), said apparatus comprises a sensor (14) for detecting the position of said shear carrier in relation to the frame; said sensor (14) being configured to provide an output signal representing a sensed position of said shear carrier (8); wherein in respect of one or more of said one or more shear carriers said apparatus comprises an actuator (204) for altering the position of the shear carrier in relation to the frame; wherein said apparatus comprises a control unit configured to receive said output signal from said sensor; wherein said control unit is configured to provide an output signal for controlling said actuator; wherein said control unit is connected to an input device, said input device being configured to allow an operator to provide said control unit with instruction relating to the desired response of the actuator, based the input signal of said sensor (14).
3.7. Intensity control of track eradicator patent

Throughout the seeding study (Paper V) an significant undesired lateral coulter depth variation, across the seed drill operational width, especially in the wheel tracks was observed. This depth variation between the coulters was found on-the-go measureable using the developed coulter depth instrumentation, studied in (Paper V). A patent was developed presenting the background and a description of the invention (Patent E), where the seed drill instrumentation detected this variation to provide the dynamic input signal to control the site-specific intensity of the track eradicator. In addition, other sensor methods were described, covering multiple sensing approaches. A principle illustration of the invention is shown in Fig. 28, with corresponding patent abstract.

![Conceptual sketch of the intelligent control track eradicators invention. The invention relates to a system (100) for soil loosening of soil (2) which has become compacted by wheels (4) of an agricultural vehicle (200) or an agricultural implement, said system comprises: -one or more soil loosening devices for loosening soil in a wheel track (12); -in respect of each soil loosening device, a sensing system (14) which is configured for sensing a height difference between soil located in said wheel track (12) and soil (18) located outside said wheel track (12); -a control unit (20); wherein each of said one or more soil loosening devices (100) comprises one or more soil loosening elements (22) for loosening soil is said wheel track (12), and wherein each of said one or more soil loosening elements (22) is/are mechanically connected to adjustment means (24) for adjusting the degree of soil loosening provided by said one or more soil loosening elements (22); wherein said sensing system (14) being configured to provide one or more sensing signals (26) representative of said sensed height difference of soil; and wherein said control unit (20) is configured to receive said one or more sensing signals (26) provided by said sensing system (14) and to provide a control signal (28) on the basis thereof; wherein said adjustment means (24) is configured to receive said control signal (28), and on the basis thereof to adjust the degree of soil loosening of said one or more soil loosening elements (22) of said one or more soil loosening devices (100).](image-url)
Chapter 4 General discussion and perspectives

1. Site-specific field operations in a Smart Farming context

A number of novel intelligent agricultural technologies and methodologies have been described and discussed throughout the thesis. All of the technologies were optimised regarding site-specific performance, by dynamically controlling machine settings in customised machines, to take full advantage of the utilised resources. The primary controllable resources utilised in plant production are: machinery, fuel, seeds, fertiliser, chemicals, agricultural land, water, wearing parts, etc. The desired efficient resources have to be chosen and applied, with the preferred site-specific quantities, but also at the optimal time, to gain the highest yield in a sustainable, effective plant production.

Site-specific, controlled field operations are considered one of the key concepts for improving yield and sustainability, when the desired operational settings and resource quantities are applied at the right location. Therefore, the studied concepts and methodologies all enabled in-field, site-specific control in order to take account of the spatial field variability (Abbaspour-Gilandeh et al., 2005; Dexter et al., 2007). To initialise site-specific, dynamic field operations, the machines were integrated with sensors, actuators, potentially with online data access, for on-the-go control of machine settings. These modifications ensured the machines operated with the site-specific settings to the encountered field conditions. The information needed for controlling the settings relative to spatial field variability can be provided from multiple measurement sources, i.e. implement-mounted or external (hand-held, for example) sensors, stationary soil sensors, satellites or drone sensors, all measuring physical parameters for monitoring or predicting soil, crop, disease or yield.

In the last decade it has become more common for accurate Real Time Kinematic (RTK) Global Navigation Satellite Systems (GNSS) to be integrated on tractor and implements, e.g. for section control (Heege, 2013; Luck et al., 2010) or auto steering, i.e. for controlled traffic farming (Gasso et al., 2013; Jensen et al., 2012). This broad integration of positioning systems paves the way for further integration of site-specific data by mapping machine measurements or applying background data for site-specific control (Jensen et al., 2012; Kaivosoja et al., 2014; Plant, 2001). Therefore, the developed machines as part of this thesis are essential for Smart Farming integration, in that they provide site-specific measurements and utilise background spatial data for site-specific control of field operations.

The concept of utilising spatial or temporal information is a part of the “Big Data” theme which can be used in intelligent farming, also known as Smart Farming, where a large number of data can be included for operation management (Wolfert et al., 2017). Examples of such information can be background maps of land/soil information, crop information, previous field operation measurements, external
information such as historical weather data or forecasts, etc. (Wolfert et al., 2017). An architecture and implementation of Big Data in Smart Farming has been studied by Kaloxyllos et al. (2014). Smart Farming supports the entire food supply chain, but it has some socio-economic challenges because a number of different stakeholders have to collaborate and satisfy their individual interests (Brewster et al., 2017; Wolfert et al., 2017). The key issues of Smart Farming are: data capture (availability, quality and formats), storage (quick and safe access), data transfer (safety, responsibility and liability), transformation (heterogeneity of sources, cleansing and preparation), analytics (scalability) and marketing (ownership and privacy) (Brewster et al., 2017; Verdouw, 2016; Wolfert et al., 2017). Big Data is being used to provide predictive insights into farming operations and for decision support, but also for the redesign of business models. Furthermore, Smart Farming can be used to document compliance with, or create new, regulations (Kaivosoja et al., 2014). When it is possible to document site-specific utilisation of resources, it might open an avenue for new improved site-specific regulations or quotas, e.g. for tillage, spraying or fertilisation, to reduce erosion or risk of leaching, to meet a more sustainable plant production. However, this descriptive insight might not be desirable for all farmers, as some potential see it as external monitoring for ongoing evaluation of their performance and behaviour, which might not create the readiness to change, potentially inhibiting the utilisation of intelligent site-specific machines.

When integrating and utilising site-specific dynamic control, qualitative improvements can be expected for the majority of agricultural operations when operating in heterogeneous fields, for example for controlling spraying (Kaivosoja et al., 2014), correct depth of tillage (Guul-Simonsen et al., 2002; Håkansson et al., 1998) with significant energy savings (Abbaspour-Gilandeh et al., 2005; Keskin et al., 2011; Raper et al., 2005; Sartori et al., 2005; Shamal et al., 2016), or site-specific seeding (Kiani, 2012; Suomi and Oksanen, 2015; Weatherly and Bowers Jr., 1997). A controlled site-specific operation for seedbed preparation and seeding aims to optimise the conditions for crop establishment, which consequently can improve crop yields (Durr et al., 1992a).

An illustrative example of crop establishment, including harvesting, in a Smart Farming context with data sharing between the operations and seasons with different measurement sources is shown in Fig. 29. Smart Farming with Big Data can be used to improve not only a single field operation but the entire cropping chain, once site-specific intelligent machines that utilise and produce new valuable data for future field operations have been integrated (Fig. 29). One example from this study is the grain yield data being used directly for modelling the site-specific ploughing depth. Other examples are draught force measurements during ploughing to work out next year’s tillage operations, for example modelling of ploughing depth or how to apply the studied section control system, regarding traction force control. Another example is using the seed drill coulter depth measurement system, which could be used for
site-specific control of secondary tillage to reduce spatially variable effects in the soil, when preparing the seedbed the following year.

Figure 29: Illustrative example of Smart Farming sharing data between field operations to control the machines site-specificity, with examples of measurement sources such as satellites, drones and machine-integrated sensors.

2. Site-specific primary tillage

One approach to site-specific tillage is the section control system for mouldboard ploughing, which was developed (Paper I) and IP protected (Patent A). When introducing the concept on a full-scale plough, the ploughing operation at the interface area between the headlands and the main working area will be significantly improved because the operation starts nearly perpendicularly to the main working area, reducing overlapping. The system was tested with a modified concept plough and a surface evaluation. A more thorough evaluation could include an analysis of the ploughed topsoil profile to validate the agronomic effects, focusing on weed control, residue incorporation, number of emerging seedling and yields response of the controlled operation when using a full-scale plough with section control. According to the calculations, the overlapped area for a five-furrow plough will be reduced by 80 %
and the improvement will increase with the number of plough sections. The system was developed with hydraulic stone release and individually activation and deactivation of the sections. By deactivating one section, a new traction force reduction control system was integrated, usable when operating in hilly areas, as more traction force is needed uphill, than downhill. Furthermore, on-the-go deactivation of the individually sections can also be used to improve wedge operations, when finalizing the main working area of the field, instead of the compromise with an ongoing reduction of the width. Theses system can be controlled manually by the operator or automatically when combined with the depth control modelled maps. The number of utilised sections can preferably be determined in the headlands; or otherwise it can be changed on-the-go in the main working area if more traction force is unexpectedly needed. In general, the developed section control system is expected to improve by a more homogeneous ploughing performance considerably in the interface and in wedge operations, and it can be used for controlling the need traction force. A homogeneous ploughing in interfaces is of crucial importance to achieve the targeted incorporation of residues and applied weed control. Optimal primary tillage can have a positive effect on subsequent operations such as reducing the need for spraying chemical or the number of passages of secondary tillage to achieve the desired seedbed for plant growth conditions.

A novel plough depth control system was developed (Study II) and IP protected (Patent B). The concept utilised an external telescopic hydraulic cylinder in the three-point linkage to achieve the stroke length needed when the tractor’s lift elevates the plough in the headlands. The concept took over the control of the tractor lift’s during the ploughing operation, independent of the communication with the tractor. This concept was the first exemplification of applying automatic depth control on a mouldboard plough. Multiple novel operational depth control methodologies were subsequently developed and discussed (Study III). All the methodologies considerably reduced energy consumption by reducing the ploughed soil volume from 0.6 up to 11.2 %. However, experimental studies are needed to independently validate the discussed methodologies by evaluating the interaction between depth, skimmers and width using different plough designs, and the interaction with soil in terms of operational performance, focusing on the incorporation of surface residues, weed control, surface evenness, energy consumption and, ultimately, yield response. Furthermore, model input parameters and calibration of their significance for site-specific depth control need additional agronomic studies. Guul-Simonsen et al. (2002) found soil texture, structure, compaction and moisture, as well as strength, plasticity and workability, to be important parameters when determining the conventional ploughing depth. However, their significance for depth modelling combined with MOG needs additional calibration studies. The combination of the developed concept plough and methodology will result in an automatic site-specific ploughing depth control system designed to improve soil structure with variable MOG quantities. A further development in modelling input to a controlled ploughing operation, could be to combine it with workability
(Edwards et al., 2016) and including additional temporal decision support i.e. by variable depth periodically, to achieve shallower ploughing in some years as it does not in all cases results in appreciable risk of yield losses (Guul-Simonsen et al., 2002). Using a shallower ploughing depth increases the risk of additional perennial weeds, which is a significant adverse effect necessitating other eradication methods such as chemicals (Guul-Simonsen et al., 2002) or the occasional deep ploughing. If changing the operation depth periodically, the compacted plough pan can be avoided (Guul-Simonsen et al., 2002; Natsis et al., 1999). If operating at a shallower depth, the soil will become more workable as the thresholds for workability depend on the operational depth (Edwards et al., 2016). A reduction in operational depth will also leads to a longer time interval for carrying out the tillage operations. Furthermore, both shallower ploughing when using the depth control and the section control for traction force control, both requires less traction force. This means that smaller tractors with lower weight might be sufficient for the operation, which also increases trafficability (Edwards et al., 2016) and reduces subsoil compaction (Schjønning et al., 2015).

The focus has been on the mouldboard plough but all tillage implements, in general, require significant energy inputs (Dalgaard et al., 2002; Sartori et al., 2005), meaning even small intensity reductions can result in considerable absolute energy improvements. The technologies and methodologies are, with modifications, transferable to the majority of tillage implements, as the intensity in most cases can be manually adjusted by the operational depth, tine angle or PTO speed. A reduction in operational depth or intensity can result in, not only in a considerable energy saving (Abbspour-Gilandeh et al., 2005; Keskin et al., 2011; Raper et al., 2005; Sartori et al., 2005; Shamal et al., 2016) but it may also have a positive effect on yield, lower risk of erosions and environmental impacts (Jensen et al., 2012; Petersen et al., 2016; Van Muysen and Govers, 2002). In this methodology study, MOG data was used as an input to determine the site-specific ploughing depth. However, this was a choice for getting started; other useful measurement sources for describing spatial field variations could be information from implement mounted sensors, drones or satellite. On-the-go measurement from implement mounted sensors could consist of penetrometers, optical probes, load cells (Shamal et al., 2016) or the Top Soil Mapper from Geoprospectors (AT) which measures soil conductivity and uses modelling to predict soil compaction, degree of water saturation and soil texture. Some of these sensors might provide suitable real-time inputs for the determination of the optimal site-specific mouldboard ploughing depth on-the-go. However, the accuracy of the measurement and calibration of the models will require additional studies to determine their usefulness, to be functional with the developed systems and methodologies.

3. **Site-specific seeding**

The soil bin study (Paper IV) showed that the mean coulter depth decreased significantly when the seedbed changed from sand to gravel due to the difference in soil-coulter resistance. Variations in soil
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Resistance in the real field operations were also found to impact the coulter depth (Paper V), however, with less significance than in the soil bin. In the soil bin a coulter angle sensing system and a hydraulic pressure control system was examined and found to be functional in maintained a consistent drill coulter depth independent of soil resistance (Paper IV). The control system of the coulter pressure showed significant improvements in achieving and maintaining the desired coulter depth independently of soil resistance variation. However, the system required accurate information of the transverse frame height to be transferable to real field applications. In the second part of the seeding study (Paper V), the coulter measurement system was further developed with soil surface sensors, to take account of the frame height, and tested on a full-scale seed drill where it was found to be able to measure the 11 coulter depths in a real field application. For accurate seed depth measurements, the soil-coulter interaction has to be considered in order to calibrate seed placement to the measured coulter depths. The presented coulter depth measurement system was found to be useful for a number of applications such as on-the-go monitoring of coulter depth variations in the field operation, depth variations between the coulters, and to provide descriptive information for the manual adjustment of the static coulter pressure while seeding in heterogeneous areas of the field. The coulter depth measurement system was also found useful for evaluating the impact of wheel tracks, the performance of track eradicators and to monitor whether obstacles like stones or crop residues accumulate on the individual coulters. When using the dynamic measurement signals as control inputs, a novel dynamic intensity control of track eradicators can be integrated as described in patent (D). If the seeding operation is carried out at a constant speed, a field map of the coulter-soil resistance measured from site-specific coulter depths can be generated, similar to other soil mapping instruments (Godwin and Miller, 2003). This map could subsequently be related to the historical management information to be used for field operation management, e.g. choice of crop species and implement, drainage modifications, or to improve the site-specific manual tillage operations to achieve a more homogeneous seedbed. Finally, a low-cost full-scale seed drill coulter depth control system was developed (Paper VI) and IP protected (Patent E). The system was developed using the dynamic coulter depth measurement system (Paper V) combined with the desired control algorithm from the soil bin study (Paper IV). The developed site-specific seed drill significantly reduced the undesired coulter depth variations caused by variable coulter-soil resistance and maintained a 15.2 % more consistent coulter depth.

The targeted depth was aimed to be consistent independent of heterogeneity in the seedbed causing variations in the soil-coulter resistance, due to previous tillage, organic matter content, texture, porosity and soil water content etc. The reason for the choice of consistent depth was that secondary seedbed preparation is usually carried out at a fixed depth and the seeds are targeted to be placed at the firm bottom of the seedbed (Håkansson et al., 2002; Karayel, 2008). The developed system accounts for the effect of spatial soil variations, however, a further development of the presented control system could
include additional field information to model site-specific depth biases so that the targeted depth can be dynamically adjusted relative to the site-specific soil conditions. Real-time coulters measurements or actuator position could be combined with background maps or on-the-go soil sensors to provide information for on-the-go decision support of the targeted site-specific coulter depth. The background maps can be generated from previous field operations such as soil strength measured from tillage, satellite/drone information or electrical conductivity. Weatherly and Bowers (1997) adjusted the seeding depth based on electrical resistance to predict soil water content, measured by two knife-shaped electrodes. The Top Soil Mapper from Geoprospectors (AT) can be installed to predict soil compaction, water saturation and soil texture, but sensor accuracy and the modelling for optimal depth determination need additional studies for all sensors, to be combined and improve the developed coulter depth control system, to be with variable controlled depth. Other approaches to be combined with the site-specific depth control system, could be to develop an improved precision seed dosage system, placing the seeds in spatial uniformity or site-specific controlled densities, relative to variable soil conditions. Such a system could be based on previous operation maps, or field information regarding texture or topography which can be combined with GNSS, using a similar approach as the plough depth control methodology. Seeding at an increased seed density and spatial uniformity has shown interesting results for the competitiveness of wheat against weeds (Kristensen et al., 2008; Olsen et al., 2005; Weiner et al., 2001), reducing the need for chemical weed control. This can be achieved by operating with narrower rows and an accurate seed dosing system. Variable doses in controlled densities, relative to soil conditions may take greater advantage of the soil growth potential. On the other hand, the conventional row distances have the advantage of allowing space for mechanical weed control (Melander et al., 2003; Znova et al., 2017).

4. Technology adoption and commercialisation

Market adoption of site-specific precision-farming management practices depends on their economic advantage (Jensen et al., 2012; Plant, 2001). The review study by Plant (2001) found three criteria for site-specific management: (1) that significant within-field spatial variability exists in factors that influence crop yield, (2) that causes of this variability can be identified and measured and (3) that the information from these measurements can be used to modify crop management practices to increase profit or decrease environmental impact. Even though the products have been honoured with innovation awards and their positive impacts on the conditions for crop establishment comprehensively verified in scientific papers, it does not follow that the products will be adopted by the market, since an economical profit has to been measurable and clearly addressed (Plant, 2001).

All the developed systems in this thesis have a higher production cost, but the systems are expected to improve resource utilisation, reducing environmental impact and potentially increase yield. The systems
can be evaluated by different measureable intermediates for determine their improvements for crop establishments. The plough section control system is expected, for example, to reduce the requirement for traction force, the need for additional tillage (ergo mechanical wear, tractor size and energy consumption) and spraying (chemicals). The plough depth control system will considerably reduce the energy consumption and mechanical wear. Furthermore, the depth control system might increase workability, as it is more flexible with reduced depths (Edwards et al., 2016), but this benefit is difficult to measure as an economic profit. For the developed seed drill, the cost of the product modification and quantity of planted seeds can be directly compared to the yield response via better crop establishment to calculate the economic benefit. However, all of these technological optimisations need to produce measurable profits for the commercial market to adoption them (Jensen et al., 2012; Plant, 2001). The cost and benefits with an economic aspect have not been studied in the thesis, but the potential of precision farming and controlled traffic farming has been addressed positively, by Jensen et al. (2012). These authors found precision farming and controlled traffic farming to be profitable for the farmers due to a higher yield, less traffic, less energy and chemicals consumed, and, not least, a reduced environmental impact.
Chapter 5 Conclusions

The conditions for crop establishment were enhanced when applying the novel control technologies and methodologies developed for site-specific sensing and control of the agricultural implements.

The novel plough section control system was found applicable for individual section control. The system improved the ploughing performance by a significant reduction in overlapping, theoretically by up to 80%, in the interface between the headlands and the main working area. A soil surface evaluation showed that the operation started nearly perpendicularly to the main working direction, which considerably optimises the interface. With this system, a more homogeneous soil inversion with less random and uncontrolled soil mixing can be expected. In addition, the functional system was developed with hydraulic stone release and individually activation and deactivation of the sections. By deactivating one section, a new traction force reduction control system was integrated, usable when operating in hilly areas, as more traction force is needed uphill, than downhill. Furthermore, on-the-go deactivation of the individually sections can also be used to improve wedge operations, when finalizing the main working area of the field. In addition, a novel mouldboard ploughing concept system was studied and developed for automatic site-specific depth control. The system was found applicable for continuous depth control independent of communication with the tractor. Multiple site-specific depth modelling methodologies were studied to determine the preferred operational method. A linear depth correlation based on MOG was used as an input example; however, this needs additional studies, as does the interaction between depth adjustment and plough designs. All of the studied methodologies considerably reduced the energy consumption. The preferred modelling methodology adjusted the operational depth every 10 m, which significantly reduced the ploughed volume by 6,638 m$^3$ of a 24 ha field, corresponding to a volume reduction of 11%.

A low-cost seed drill was developed as a novel instrumentational system and found to be functional for individual coulter depth measurements. The power spectrum density analysis showed that the majority of coulter oscillations were below 1 Hz without any natural vibration frequency. The coulter depth measurement system is usable for mapping or on-the-go monitoring of the individual coulter depths. The coulter depth decreased with increasing speed, although not significantly. However, the lateral coulter position of the machine mounting and the mechanical soil properties significantly affected the coulter depths. After initial investigation in a soil bin, a full-scale seed drill was developed with a dynamic coulter depth control system. The seed drill maintained a more consistent coulter depth independent of variations in soil conditions, as verified in a field experiment. Without the control system activated the seed drill measured a significant spatial coulter depth variation, due to the variability in the soil mechanical properties. After smoothing the data using a moving average filter, this
variation was calculated as being up to ±8 mm across the experimental blocks; however the variation was significantly reduced to ±2 mm when the coulter depth control system was activated. An overall improvement in coulter depth deviations of 15% was found when comparing to the conventional static seed drill. Providing a more accurate and consistent depth will generate more homogeneous crop germination, improving seedling competitiveness against weeds which is important for achieving the desired yield potential.

However, additional studies are still needed to validate the environmental and agronomic effects, and the ultimate influence on yield, when utilising the developed ploughing and seeding technologies and methodologies.
Chapter 6 Future work

Currently the majority of agricultural machine settings are static and subjectively determined by the operators. This thesis, combined with future work supports the utilisation of objective, automatic, site-specific control systems, to be integrated in Smart Farming, as it is considered a key concept for improving future farming. This thesis describes and discusses automatic, site-specific controlled implements, but additional studies can still be conducted for further validation of the systems:

The plough section control system (I) needs a performance analysis of the topsoil profile when using a full-scale plough, in order to validate the agronomic effect of the controlled operation. The focus should be on the plough’s ability to improve the reduced area overlap in the headlands-main field interface. The plough depth control study (II) needs additional design analyses of the ability for on-the-go depth adjustment, again focusing on the agronomic effects. Parameters that need to be considered are the interaction between depth, skimmers and width for different plough designs, and soil interaction with respect to ploughing performance (incorporation of surface residues, weed control, surface evenness and energy consumption). The study can subsequently be combined with the operational depth modelling methodology study (III) by analysing additional model input parameters, starting with soil compaction and root weed, calibrated with their significance for determining the desired agronomic site-specific depth. Finally, need experimental studies ae needed after considering an improved model.

For the study of secondary tillage with the rotavator (IX), the intensity and forward-speed were found to be significant for the aggregate size distribution. As aggregate size is crucial for achieving the desired seedbed, a system could be studied and developed for sensing and providing information of seedbed quality, i.e. modelling the aggregate size, from surface roughness. Such a system could provide on-the-go seedbed information to adjust the forward speed, either manually or automatically, as it would be a generic solution for multiple tillage implements. Furthermore, a speed control system could be used for multiple operations, such as for stabilising seed drill coulters and booms of spreaders or sprayers.

Future progression of the presented seed drill coulter depth measurement and control system presented in papers (IV, V, VI) could include additional studies of soil-coulter interactions to determine the accurate relationship between coulter depth and the actual seeding depth for a range of coulter designs, against a number of soil conditions. Prediction of this relationship could eliminate the initial calibration of seed versus the coulter depth for the specific soil-coulter interaction.

Finally, all of the systems need to be tested in the large-scale field experiments for evaluating the environmental impact, their expected agronomic benefits, and ultimately against yield, combined with cost-benefit analyses of their bottom-line profit for farmers to adopt the site-specific controlled systems.
Chapter 7 Research contributions

The thesis contributes with multiple novel technologies and methodologies to improve the conditions for crop establishment by integrating site-specific controlled field operations using intelligent agricultural implements. More specifically, the main findings were the developments and scientific verification of:

- A novel section control concept system for mouldboard ploughing, reducing the undesirable triangular overlapping segments at the interface between the headlands and the main working area. The system will virtually eliminate these segments as the ploughing operation starts in a near straight line, perpendicular to the main working area of the field.
- A site-specific novel automatic depth control concept system for mouldboard ploughs which dynamically controls and maintains the operational depths, independent of tractor communication.
- Four operational modelling methodologies for applying site-specific mouldboard ploughing depth control, using MOG as an input example, which significantly reduces energy consumption.
- Verification of a novel coulter depth measurement concept system and control methodologies to reduce the low-frequency vibrations, independently of variations in soil-coulter resistance.
- A novel full-scale seed drill coulter depth measurement concept system, applicable for individual coulter depth monitoring or mapping.
- Verification of a novel full-scale seed drill with automated coulter pressure control to limit undesired deviations and stabilise the targeted coulter depth, for real field applications.
Chapter 8 Collection of references and appendices


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1. Appendix / Paper I – Plough section control for optimized uniformity in primary tillage
Plough section control for optimised uniformity in primary tillage

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Primary tillage is in many cases crucial for successful crop establishment and weed and pest control. Inversion tillage using a mouldboard plough may be required when a uniform ploughing operation covering the entire field is preferred. The ploughing operation is especially challenging at the interface area between headlands and the main cropping area. Overlapping at the interface causes a mixing of the topsoil, rather than a soil inversion, and poor burial of residues and weeds, especially of concern in organic farming. The aim of the research was to study novel plough section control designs to optimise the interface area. Concept designs with hydraulic control were studied and the preferred was developed and tested in real field operations. The research concluded that the concept was functional and by visual inspection the interface was optimised. In addition, the section control can improve operations in irregularly shaped fields.

Keywords: Plough section control, novel concept design, proof-of-concept

Introduction

When cultivating crops, soil and seedbed quality is crucial for crop establishment and can have direct impact on the yield (Braunack and Dexter, 1989; Guthrie et al., 2001; Hiller et al., 2011). The primary seedbed tillage operation is crucial for a homogeneous development of a crop and requires an adequate and uniform ploughing operation across the entire field. This is especially challenging to achieve at the interface between the headland and the main working area of the field. This occurs both when the plough is elevated and lowered in the headland, forming an inconsistent tillage operation and undesirable triangular shapes of unploughed segments (Fig. 1, left). This leads to overlapping operations when ploughing the headland perpendicularly to the main working direction (Fig. 1, right), which also is time- and energy-consuming and increases wear of the plough. Poor soil inversion is typically seen in interface areas with overlap, which may cause problems with seeding as well as pest and weed control. This is especially of concern in organic farming when large ploughs are used, because chemical weed and pest control not is an option.

Soil compaction has been studied in relation to machine traffic and tillage practices (Hamsa and Anderson, 2005; Shamal et al., 2015). Other studies have analysed the effect and impact on the tillage quality and energy consumption of different soil types, water contents and wear (sharpness and thickness) of the cutting edge (Natis et al., 1999; Vlode, 2008). Site-specific tillage effects on energy consumption have been quantified in a number of studies (Abbaspour-Gilandeh et al., 2005; Bartosco et al., 2008; Kenton et al., 2010; Rapier et al., 2003) and a range of studies have measured and predicted draught forces for mouldboard ploughing from different soil parameters, plough geometries, forward speed and operation depth (Gidwani et al., 2007; Kuznezov, 1981; Mari et al., 2015; Qi et al., 1986). To our knowledge, there have been no studies on section control of a mouldboard plough and on tested the operational effect. Section control is well known in other agricultural operations such as spraying (Luck et al., 2010), and therefore the GNSS technology and high-level control will not be presented in this study.

By introducing section control on the plough, each plough section can be independently controlled for elevating and lowering into the soil. The hypothesis was that with independent section control, the undesirable triangular segments at the interface between the headlands and the main working area will be near eliminated. i.e. starting the ploughing operation in an approximately straight line, perpendicular to the main working area of the field. Different concepts were described, modelled and the selected "optimal" solution was implemented on a real concept plough. The aim of the research was to investigate, describe and perform a proof-of-concept of a novel innovative plough concept design with individual section control, to significantly optimise ploughing operation in the interface area between the headland and the main working area.

Experimental method for draught forces determination

Initial field experiments were carried out to determine the draught forces used in the ploughing operation. These results were used for dimensioning the section control system. The first step was to describe and compare different concepts of

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section control, using a modelling tool. In the second step, the selected ‘best’ concept was constructed and implemented on a real plough, for additional evaluation. The concept plough was a five-furrow Agrolux MRW5-P with shear bolts, fully-mounted reversible from Kongskilde Industries A/S, DK.

The accumulated draft force was determined in the initial field experiment before starting analyzing different hypothetical concepts. The ploughed soil texture consisted of 37% organic matter, 9.6% clay, 22.3% silt, and 45.5% sand, with at 25 kg 100 kg m$^{-3}$ gravimetric water content. The experiment was carried out with force transducers (strain-gauges) mounted in the tractor lift (three point linkage), measuring the horizontal draught forces (Fig 2, left). The soil was ploughed to 0.25 m depth at 8 km h$^{-1}$ and a furrow width of 0.4 m. This corresponds to a soil volume flow of 0.22 m$^3$ m$^{-2}$ h$^{-1}$ for each furrow.

An even distribution of the horizontal forces between each furrow was assumed and the equilibrium equation could therefore be established (Eq. 1):

$$ F_x = F_{x1} + F_{x2} + F_{x3} + 5F_{x4} + F_{x5} = 0 $$

(1)

where $F_x$ is the sum of the horizontal forces, $F_{x1}$ is the left lift arm force, $F_{x2}$ is the right lift arm force, $F_{x3}$ is the top linkage force, $F_{x4}$ is the furrow counter draught force, $F_{x5}$ is the plough wheel counter draught friction force for rolling. When neglecting the inconsiderable rear wheel draught force of the plough, Eq. 1 can be rewritten as Eq. 2:

$$ F_{x5} \approx 0 \quad \Rightarrow \quad F_x = F_{x1} + F_{x2} + F_{x3} + \frac{F_{x4}}{5} $$

(2)

The accumulated horizontal furrow draught forces ($F_{x1} + F_{x2} + F_{x4}$) were measured to approx. 32 kN in the experiment. Therefore, each section draught force $F_{x4}$ was estimated to be 6.4 kN.

To determine the resulting force position, an additional experiment was conducted where a force transducer was used, replacing the shear bolt (Fig. 2, right). With this experimental setup it was possible to measure the moment around the beam rotation point. By combining the measured moment in the furrow beam with the determined horizontal force $F_{x4}$, the resulting horizontal force point of attack was found by equilibrium calculations.

The point of attack for the force $F_{x}$ was calculated to be 0.67 m below the surface of the common plough frame (Fig. 2, right). The calculated position combined with the draught force measurement was used for dimensioning the hydraulic system and the mechanical construction of the concept plough model.

Concept investigation

System requirements

In general, the concept must not interfere with conventional ploughing performance and it must match its original operational ability. The developed concept system must be able to resist the counter forces without permanent deformation of the construction and withstand the rough environmental impacts. The plough section must be able to elevate the section above the ground surface, corresponding to 0.30 m, when the plough frame is lowered. The sections should operate with an elevation velocity that ensures rapid activation and deactivation of the modified section. Due to the great force and velocity demands, a hydraulic supply from the tractor was required. The concepts were designed to be implementable on most existing low-cost reversible ploughs. Therefore, the simple five-furrow reversible plough with shear bolts was chosen.

Considered concepts

The functionalities and material stress of the considered section control concepts were analysed using SolidWorks (Dassault Systems SolidWorks Corp, USA). The six considered concepts are illustrated in Fig. 2.

Concept 1. Concept 1 removed the shear bolt and used the existing bolted connection as a hinge to rotate the body. This concept model showed that the body was not able to rotate above the soil surface. A similar solution was tested by using the original shear bolt as a rotation hinge. This solution would not work because the rotated mouldboard interfered with the above mouldboard. Therefore, this solution was considered unusable.

Concept 2. In concept 2 an attempt was made to model a solution where a parallelogram raised and lowered the entire section. This solution ensured that the body kept its...
original operational angle regarding to the beam position of the plough. In addition, it would be possible to control the depth of the individual furrows. The parallelogram mechanism had to be able to elevate the body of the plough above the soil surface, resulting in an unsteady construction. To withstand the forces of the soil acting on the body, the steel material had to be particularly strong. Furthermore, the geometry of the parallelogram required a specially crafted double-acting telescopic hydraulic cylinder, which was less robust and more expensive. Therefore, this concept was rejected, although it had considerable potential for controlling the operation depth of the sections.

Concept 2. Rotation of the entire section was considered in concept 3. This concept used one double-acting hydraulic cylinder, which was able to control the section in both directions. In order to rotate/tilt the body above the soil surface, the bracket of the section had to be extended. This concept was robust and met all the requirements for the concept model.

Concept 4. This concept used a milled track to be able to rotate and traverse the body to achieve the required elevation height without interfering with the above mouldboard. The mechanism was not robust and after wearing it could
Plough section control for optimised uniformity in primary tillage

Potentially lead to an unstable arrangement. In addition, using milled tracks was not considered as preferred methods, due to the large operational forces.

Concept 5. Concept 5 was a model with a linear rail moving the section. This solution had the same benefit as in concept 2, regarding depth control. The linear rail needed to be at least 0.5 m to be able to lower and elevate the bodies in both directions, above the surface. With this large length of stroke, the linear rail took up too much of the clearance height between the beam and the soil.

Moreover, the linear mechanism was also vulnerable to the rough environment and the large operational forces.

Concept 6. Concept 6 used a model with a linear movement of the body, similar to concept 5. In this model, each body was able to be controlled individually. The rail replaced the body and beam, but it also took up too much of the clearance height. This required a travel length of 0.3 m which caused the bodies to interfere with each other unless the entire plough was reconstructed. Similar to concept 5, the linear mechanism was not robust.

Description of the selected concept
Concept No. 3 was chosen as the "best" concept to control the individual sections (Fig. 4). With this concept only one conventional hydraulic cylinder was required per section to control the rotating mechanism. The hydraulic cylinder and the rotating mechanism formed a robust construction where maintenance is restricted to grease lubrication. Material construction was optimised regarding deflection and deformation by using the finite element method (FEM) based on the forces, determined in the initial experiments.

Instrumentation hardware
For positioning the section, a linear displacement sensor, TX2, was implemented (Novoteknik, U.S.) operating with a resolution of 0.01 mm and linearity of up to 0.05%, and protected against the environment (IP67). For real-time data processing, a B&R RX20 controller with a 12-bit A/D converter was used (B&R Industrial Automation, AUT). For global positioning the GNSS unit BT-Q1000XT was used (Ostarz, TWIN).

Hydraulic system
The full-scale hydraulic system for controlling all sections is shown in Fig. 5. Only one section was used for the physical

Figure 4. Final model of the chosen concept for controlling the individual sections, consisting of the rotational construction of the section, controlled by the hydraulic cylinder.

Figure 5. Full-scale hydraulic diagram. The dotted lines indicate the additional four sections that not were modified on the concept plough.
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Modification used in the proof-of-concept plough. The cylinder was double-acting for elevating and lowering the section (Dₘ = 80 mm & Dₐₙ = 40 mm). For section control, a 4/3 directional oil control valve was implemented with a closed centre, which was electrically controlled by two solenoids. To generate the system generic, a bypass valve was implemented allowing unhindered oil circulation. A new hydraulic stone release system was introduced, controllable by stone release pressure valves (Fig. 5). The pressure valves were set to be activated when a force of approx. 7 kN acts on the body. The horizontal length of stroke is 0.48 m, and when ploughing at 8 km h⁻¹, the section should be able to travel the entire length of stroke within 120 ms. This rapid operation induces an oil flow of 134 l min⁻¹, which should be led through the stone release pressure valves. To avoid cavitation in the cylinder, the system was supplied with oil, by using a low-pressure refilling system (Fig. 5). For additional cost optimisation, the cavitation refilling system all one-way valves and the stone release pressure valves can be removed.

Theoretical validation of the concept

When introducing the concept on the full-scale plough, the interface area (A) between the headland and the main working area (B) will theoretically be significantly reduced, as shown in Fig. 6 left (conventional) and right (new concept).

The overlapping area can be calculated with section control, Aₓc, (Eq. 4), and without section control, Aₑ, (Eq. 3):

$$Aₓc = \frac{F_{w}nF_{r}}{2}$$

(3)

$$Aₑ = \frac{F_{w}nF_{r}}{2}$$

(4)

where Fₑ is the width of one furrow, n is the number of furrows and Fᵣ is the length of each furrow. The percentage of the reduced overlapping area with section control, Pₛₑ, can be calculated (Eq. 5):

$$Pₛₑ = \left(1 - \frac{Aₑ}{Aₓc}\right) \times 100$$

(5)

This means that theoretically, the overlapping area for a five-furrow plough will be reduced by 80%, increasing with the number of furrows. Additional benefits will occur when ploughing irregularly shaped fields.

Visual field validation of the concept plough

The concept model was implemented on the conventional reversible plough by modifying the section (Fig. 7, left). The concept plough was used to validate the modelled concept on a real physical plough. Furthermore, it allowed demonstration of the concept to illustrate the impact on the soil surface from a real ploughing operation.

The concept optimised the operation towards a homogeneous soil reversal at the interface, demonstrated in the final field experiment (Fig. 7, right). Furrow 1 to furrow 4 clearly showed the addressed interface problem. When activating the concept, implemented on section 5, the ploughing operation started nearly perpendicular to the main working area, as it can be seen by a visual surface inspection (Fig. 7, right).

Conclusion

Six plough section control concepts were evaluated by modelling, and the selected ‘best’ functional concept was constructed and implemented on a conventional five-furrow plough. In addition, a new hydraulically adjustable stone release system was integrated. The modified plough with the novel concept showed great performance in controlling

Figure 6 Conventional ploughing (left) and ploughing with section control (right)

Figure 7 Concept plough with one section modified (left) and operational result from the concept plough (right)
the individual section when demonstrated in a real field operation. A more homogeneous soil reversal and less random soil mixing can therefore be expected in the interface area between headlands and cropping areas. Another benefit of the system is that irregularly shaped fields can be ploughed at a constant furrow width, by activate or deactivate the individual sections, in the operation.

Acknowledgements

The project was funded by Innovation Fund Denmark through ‘Future Cropping’.

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2. Appendix / Patent A – A system for section control of a mouldboard ploughing implement
(12) International Application Status Report

Received at International Bureau: 14 July 2016 (14.07.2016)
Information valid as of: 29 May 2017 (29.05.2017)
Report generated on: 07 June 2017 (07.06.2017)

(10) Publication number: WG2017/005263
(21) Application Number: PCT/DK2016/000028
(31) Priority number(s): PA 2015 00395 (DK)

(26) Publication language: English (EN)
(22) Filing Date: 08 July 2016 (08.07.2016)
(31) Priority date(s): 08 July 2015 (08.07.2015)

(25) Filing language: English (EN)
(31) Priority status: Priority document received (in compliance with PCT Rule 17.1)

(51) International Patent Classification:
A01B 33/36 (2006.01); A01B 63/00 (2006.01)

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(54) Title (EN): A PLough SYSTEM

(54) Title (FR): SYSTÈME DE CHARRUE

(57) Abstract:
(EN): The present invention relates to a plough system (100) comprising: i) a plough frame (2), said plough frame comprising coupling means (4) for coupling said plough frame to a towing vehicle; wherein said plough frame having an extension in a longitudinal direction (X), and an extension in a transverse direction (Y); wherein said plough frame comprising two or more lifting means (6, 6'); said lifting means comprising a fixed part (5) being mounted on said plough frame (2), and a moving part (10) carrying a plough share (12, 12') wherein each said lifting means (6, 6') comprising an actuator (14, 14'); wherein said actuator being configured to allow altering of said plough shares (12, 12') from a lowered position to a raised position, and vice versa; wherein said plough shares (12, 12') being arranged on said frame in mutual staggered orientation in relation to a longitudinal direction as well as to a transverse direction; ii) a control unit (16) configured to receive controlling input (18), and in response thereto independently activate one or more actuators (14, 14') associated with said lifting means, thereby enabling independent raising and/or lowering of one or more of said plough shares (12, 12'). The plough system provides improved ploughing quality of fields of soil comprising a mainland and a headland.

(FR): La présente invention concerne un système de charrue (100) qui comprend : i) un châssis de charrue (2), le dit châssis de charrue comprenant un moyen de couplage (4) pour coupler le dit châssis de charrue à un véhicule de remorquage ; le dit châssis de charrue ayant une extension dans une direction longitudinale (X) et une extension dans une direction transversale (Y) ; le dit châssis de charrue comprenant au moins deux moyens de levage (6, 6') ; lesdits moyens de levage comprenant une partie fixe (8), montée sur le dit châssis de charrue (2), et une partiemobile (10), portant des cœurs de charrue (12, 12') ; chacun desdits moyens de levage (6, 6') comprenant un actionneur (14, 14') ; le dit actionneur étant configuré pour permettre le changement des cœurs de charrue (12, 12') d'une position abaissée à une position relevée, et inversement ; lesdits cœurs de charrue (12, 12') étant agencées mutuellement sur le dit châssis dans une orientation étagée par rapport à une direction longitudinale ainsi qu'une direction transversale ; ii) une unité de commande (16) configurée pour recevoir une entrée de commande (18) et, en réponse à celle-ci, pour activer de manière indépendante un ou plusieurs actionneurs (14, 14') associés aux moyens de levage, permettant ainsi l'élévation et/ou l'abaissement d'un ou des cœurs de charrue (12, 12'). Le système de charrue fournit une meilleure qualité de labouage de champs de terre grâce à son système de charrue de pleine terre et de charrue déportée.
International search report:
Received at International Bureau: 03 October 2016 (03.10.2016) [EP]

International Report on Patentability (IPRP) Chapter II of the PCT:
Not available

(81) Designated States:

European Patent Office (EPO): AL, AT, BE, BG, CH, CY, CZ, DI, DK, EE, ES, FI, FR, GB, GR, HR, HU, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR


Eurasian Patent Organization (EAPO): AM, AZ, BY, KG, KZ, RU, TJ, TM
Title: A PLOUGH SYSTEM

Abstract: The present invention relates to a plough system (100) comprising: (1) a plough frame (2), said plough frame comprising coupling means (4) for coupling said plough frame to a towing vehicle; wherein said plough frame having an extension in a lengthwise direction (X), and an extension in a transverse direction (Y); wherein said plough frame comprising two or more lifting means (6, 6'); said lifting means comprising a fixed part (8) being mounted on said plough frame (2); and a moving part (10) carrying a plough shears (12, 12'); wherein each said lifting means (6, 6') comprising an actuator (14, 14'), wherein said actuator being configured to allow altering of said plough shears (12, 12') from a lowered position to a raised position, and vice versa; wherein said plough shears (12, 12') being arranged on said frame in a mutual staggered orientation to a lengthwise direction as well as to a transverse direction; (ii) a control unit (16) configured to receive controlling input (18), and in response thereto independently activate one or more actuators (14, 14') associated with said lifting means; thereby enabling independent raising and/or lowering of one or more of said plough shears (12, 12'). The plough system provides improved ploughing quality of fields of soil comprising a mainland and a headland.
Field of the invention

The present invention relates in a first aspect to a plough system for ploughing soil. The present invention relates in a second aspect to the use of a plough system of the first aspect for ploughing soil. The present invention relates in a third aspect to a method of ploughing.

Background of the invention

Within the field of agriculture ploughing has been around a long time as an effective tillage method.

Ploughing is used as a way to prepare the soil for seeding. When ploughing the soil is turned around, so that soil previously located in a certain depth will appear as a top layer of the soil. A typical ploughing depth is 18 to 20 cm, but can vary between 5 and 100 cm.

The turning of the soil upon ploughing will provide for aerating the soil and in this way will provide mineralization of soil and better drainage of water which improve fertility. Also, ploughing will remove residues of last year’s crops as well as removal of any weed present on the ploughed field. In this way ploughing may be used as a mechanical weed control method, especially in ecological agriculture where herbicides are forbidden.

Today’s ploughs comprise a frame to be towed behind or carried by a tractor or the like. The frame carries a number of plough bodies arranged inline in a staggered configuration in relation to a direction transversal to the direction of movement and to the direction of movement itself. The frame comprises a hoist mechanism for raising from the soil or lowering into the soil all the plough shears simultaneously.

When ploughing a field the farmer usually, at least mentally, divide the land to be ploughed into a main part comprising a regularly shaped inner part (the main land) of the field and a surrounding headland. In this way the farmer can concentrate in first ploughing the main part by following a regular serpentine path, whereas the headland is used for turning the tractor in order to plough a subsequent leg of the serpentine path. After having ploughed the inner main part of the field, the farmer ploughs the headland.

When ploughing the inner main part of the field, the farmer raises all the plough shears from the soil upon entering the headland. Similarly when moving from the headland into the main, inner part of the field, the farmer lowers all the plough shears into the soil.

Although this way of performing the ploughing has proven efficient, there are however some drawback using this technique.
One drawback is, that due to the fact that all the plough shears are arranged in a staggered configuration which is not perpendicular to the direction of movement of the plough through the soil, it will not be possible, at the boundary between the inner, main part of the field and the headland to exactly and precisely plough the soil up to this boundary.

If the farmer wishes to plough all the inner, main part of the field, the ploughing will in respect of some plough shears – due to the staggered configuration of the plough shears – inevitably plough into the headland.

Consequently, when the farmer after having ploughed the whole area of the inner, main part of the field, subsequently ploughs the headland, part of the soil of the headland, will be ploughed again and thus become turned around twice.

Turning around soil twice corresponds to some extent to not turning around the soil at all, at least when it comes to allow weed to continue growth.

Accordingly, part of the headland will exhibit areas of soil in which the weed, which was supposed to be buried with soil during ploughing, will have an initial advantage in terms of rooting and growth, compared to the crops being sown.

This obviously has the consequence that the crop seeds to be sown will encounter so much competition from the weed that has been turned around twice, that the growth conditions for these seeds and hence the total economical crop yield will be far from optimum.

Additionally, the overlap will result in an uneven surface after ploughing, while the boundary of the ploughing of the main land conflicts with the following ploughing of the headland.

Furthermore, ploughing the headland will due to ploughing the soil twice result in a situation, where crop residues at least partly will not be covered by soil.

Hence, there is a need for an improved plough system which overcomes these disadvantages.

It is an object of the present invention to provide a plough system which overcomes the above-identified disadvantages.

**Brief description of the invention**

This object is fulfilled by a plough system having the features as defined in claim 1, by the use having the features as defined in claim 22 and the method having the features as defined in claim 23.

Preferred embodiments are defined in the dependent claims and explained in the following description and illustrated by the accompanying drawings.

Accordingly, the present invention relates in a first aspect to a plough system comprising:
i) a plough frame, said plough frame comprising coupling means for coupling said plough frame to a towing vehicle;

wherein said plough frame having an extension in a lengthwise direction, and an extension transverse direction;

wherein said plow frame comprising two or more lifting means; said lifting means comprising a fixed part being mounted on said plough frame, and a moving part carrying a plough shear;

wherein each said lifting means comprising an actuator;

wherein said actuator being configured to allow altering of said plough shear from a lowered position to a raised position, and vice versa;

wherein said plough shears being arranged on said frame in mutual staggered orientation in relation to a lengthwise direction as well as to a transverse direction;

ii) a control unit configured to receive controlling input, and in response thereto independently activate one or more actuators associated with said lifting means, thereby enabling independent raising and/or lowering of one or more of said plough shears.

In a second aspect the present invention relates to a use of a plough system according to the first aspect of the present invention for ploughing a field at least partly surrounded by a headland.

In a third aspect the present invention relates to a method for ploughing a field, at least partly surrounded by a headland, said method comprising:

i) defining coordinates of one or more boundaries between an inner, main field to be ploughed and the surrounding headland;

ii) providing a plough system comprising a plough frame having an extension in a lengthwise direction, and an extension transverse direction; said plow frame comprising two or more lifting means; said lifting means comprising a fixed part being mounted on said plough frame, and a moving part carrying a plough shear; wherein said lifting means comprising an actuator; wherein said actuator being configured to allow altering said plough shear from a lowered position to a raised position and vice versa; wherein said plough shears being arranged in a mutual staggered orientation in relation to a lengthwise direction as well as to a transverse direction;

iii) in respect of each of the plough shears, raising a specific plough shears in case a specific plough shear is crossing the boundary between the inner, main
field to be ploughed and an associated headland, in a direction from the inner, main field to be ploughed to the headland;

iv) in respect of each of the plough shears, lowering a specific plough shears in case a specific plough shear is crossing the boundary between the inner, main field to be ploughed and an associated headland, in a direction from the headland to the inner, main field to be ploughed.

v) ploughing the area of the headland at least partly surrounding the inner, main field.

The present invention in its first, second and third aspects provide for improved germination and growth conditions for crops seeds which are being sown in a field comprising an inner, main field, which is at least partly surrounded by a headland, subsequent to ploughing thereof.

Additionally, the present invention in its various aspects provides for a more efficient ploughing in that necessity to plough certain areas of the field twice is avoided.

15 Brief description of the figures

Fig. 1 is a plan view of a field being ploughed with a prior art ploughing system.

Fig. 2 is a perspective view illustrating a ploughing system according to the first aspect of the present invention.

Fig. 3 is a schematic drawing illustrating the structure of a controlling system for controlling a plough system of the first aspect of the present invention.

Detailed description of the invention

The present invention relates in a first aspect to a plough system comprising:

i) a plough frame, said plough frame comprising coupling means for coupling said plough frame to a towing vehicle;

wherein said plough frame having an extension in a lengthwise direction, and an extension transverse direction;

wherein said plow frame comprising two or more lifting means, said lifting means comprising a fixed part being mounted on said plough frame, and a moving part carrying a plough shear;

wherein each said lifting means comprising an actuator;

wherein said actuator being configured to allow altering of said plough shear from a lowered position to a raised position, and vice versa;
wherein said plough shears being arranged on said frame in mutual staggered orientation in relation to a lengthwise direction as well as to a transverse direction;

ii) a control unit configured to receive controlling input, and in response thereto independently activate one or more actuators associated with said lifting means, thereby enabling independent raising and/or lowering of one or more of said plough shears.

The plough system according to the first aspect of the present invention allows for raising/lowering each plough shear independently upon crossing a boundary between a main land and a headland. Thereby double ploughing of the headland can be avoided. This result is brought about by the plough system comprising means for individually raising from or lowering into the soil the plough shears.

It should be noted that in the present description and in the appended claims the noun “controlling input” shall be interpreted as being input provided by human interaction, either directly by manual instruction or by an automatically system which has been programmed in accordance with predetermined criteria for raising/lowering the individually plough shears, e.g. in response to geographical coordinates.

Accordingly, in the present description and in the appended claims the noun “controlling input” shall not be interpreted as a “mechanical input” in the sense of a mechanical impact between a stone, a boulder or a rock located in the soil and the plough shear which will imply raising/lowering of a plough shear, such as it is known in respect of plough systems which comprise a stone release system as described in more detail below.

In one embodiment of the first aspect of the present invention, said actuators are independently being selected from the group comprising, hydraulic actuators, electric actuators, and pneumatic actuators.

In one embodiment of the first aspect of the present invention said actuators are being hydraulic actuators and wherein said control unit comprises hydraulic valves configured for activating said hydraulic actuators, or wherein said actuators are being electric actuators and wherein said control unit comprises electric switches configured for activating said electric actuators, or wherein said actuators are being pneumatic actuators and wherein said control unit comprises pneumatic valves configured for activating said pneumatic actuators.

Such actuators and types of control system have proven efficient for the intended purpose.

In one embodiment of the first aspect of the present invention in which said actuators are being hydraulic actuators it will also be possible to provide the plough system with measuring means for measuring and optionally logging the hydraulic pressure in each of the hydraulic actuators. Similar types of measuring means, and logging, may be provided in respect of electrical or pneumatic actuators.
In one embodiment of the first aspect of the present invention the plough system comprises 2 – 40 plough shears, such as 4 – 35 plough shears, for example 6 – 30 plough shears, such as 10 – 25 plough shears, e.g. 15 – 20 plough shears.

These numbers of plough shears are common in modern plough systems and thereby suit the modern demands for ploughing systems.

In one embodiment of the first aspect of the present invention said plough system is a reversible plough or a non-reversible plough.

The plough system according to the first aspect of the present invention is equally well-suited for reversible ploughs and for non-reversible ploughs.

In one embodiment of the first aspect of the present invention the two or more lifting means being configured in such a way that the raising and lowering of the plough shears are being performed by a pivotally movement of the moving part carrying the plough shear.

In one embodiment of the first aspect of the present invention the system is designed in such a way that in respect of one or more of said lifting means, preferably in respect of all said lifting means, said lifting means are being configured in such a way that one end of said actuator is being pivotally mounted to said fixed part of said lifting means, and in such a way that the opposite end of said actuator is being pivotally mounted to said moving part of said lifting means, wherein said two opposite ends of said actuator are being moveable in relation to each other.

This embodiment provides a simple type of construction of the feature of raising/lowering of the plough shear. Additionally this type of construction allows using a plough having a stone release system as a plough system forming the basis for the plough system according to the first aspect of the present invention. A stone release system is a plough system comprising pivotally suspended plough shears. The plough shears are being suspended and controlled by a hydraulic controller which comprises a number of hydraulic valves and tubings. A stone release system allows each plough shear to pivot in a backward direction in case a specific plough shear hits a large stone, rock or boulder in the soil, thereby avoiding mechanical destruction of the plough shears by impact with stones, rocks or boulders. The size of the impact necessary for allowing a specifically plough shear to pivot is predetermined and adjustable. Once a specific plough shears has hit a stone, rock or boulder in the soil and has pivoted backward, hydraulic valves will imply that a hydraulic pressure is reestablished so that that specific plough shear regains its lowered position into the soil.

In one embodiment of the first aspect of the present invention, the plough system comprises a stone release mechanism and wherein said two or more lifting means being integrated with said stone release mechanism.

In one embodiment of the first aspect of the present invention the plough system further comprises an interphase, said interphase being configured so as to enable providing instructions to an actuator in relation to independently lowering/raising a specific plough shear.
In one embodiment of the first aspect of the present invention said interphase being configured to enable providing instructions to said actuator in relation to independently lowering/raising a specific plough shear, by providing controlling input to said control unit.

An interphase may serve as an intermediate unit between the control unit and the specific lifting means of the plough shears, thereby effecting the raising and/or lowering of the plough shears.

In one embodiment of the first aspect of the present invention, the plough system furthermore comprising input means, such a keyboard or a tablet for programming said interphase; said system optionally furthermore comprising a monitor.

In one embodiment of the first aspect of the present invention said monitor is being configured for monitoring the settings and/or the status of the operation of the plough system.

Input means and a monitor allows a user to input data to the system in relation to program the system with the view to provide an automatically controlled plough system. Further, the monitor allows monitoring the settings and performance of the system during use. This will enable monitoring and controlling by an operator, the proper functioning of the plough system during use thereof.

In one embodiment of the first aspect of the present invention the plough system further comprising a data storage; said data storage being configured to allow storing of coordinates relating to one or more boundaries between a main, inner field to be ploughed and a surrounding headland.

A data storage allows for automatically control a ploughing of soil.

In one embodiment of the first aspect of the present invention, the interphase being configured to receive position indication coordinates from a position indication receiver.

In one embodiment of the first aspect of the present invention, the position indication coordinates are provided by a satellite navigation system, such as a Global Navigation Satellite System (GNSS), such as a GPS system.

In one embodiment of the first aspect of the present invention, the system further comprising one or more of such a position indication receiver, such as a satellite navigation system, for example a GPS system.

In one embodiment of the first aspect of the present invention, the number of position indicating receivers is equal to the number of plough shears; and wherein a position indication receiver is being arranged at the position of each plough shear.

Providing the plough system with one or more position indication receiver allows knowing with great accuracy, at any given time, the position of that position indication receiver. This will allow knowing, at any given time, the position of one or more, preferably all, of said plough shears.
In one embodiment of the first aspect of the present invention, the plough system further comprising a data storage configured to enable storing thereon, data relating to the relative position of the one or more, preferably all, of said plough shears, in relation to said position indication receiver, and wherein said interface being configured to calculate, on the basis thereof and on the basis of the coordinates received by a position indication receiver, the absolute coordinates of the one or more, preferably all of the plough shares.

Such systems enables constantly knowing the exact position of each of the plough shears and thereby allows determining whether a specific plough shear is to be lowered into the soil or raised above the soil.

In one embodiment of the first aspect of the present invention said control unit is being configured for automatically controlling said activation of one or more actuators with the view to automatically and independently raising and/or lowering of one or more of said plough shears.

This will allow an easy and convenient precise ploughing operation by the user, thereby making the ploughing operation more efficient.

In one embodiment of the first aspect of the present invention, the plough system being configured, via said interface, to provide signals to said control unit relating to instructions of independently lowering or raising one or more plough shears according to a predetermined strategy.

In one embodiment of the first aspect of the present invention, said predetermined strategy comprises the following elements:

a) in case a specific plough shear being located within the inner, main field to be ploughed, said plough shear must be arranged in a lowered position;

b) in case a specific plough shear being located within a headland, said plough shear must be arranged in a raised position;

c) in case a specific plough shear is crossing the boundary between the inner, main field to be ploughed and an associated headland, in a direction from the inner, main field to be ploughed to the headland, that specific plough shear must change position from a lowered position to a raised position;

d) in case a specific plough shear is crossing the boundary between the inner, main field to be ploughed and an associated headland, in a direction from the headland to the inner, main field to be ploughed, that specific plough shear must change position from a raised position to a lowered position.

Such a strategy allows automatically controlling of the plough system.
In a second aspect the present invention relates to a use of a plough system according to the first aspect of the present invention for ploughing a field at least partly surrounded by a headland.

In a third aspect the present invention relates to a method for ploughing a field, at least partly surrounded by a headland, said method comprising:

i) defining coordinates of one or more boundaries between an inner, main field to be ploughed and the surrounding headland;

ii) providing a plough system comprising a plough frame having an extension in a lengthwise direction, and an extension transverse direction; said plow frame comprising two or more lifting means; said lifting means comprising a fixed part being mounted on said plough frame, and a moving part carrying a plough shear, wherein said lifting means comprising an actuator, wherein said actuator being configured to allow altering said plough shear from a lowered position to a raised position and vice versa; wherein said plough shears being arranged in a mutual staggered orientation in relation to a lengthwise direction as well as to a transverse direction;

iii) ploughing a field of soil by moving the plough shears through the soil of the inner, main field to be ploughed;

iv) in respect of each of the plough shears, raising a specific plough shears in case a specific plough shear is crossing the boundary between the inner, main field to be ploughed and an associated headland, in a direction from the inner, main field to be ploughed to the headland;

v) in respect of each of the plough shears, lowering a specific plough shears in case a specific plough shear is crossing the boundary between the inner, main field to be ploughed and an associated headland, in a direction from the headland to the inner, main field to be ploughed.

In one embodiment of the third aspect of the present invention said raising and lowering of a specific plough shear is being performed automatically.

In one embodiment of the first aspect of the present invention, the method being performed by using a plough system according to the first aspect of the invention.

According to the use and the method of the second and third aspect, respectively, the plough system may be suitable for plough irregularly shaped fields or parts of fields, such as a wedged shaped fields, where not all plough shears are desired to be lowered into the soil at all
time. In ploughing such shapes of fields or parts of fields, one or more of the plough shires may be lifted, while one or more of the plough shears are submerged into the soil for ploughing purposes.

Referring now in detail to the drawings for the purpose of illustrating preferred embodiments of the present invention, Fig. 1 illustrates the problems associated with ploughing using a prior art plough system in which a number of staggered arranged plough shears may only be raised and lowered simultaneously.

Fig. 1 shows a plan view of a field 70 to be ploughed. The field 70 is having a rectangular shape and being oblong in a north-south direction. The field 70 to be ploughed comprises an inner, main field 72. North and south to the inner, main field 72, respectively is located a headland 74, 74'.

The northern headland 74 is separated from the inner main field 72 by a boundary 76. Likewise, the southern headland 74' is separated from the inner main field 72 by a boundary 76'.

When ploughing the field 70 using a traditional and prior art plough system, the farmer will use a plough system having a number of plough shears arranged in a staggered configuration in relation to the longitudinal direction as well as to the transverse direction of the plough system. The rightmost plough shear accordingly is the leading plough shear, whereas the leftmost plough shear is the trailing plough shear.

The farmer will start ploughing in the northern headland 74 in a western end thereof. The farmer will move forward in a southern direction and he will lower all the plough shears simultaneously when the leading rightmost plough shear crosses the boundary 76. This will have the consequence that the part 80 of the headland 74 will be ploughed.

The farmer continues ploughing in a southern direction following the leg 78 of the ploughing trail into the southern headland 74' and when the trailing and leftmost plough shear crosses the boundary 76' he will simultaneously raise all the plough shears. This will have the consequence that the part 80 of the headland 74' will be ploughed.

In the headland 74' the farmer will turn the vehicle towing the plough system and continue ploughing in a northern direction.

Accordingly, the farmer continues ploughing in this way in a successive southern and northern direction following a serpentine path.

The farmer will finalize ploughing the inner main field 72 when he reaches the eastern part of the northern headland 74.

At this time, all of the inner main field 72 has been ploughed. However, also soil of the parts 80 of the northern headland 74 as well as soil of the parts 80 of the southern headland 74' will have been ploughed this way.
In order to finish ploughing the field 70, the farmer finally ploughs the northern headland 74 and the southern headland. In this specific example he will follow a western-eastern serpentine path when doing so.

When the field 70 comprising the inner main field 72 and the northern headland 74 as well as the southern headland 74' have been ploughed, all the parts 80 in the northern headland 74 the southern headland 74' will have been subjected to ploughing twice which means that any soil in the areas 80 containing weed will have been turned around twice which means that the weed will not have been buried to the extent that the growth conditions for the weed will be impaired.

Accordingly, crop seeds which will subsequently be sown in the soil of the areas 80 will encounter a strong competition in relation to seeding and growth in relation to the weed which was previously present in these areas. For this reason, the areas 80 will not provide optimum growth conditions for the crop seeds to be sown.

Fig. 2 is a perspective view illustrating a plough system 100 according to the first aspect of the present invention. The plough system 100 comprises i) a plough frame 2; and ii) a control unit 16 (not seen in fig. 2).

The plough frame 2 comprising coupling means 4 for coupling said plough frame to a towing vehicle, wherein said plough frame having an extension in a lengthwise direction X, and an extension transverse direction Y. The lengthwise direction X is essentially parallel to the intended direction of movement of the plough shears through the soil; whereas the transverse direction Y is essentially perpendicular thereto.

The plough frame comprising two or more lifting means 6,6' comprising a fixed part 8 being mounted on said plough frame 2, and a moving part 10 carrying a plough shear 12,12'. The moving part 10 is pivotally moveable in relation to the frame 2.

Each said lifting means 6,6' comprising an actuator 14,14'. Each said actuator being configured to allow altering of said plough shears 12,12' from a lowered position to a raised position, and vice versa.

The plough shears 12,12' being arranged on said frame in mutual staggered orientation in relation to a lengthwise direction as well as to a transverse direction.

A control unit 16 (not seen in fig. 2) is configured to receive controlling input 18, and in response thereto independently activate one or more actuators 14,14' associated with said lifting means; thereby enabling independent raising and/or lowering of one or more of said plough shears 12,12'.

Fig. 3 illustrates one embodiment of a controlling system of the plough system 100 of the first aspect of the present invention. The controlling system comprises an interphase 20.

The interphase being configured to enable providing instructions to an actuator 14,14' in relation to lowering/raising a specific plough shear 12,12'. This is brought about via the control
unit 16 which is a control unit for controlling the hydraulic actuators 14, 14' upon receipt of instructions to this end and by controlling the hydraulic pressure in the hydraulic hoses 34, 34'. The actuation of the actuators 14, 14' will effect lowering or raising the plough shears 12, 12' pivotally suspended on the frame 2 of the plough system.

The interphase 20 is being managed or programmed via input means 22 in the form of a keyboard or a tablet 24. A monitor 26 allows an operator to monitor the settings of the interphase.

The interphase 20 comprises a data storage 28. The data storage is configured to allow storing of coordinates relating to one or more boundaries 76, 76' between a main, inner field 72 to be ploughed and a surrounding headland 74, 74'.

The interphase 20 is also configured to receive position indication coordinates from a position indication receiver 30 in the form of GNSS, e.g., a GPS satellite navigation system 32.

A data storage 28' is configured to enable storing thereon, data relating to the relative position of the one or more, preferably all, of said plough shears 12, 12', in relation to said position indication receiver 30. Furthermore, the interphase 20 is configured to calculate, on the basis thereof and on the basis of the coordinates received by the position indication receiver 30, the absolute coordinates of the one or more, preferably all, of the plough shears 12, 12'. The data storage 28' may be the same or different form the data storage 28.

In this way, based on the absolute position of the position indication receiver 30 and the relative position of each plough shear 12, 12', the absolute position of each plough shear 12, 12' will continuously be calculated.

The interphase 20 is configured to provide signals to the control unit 16 relating to instructions of independently lowering or raising one or more plough shears 12, 12' according to a predetermined strategy.

One preferred predetermined strategy comprises the following elements:

a) in case a specific plough shear 12, 12' being located within the inner, main field 72 to be ploughed, said plough shear must be arranged in a lowered position;

b) in case a specific plough shear 12, 12' being located within a headland 74, 74', said plough shear must be arranged in a raised position;

c) in case a specific plough shear 12, 12' is crossing the boundary 76, 76' between the inner, main field to be ploughed and an associated headland 74, 74', in a direction from the inner, main field to be ploughed to the headland, that specific plough shear must change position from a lowered position to a raised position;

d) in case a specific plough shear 12, 12' is crossing the boundary 76, 76' between the inner, main field 72 to be ploughed and an associated headland 74, 74', in a direction from the
headland to the inner, main field to be ploughed, that specific plough shear must change position from a raised position to a lowered position.

Accordingly, the plough system 100 schematically illustrated in fig. 3 allows for independently and automatically controlling the raising and lowering of the plough shears based on the position of each plough shear 12, 12' and based on whether each specific plough shear is located in an inner, main field 72 to be ploughed or in an associated headland 74, 74'.

Hence, the plough system depicted in fig. 3 allows for avoidance of turning part of the soil twice and thereby will improve germination and growth conditions for crops seed to be sown following ploughing.
List of reference numerals

2  Plough frame
4  Coupling means
6,6' Lifting means
5  8  Fixed part of lifting means
10 Moving part of lifting means carrying a plough shear
12,12' Plough shear
14,14' Actuator
16 Control unit
10 18 Controlling input
20 Interphase
22 Input means
24 Keyboard
26 Monitor
15 28,28' Data storage
30 Position indicating receiver
32 Satellite navigation system
34 Hydraulic hose
70 Field to be ploughed
20 72 Inner, main field to be ploughed
74,74' Headland at least partly surrounding the main area of field to be ploughed
76,76' Boundary between inner, main field to be ploughed and headland
78 Legs of ploughing trails
80 Areas subject to ploughing twice
25 82 Ploughing direction
100 Plough system
X Lengthwise direction
Y       Transverse direction
Claims

1. A plough system (100) comprising:

   i) a plough frame (2), said plough frame comprising coupling means (4) for coupling said plough frame to a towing vehicle;

   wherein said plough frame having an extension in a lengthwise direction (X), and an extension in a transverse direction (Y);

   wherein said plough frame comprising two or more lifting means (6,6’); said lifting means comprising a fixed part (8) being mounted on said plough frame (2), and a moving part (10) carrying a plough shear (12,12’);

   wherein each said lifting means (6,6’) comprising an actuator (14,14’);

   wherein said actuator being configured to allow altering of said plough shears (12,12’) from a lowered position to a raised position, and vice versa;

   wherein said plough shears (12,12’) being arranged on said frame in mutual staggered orientation in relation to a lengthwise direction as well as to a transverse direction;

   ii) a control unit (16) configured to receive controlling input (18), and in response thereto independently activate one or more actuators (14,14’) associated with said lifting means; thereby enabling independent raising and/or lowering of one or more of said plough shears (12,12’).

2. A plough system (100) according to claim 1, wherein said actuators (14,14’) independently being selected from the group comprising: hydraulic actuators, electric actuators, pneumatic actuators.

3. A plough system (100) according to claim 1 or 2, wherein said actuators (14,14’) are being hydraulic actuators and wherein said control unit (16) comprises hydraulic valves configured for activating said hydraulic actuators; or wherein said actuators (14,14’) are being electric actuators and wherein said control unit (16) comprises electric switches configured for activating said electric actuators; or wherein said actuators (14,14’) are being pneumatic actuators and wherein said control unit (16) comprises pneumatic valves configured for activating said pneumatic actuators.

4. A plough system (100) according to any of the claims 1 - 3 comprising 2 - 40 plough shears (12,12’), such as 4 - 35 plough shears, for example 6 – 30 plough shears, such as 10 – 25 plough shears, e.g. 15 – 20 plough shears.

5. A plough system (100) according to any of the preceding claims, wherein said plough system is a reversible plough or a non-reversible plough.
6. A plough system (100) according to any of the preceding claims, wherein said two or more lifting means (6, 6') being configured in such a way that the raising and lowering of the plough shears (12, 12') are being performed by a pivotally movement of the moving part (10) carrying the plough shear (12, 12').

7. A plough system (100) according to any of the preceding claims, wherein in respect of one or more of said lifting means, preferably in respect of all said lifting means, said lifting means are being configured in such a way that one end of said actuator (14, 14') is being pivotally mounted to said fixed part (8) of said lifting means, and in such a way that the opposite end of said actuator is being pivotally mounted to said moving part (10) of said lifting means, wherein said two opposite ends of said actuator are being moveable in relation to each other.

8. A plough system (100) according to any of the preceding claims further comprising an interphase (20), said interphase being configured so as to enable providing instructions to an actuator (14, 14') in relation to independently lowering/raising a specific plough shear (12, 12').

9. A plough system (100) according to claim 8, wherein said interphase being configured to enable providing instructions to said actuator (14, 14') in relation to independently lowering/raising a specific plough shear (12, 12'), by providing controlling input to said control unit (16).

10. A plough system (100) according to claim 8 or 9, wherein said system furthermore comprising input means (22), such a keyboard or a tablet (24) for programming said interphase; said system optionally furthermore comprising a monitor (26).

11. A plough system (100) according to claims 10, wherein said monitor (26) is being configured for monitoring the settings and/or the status of the operation of the plough system.

12. A plough system (100) according to any of the preceding claims further comprising a data storage (28); said data storage being configured to allow storing data associated with coordinates relating to one or more boundaries (76, 76') between a main, inner field (72) to be ploughed and a surrounding headland (74, 74').

13. A plough system (100) according to any of the claims 8 – 12, wherein said interphase (20) being configured to receive position indication coordinates from a position indication receiver (30).

14. A plough system (100) according to claim 9, wherein said position indication coordinates are provided by a satellite navigation system (32), such as a Global Navigation Satellite System (GNSS), such as a GPS system.

15. A plough system (100) according to claim 13 or 14 further comprising one or more of such a position indication receiver, such as a satellite navigation system (32), for example a GPS system.
16. A plough system (100) according to any of the claims 13 – 15 wherein the number of position indicating receivers is equal to the number of plough shears, and wherein a position indication receiver is being arranged at the position of each plough shear.

17. A plough system (100) according to any of the claims 8 – 15 further comprising a data storage (28') configured to enable storing thereon, data relating to the relative position of the one or more, preferably all, of said plough shears (12,12'), in relation to said position indication receiver (30), and wherein said interphase (20) being configured to calculate, on the basis thereof and on the basis of the coordinates received by a position indication receiver, the absolute coordinates of the one or more, preferably all, of the plough shares (12,12').

18. A plough system (100) according to any of the preceding claims wherein said control unit (16) is being configured for automatically controlling said activation of one or more actuators (14,14') with the view to automatically and independently raising and/or lowering of one or more of said plough shears.

19. A plough system (100) according to any of the claims 1 - 18, wherein said plough system being configured, via said interphase (20), to provide signals to said control unit (16) relating to instructions of independently lowering or raising one or more plough shears (12,12') according to a predetermined strategy.

20. A plough system (100) according to claim 19, wherein said predetermined strategy comprises the following elements:

a) in case a specific plough shear (12,12') being located within the inner, main field (72) to be ploughed, said plough shear must be arranged in a lowered position;

b) in case a specific plough shear (12,12') being located within a headland (74,74'), said plough shear must be arranged in a raised position;

c) in case a specific plough shear (12,12') is crossing the boundary (76,76') between the inner, main field to be ploughed and an associated headland (74,74'), in a direction from the inner, main field to be ploughed to the headland, that specific plough shear must change position from a lowered position to a raised position;

d) in case a specific plough shear (12,12') is crossing the boundary (76,76') between the inner, main field (72) to be ploughed and an associated headland (74,74'), in a direction from the headland to the inner, main field to be ploughed, that specific plough shear must change position from a raised position to a lowered position.
21. A plough system (100) according to any of the preceding claims, wherein said plough system comprises a stone release mechanism and wherein said two or more lifting means (6,6') being integrated with said stone release mechanism.

22. Use of a plough system (100) according to any of the claims 1 – 21 for ploughing a field (72) at least partly surrounded by a headland (74,74').

23. A method for ploughing a field (72), at least partly surrounded by a headland (74,74'), said method comprising:

   i) defining coordinates of one or more boundaries (76,76') between an inner, main field (72) to be ploughed and the surrounding headland (74,74');

   ii) providing a plough system (100) comprising a plough frame (2) having an extension in a lengthwise direction (X), and an extension transverse direction (Y); said plow frame comprising two or more lifting means (6,6'); said lifting means comprising a fixed part (8) being mounted on said plough frame, and a moving part (10) carrying a plough shear (12,12'); wherein said lifting means comprising an actuator (14,14'); wherein said actuator being configured to allow altering said plough shear from a lowered position to a raised position and vice versa, wherein said plough shears being arranged in a mutual staggered orientation in relation to a lengthwise direction as well as to a transverse direction;

   iii) ploughing a field of soil by moving the plough shears (12,12') through the soil of the inner, main field (72) to be ploughed;

   iv) in respect of each of the plough shears (12,12'), raising a specific plough shears in case a specific plough shear is crossing the boundary (76,76') between the inner, main field (72) to be ploughed and an associated headland (74,74'), in a direction from the inner, main field to be ploughed to the headland;

   v) ploughing the area of the headland (74,74') at least partly surrounding the inner, main field (72).

24. A method according to claim 16, wherein said raising and lowering of a specific plough shear (12,12') is being performed automatically.

25. A method according to claim 23 or 24 performed by using a plough system (100) according to any of the claims 1 – 21.
### INTERNATIONAL SEARCH REPORT

**International application No**

PCT/DK2016/000028

**A. CLASSIFICATION OF SUBJECT MATTER**

INV. A01B3/36 A01B63/00

**ADD.**

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELD SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

A01B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

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Further documents are listed in the continuation of Box O.

See patent family annex.

**Date of the actual completion of the international search**

27 September 2016

**Date of mailing of the international search report**

06/10/2016

Name and mailing address of the ISA

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Authorized officer

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Form PCT/ISA/91 (second sheet) (26/1999)
## INTERNATIONAL SEARCH REPORT

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- **Patient family member(s)**
- **Publication date**

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3. Appendix / Patent B – A system for controlling the working depth of an agricultural implement
(12) International Application Status Report

Received at International Bureau: 16 December 2016 (16.12.2016)
Information valid as of: 25 April 2017 (25.04.2017)
Report generated on: 03 August 2017 (03.08.2017)

(10) Publication number: WO2017/101930
(43) Publication date: 22 June 2017 (22.06.2017)
(26) Publication language: English (EN)

(21) Application Number: PCT/DK2016/050436
(22) Filing Date: 16 December 2016 (16.12.2016)
(25) Filing language: English (EN)

(31) Priority number(s): PA 2015 00813 (DK)
(31) Priority date(s): 17 December 2015 (17.12.2015)
(31) Priority status: Priority document received (in compliance with PCT Rule 17.1)

(51) International Patent Classification:
A01B 63/114 (2006.01)

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(54) Title (EN): A SYSTEM FOR CONTROLLING THE WORKING DEPTH OF AN AGRICULTURAL IMPLEMENT

(54) Title (FR): SYSTÈME PERMETTANT DE COMMANDER LA PROFONDEUR DE TRAVAIL D'UNE MACHINE AGRICOLE

(57) Abstract:
(EN): The invention relates to a coupling mechanism (100) for coupling an agricultural implement (200) to a tractor (300); said coupling mechanism comprising: a top link (2), said top link having a front end (4) configured to be pivotally mounted on a rear end (6) of a tractor; and said top link having an opposite rear end (8) configured to be pivotally mounted on a three point linkage (10) of an agricultural implement; a first lift arm (12) and a second lift arm (14); said first lift arm and said second lift arm each having a front end (16) configured to be pivotally mounted on a rear end of a tractor and an opposite rear end (18) configured to be pivotally mounted on a three point linkage of an agricultural implement; said two front ends of the first and second lift arm, at their points of mounting, are configured to share a common pivot axis (20); wherein said first and second lift arms being adapted to be arranged below the top link; a first hydraulic actuator (22); said hydraulic actuator is having a first end (24) configured to be pivotally mounted at a rear end of a tractor; and a second end (26) configured to be pivotally connected to a three point linkage of an agricultural implement; a hydraulic control valve (28) comprising an inlet (30) and an outlet (32) for pressurized hydraulic fluid; one or more primary outlets (32) for supplying pressurized hydraulic fluid to said first hydraulic actuator (22); and one or more secondary outlets (34) for supplying pressurized hydraulic fluid to a second hydraulic actuator (36) being located on said implement (200) to be moved by said tractor (300); wherein said hydraulic control valve (28) comprising one or more individual valves for controlling the flow of hydraulic fluid from the inlet (30) for pressurized hydraulic fluid to the first hydraulic actuator (22) and the second hydraulic actuator (36), respectively.

(FR): L'invention concerne un mécanisme de couplage (100) permettant de coupler une machine agricole (200) à un tracteur (300); dit mécanisme de couplage comprenant : une liaison supérieure (2), ladite liaison supérieure ayant une extrémité avant (4) conçue pour être montée pivotante sur une extrémité arrière (6) d'un tracteur ; et ladite liaison supérieure étant dotée d'une extrémité arrière opposée (8) conçue pour être montée pivotante sur un embardage trois points (10) d'une machine agricole ; un premier bras de levage (12) et un second bras de levage (14) ; dit premier bras de levage et dit second bras de levage présentant chacun une extrémité avant (16) conçue pour être montée pivotante sur une extrémité arrière d'un tracteur et une extrémité arrière...
opposée (18) conçue pour être montée pivotante sur un attelage trois points d'une machine agricole ; lesdites deux extrémités avant des premier et second bras de levage, au niveau de leurs points de montage, étant conçues pour partager un axe commun de pivotement (20) ; le premier et le second bras de levage étant conçus pour être placés sous la liaison supérieure ; un premier actionneur hydraulique (22) ; ledit actionneur hydraulique ayant une première extrémité (24) conçue pour être montée pivotante sur une extrémité arrière d'un tracteur ; et une seconde extrémité (26) conçue pour être raccordée pivotante à un attelage trois points d'une machine agricole ; une soupape de commande hydraulique (28) comprenant un orifice d'admission (30) et un orifice de refoulement (30) pour le fluide hydraulique sous pression ; un ou plusieurs orifices de refoulement secondaires (32) permettant de fournir un fluide hydraulique sous pression audit premier actionneur hydraulique (22) ; et un ou plusieurs orifices de refoulement secondaires (34) permettant de fournir un fluide hydraulique sous pression à un second actionneur hydraulique (36) situé sur ladite machine (200) devant être déplacé par ledit tracteur (300) ; ladite soupape de commande hydraulique (28) comprenant une ou plusieurs soupapes individuelles afin de réguler l'écoulement du fluide hydraulique à partir de l'orifice d'admission (30), pour le fluide hydraulique sous pression vers le premier actionneur hydraulique (22) et le second actionneur hydraulique (36) respectivement.

**International search report:**
Received at International Bureau: 03 April 2017 [03.04.2017] [EP]

**International Report on Patentability (IPRP) Chapter II of the PCT:**
Not available

**(S1) Designated States:**

European Patent Office (EPO) : AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SL, SK, SM, TR


Eurasian Patent Organization (EPO) : AM, AZ, BY, KG, KZ, RU, TJ, TM
(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
22 June 2017 (22.06.2017)

(41) IWPO

WO 2017/010950 A1

(51) International Patent Classification:
A01B 63/00 (2006.01)

(21) International Application Number:
PCT/DK2016/050436

(22) International Filing Date:
16 December 2016 (16.12.2016)

(25) Filing Language:
English

(26) Publication Language:
English

(30) Priority Data:
PA 2015 00931 17 December 2015 (17.12.2015) DK

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM,
AO, AT, AZ, BA, BB, BG, BI, BN, BR, BW, BY,
BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM,
DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT,
HN, HR, HT, IL, IN, IR, IS, IE, IT, JP, KE, KH, KI,
KN, KP, KR, KW, KZ, LA, LC, LK, LI, LT, LU, LV, LY,
MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG,
NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS,
RU, RW, SA, SC, SD, SE, SG, SK, SL, SI, SM, ST, SV, SY,
TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN,
ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): AEPR (KW, GH,
GM, KE, LS, MW, MZ, NA, RW, SD, SL, ST, SZ,
TZ, UG, ZM, ZW), Eurapin (AM, AZ, BY, KG, KZ, RU,
TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE,
DK, EE, ES, FI, FR, GB, GR, HR,HU, IE, IS, IT, LT, LU,
LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK,
SM, TR), OAPI (BF, BJ, CF, CG, CI, CL, CM, QA, GN, GQ,
GW, KM, ML, MR, NE, SN, TD, TG).

Published: with international search report (arts. 21(1))

(54) Title: A SYSTEM FOR CONTROLLING THE WORKING DEPTH OF AN AGRICULTURAL IMPLEMENT

(57) Abstract: The invention relates to a controlling mechanism (100) for controlling an agricultural implement (200) to a tractor (300); said controlling mechanism comprising: a top link (22), said top link having an end (24) configured to be pivotally mounted on a rear end (6) of a tractor; and said top link having an opposite end (28) configured to be pivotally mounted on a three point linkage (10) of an agricultural implement; a first lift arm (12) and a second lift arm (14); said first lift arm and said second lift arm each having a front end (16) configured to be pivotally mounted on a rear end (6) of a tractor; and an opposite rear end (18) configured to be pivotally mounted on a three point linkage of an agricultural implement; said two front ends of the first and second lift arm, at their points of mounting, are configured to share a common pivot axis (20); wherein said first and second lift arms being adapted to be arranged below the top link; a first hydraulic actuator (22); said hydraulic actuator is having a first end (24) configured to be pivotally mounted on the rear end of a tractor, and a second end (29) configured to be pivotally connected to a three point linkage of an agricultural implement, a hydraulic control valve (28) comprising an inlet (30) and an outlet (30) for pressurized hydraulic fluid; one or more primary outlets (32) for supplying pressurized hydraulic fluid to said first hydraulic actuator (22); and one or more secondary outlets (34) for supplying pressurized hydraulic fluid to a second hydraulic actuator (36) being located on said implement (300) to be moved by said tractor (300); wherein said hydraulic control valve (28) comprising one or more individual valves for controlling the flow of hydraulic fluid from the inlet (30) for pressurized hydraulic fluid to the first hydraulic actuator (22) and the second hydraulic actuator (30), respectively.
A system for controlling the working depth of an agricultural implement

Field of the invention

The present invention relates to the field of agriculture. More specifically, the present invention relates in a first aspect to a coupling mechanism for coupling an agricultural implement to a tractor. In a second aspect the present invention relates to a tractor comprising a coupling mechanism according to the first aspect. In a third aspect the present invention relates to an agricultural system comprising a tractor according to the second aspect of the present invention in combination with an agricultural implement. In a fourth aspect the present invention relates to the use of a coupling mechanism according to the first aspect of the present invention or of a tractor according to the second aspect of the present invention or of an agricultural system according to the third aspect of the present invention. In a fifth aspect the present invention relates to a kit for installing on a tractor for improving the control of the working depth of a soil conditioning agricultural implement.

Background of the invention

In the field of agriculture it has for centuries been acknowledged that in order to obtain a good yield of crops in terms of quantity and quality it will be necessary at regular intervals to provide a conditioning of the soil in which the crops are to be grown.

Such conditioning may relate to ploughing, cultivation, harrowing etc. The conditioning serves the purpose of aerating the soil, destroy the rooting of weed and to bury residues of last year’s crops.

Conditionings like ploughing, cultivation and harrowing are typically performed by towing an agricultural tool or implement behind a tractor.

Such agricultural implement are having a not insignificant extension in the direction of the intended movement through the soil. For this reason it will often be necessary to support the implement with one or more wheels located at a front part of the implement as well as with one or more wheels at a rear part of the implement.

For achievement of an optimum conditioning of the soil it is with certain implements of paramount importance that the working depth of the tool is being held within certain limits.

In case an implement is having front wheels as well as rear wheels, the attaining of an optimum working depth of the implement will require height adjustment of the front wheels as well as the rear wheels.

To this end, in many implements the height adjustment of the rear wheels and thereby the working depth of the rear part of the implement may be manually adjusted by turning a handle
at the rear part of the implement, which handle thereby adjusts the vertical position of the rear wheel relative to the rest of the implement. Other implements may be provided with a hydraulic cylinder for adjustment of the height of the rear wheel.

The height adjustment of the front wheels and thereby the working depth of the front part of the implement will typically be adjusted by manually adjustment of the height of the three point hitch of the tractor towing the implement.

A three point hitch is a mounting or coupling arrangement positioned at a rear part of a tractor. A three point hitch comprises two lower lift arms attached to the tractor’s hydraulic system enabling hydraulic lift and lowering of these two lift arm. Additionally a three point hitch comprises an upper rigid top link, which length may be manually adjustable by turning a turnbuckle having two oppositely threaded inner threads connecting two oppositely threaded end bars. In addition, manually hydraulic top linkages are also available on the market.

However as each manufacturer of tractors provides their equipment with its own proprietary hydraulic systems it will usually not be possible to fit an agricultural soil conditioning implement having hydraulics for adjusting the height above ground of a rear part of that implement to the specific hydraulic system of a specific tractor, thereby allowing a centralized, combined, simultaneous and simple height adjustment, and thereby also working depth of the front part as well as the rear part of that soil conditioning implement.

To the contrary it will be necessary to adjust separately the working depth at the front end of the soil conditioning implement using the tractor’s three point hitch on the one hand and the working depth at the rear end of the soil conditioning implement using the implements own height adjustment means on the other hand.

This adjustment process poses some difficulties because an adjustment of the height above ground of the implement at the front end, and thus the adjustment of the working depth at the front end will affect the height above ground of the implement at the rear end, and thus the adjustment of the working depth at the rear end.

This fact is mainly due to the fact that an adjustment of the height above ground of the implement at one end thereof will change the implement’s longitudinal angle and thereby affect the height above ground of the implement at its opposite end.

Accordingly, the prior art systems require a significant effort and time in order for making a correct adjustment of the working depth at the two opposite ends thereof prior to a working operation thereof.

In addition, change in soil composition or individually wheel penetration affects the operation depth which poses challenges for the operator to take into account, during operation.

Specifically soil strength and soil composition can influence the work performed by the soil working implement if working depth is not adjusted.
It is an objective of the present invention to alleviate or even eliminate the above stated disadvantages.

**Brief description of the invention**

This objective is attained with the present invention in its first, second, third, fourth, and fifth aspect, respectively.

Accordingly, the present invention relates in a first aspect to a coupling mechanism for coupling an agricultural implement to a tractor;

said coupling mechanism comprising:

a top link, said top link is having a front end configured to be pivotally mounted on a rear end of a tractor; and said top link is having an opposite rear end configured to be pivotally mounted on a three point linkage of an agricultural implement;

a first lift arm and a second lift arm; said first lift arm and said second lift arm each having a front end configured to be pivotally mounted on a rear end of a tractor and an opposite rear end configured to be pivotally mounted on a three point linkage of an agricultural implement;

said two front ends of the first and second lift arm, at their points of mounting, are configured to share a common pivot axis;

wherein said first and second lift arms being adapted to be arranged below the top link;

a first hydraulic actuator, said hydraulic actuator is having a first end configured to be pivotally mounted at a rear end of a tractor; and a second end configured to be pivotally connected to a three point linkage of an agricultural implement;

a hydraulic control valve comprising an inlet and an outlet for pressurized hydraulic fluid; one or more primary outlets for supplying pressurized hydraulic fluid to said first hydraulic actuator; and one or more secondary outlets for supplying pressurized hydraulic fluid to a second hydraulic actuator being located on said implement to be moved by said tractor;

wherein said hydraulic control valve comprising one or more individual valves for controlling the flow of hydraulic fluid from the inlet for pressurized hydraulic fluid to the first hydraulic actuator and the second hydraulic actuator, respectively.

In a second aspect the present invention relates to a tractor comprising a coupling mechanism according to the first aspect of the present invention.

In a third aspect the present invention relates to an agricultural system comprising a tractor according to the second aspect in combination with an agricultural implement, wherein said second hydraulic actuator is being mounted on said agricultural implement and being configured to allow hydraulic adjustment of the working depth of a rear part of said agricultural implement.
In a fourth aspect the present invention relates to a use of a coupling mechanism according to the first aspect of the present invention or of a tractor according to the second aspect of the present invention or of an agricultural system according to the third aspect of the present invention for a soil conditioning purpose.

In a fifth aspect the present invention relates to a kit for installing on a tractor for improving the control of the working depth of a soil conditioning agricultural implement to be towed behind said tractor, said kit comprising:

- a first hydraulic actuator, said hydraulic actuator is having a first end configured to be pivotally mounted at a rear end of a tractor, and a second end configured to be pivotally connected to a three point linkage of an agricultural implement;
- a hydraulic control valve comprising an inlet and an outlet for pressurized hydraulic fluid; one or more primary outlets for supplying pressurized hydraulic fluid to said first hydraulic actuator; and one or more secondary outlets for supplying pressurized hydraulic fluid to a second hydraulic actuator being located on said implement to be moved by said tractor;

wherein said hydraulic control valve comprising one or more individual valves for controlling the flow of hydraulic fluid from the inlet for pressurized hydraulic fluid to the first hydraulic actuator and the second hydraulic actuator, respectively.

The present invention in its various aspects provides for allowing an easy and fast adjustment of the working depth at the two opposite ends of an agricultural soil conditioning implement to be towed behind a tractor.

The coupling mechanism utilized in the various aspects of the present invention allows for improved adjustment of the working depth of an implement by adjustment of the height of a front part and a rear part of the implement, and hence the working depth at a front part and at a rear part, fully independently of the control system of the hydraulic system of the tractor.

This concept of adjustment allows a high level of control to be implemented, making agricultural implements fully automatically controllable.

The invention in its various aspects will enable utilizing on-board, de-centralized control system for optimization of the soil working depth. A centralized on-line auxiliary system will further enable control based on e.g. soil maps, soil texture or soil composition maps, residue maps, soil compaction maps etc.

**Brief description of the figures**

Fig. 1 schematically illustrates a prior art coupling mechanism of a tractor.
Detailed description of the invention

The present invention relates in a first aspect to a coupling mechanism for coupling an agricultural implement to a tractor,

said coupling mechanism comprising:

a top link, said top link is having a front end configured to be pivotally mounted on a rear end of a tractor, and said top link is having an opposite rear end configured to be pivotally mounted on a three point linkage of an agricultural implement;

a first lift arm and a second lift arm; said first lift arm and said second lift arm each having a front end configured to be pivotally mounted on a rear end of a tractor and an opposite rear end configured to be pivotally mounted on a three point linkage of an agricultural implement; said two front ends of the first and second lift arm, at their points of mounting, are configured to share a common pivot axis;

wherein said first and second lift arms being adapted to be arranged below the top link;

a first hydraulic actuator, said hydraulic actuator is having a first end configured to be pivotally mounted at a rear end of a tractor, and a second end configured to be pivotally connected to a three point linkage of an agricultural implement;

a hydraulic control valve comprising an inlet and an outlet for pressurized hydraulic fluid; one or more primary outlets for supplying pressurized hydraulic fluid to said first hydraulic actuator; and one or more secondary outlets for supplying pressurized hydraulic fluid to a second hydraulic actuator being located on said implement to be moved by said tractor;

wherein said hydraulic control valve comprising one or more individual valves for controlling the flow of hydraulic fluid from the inlet for pressurized hydraulic fluid to the first hydraulic actuator and the second hydraulic actuator, respectively.

The coupling mechanism is intended to be used on a tractor when towing an agricultural implement having hydraulic means for raising and lowering a rear end thereof, in relation to the ground, thereby allowing full and independent adjustment of the working depth into the soil of the working tools of that agricultural implement.
The coupling mechanism is being independent of the hydraulic control system incorporated into the tractor, thus allowing control without the necessity to interfere with a proprietary hydraulic control system of the tractor. Only hydraulic pressurized fluid is needed from the tractor's hydraulic system. Such availability of hydraulic pressurized fluid is a standard feature of essentially all tractors.

In one embodiment of the coupling mechanism of the first aspect of the present invention, the coupling mechanism furthermore comprising a hydraulic hose for connecting the inlet for pressurized hydraulic fluid of the hydraulic control valve and/or comprising a hydraulic hose for connecting the outlet for pressurized hydraulic fluid of the hydraulic control valve to a hydraulic pump or a reservoir for pressurized hydraulic fluid on a tractor and/or furthermore comprising hydraulic hoses for connecting the hydraulic control valve to the first hydraulic actuator and the second hydraulic actuator, respectively.

Hydraulic hoses provide for conveying the pressurized hydraulic fluid form the pump or reservoir to the hydraulic control valve and further on to the first hydraulic actuator and the second hydraulic actuator, respectively.

In one embodiment of the coupling mechanism of the first aspect of the present invention the top link comprises means, such as a turnbuckle for adjusting the effective length of said top link.

A turnbuckle may provide an easy, manual fine tuning of a rest setting of the three point hitch of the tractor.

In one embodiment of the coupling mechanism of the first aspect of the present invention the coupling mechanism furthermore comprising a control unit for controlling the individual valves of the hydraulic control valve.

Such a control unit allows for controlling the control valve according to a predefined control scheme.

In one embodiment of the coupling mechanism of the first aspect of the present invention the control unit comprising input means, such as an alphanumerical keyboard, for allowing a user to provide instructions to said control unit with the view to control said hydraulic control valve.

In one embodiment of the coupling mechanism of the first aspect of the present invention the control unit furthermore comprising display means, such as a monitor or a user interphase (UI), for displaying to a user the settings and/or status of the coupling mechanism or parts thereof.

Such means allows for controlling and communicating with the control unit.

In one embodiment of the coupling mechanism of the first aspect of the present invention the control unit comprises means for providing a calibration relating to the general degree of movement of the first hydraulic actuator relative to the second hydraulic actuator.
Such means allows for adjustment in such a way that the front end and the rear end of the agricultural implement will move up and down the same amount of distance, upon a height adjustment.

In one embodiment of the coupling mechanism of the first aspect of the present invention the one or both of said hydraulic actuators is/are being double acting hydraulic actuator(s).

In one embodiment of the coupling mechanism of the first aspect of the present invention the one or both of said hydraulic actuators is/are being a pair of oppositely arranged single acting hydraulic actuators.

These types of hydraulic actuators will both provide the desired effect of movement.

In one embodiment of the coupling mechanism of the first aspect of the present invention the coupling mechanism is configured to allow operation of the first actuator and the second actuator, respectively, independently from any hydraulic control system of said tractor.

Such a feature allows for easy add-on on an existing three point linkage between a tractor and an agricultural implement to be towed or moved behind that tractor.

In one embodiment of the coupling mechanism of the first aspect of the present invention the coupling mechanism further comprising a bracket for mounting on an agricultural implement, wherein said bracket comprising a transversal beam, a first longitudinal side wing and a second longitudinal side wing; wherein said first longitudinal side wing and said second longitudinal side wing each comprises means for mounting on an agricultural implement; and wherein said transversal beam comprises means for mounting said second end of said first hydraulic actuator.

Such a bracket is intended to be clamped onto an agricultural implement and due to the presence on the transversal beam of means for mounting said second end of said first hydraulic actuator, allows for easy and fast connecting the second end of said first hydraulic actuator to the agricultural implement.

In one embodiment of this embodiment, the means for mounting on an agricultural implement comprises an opening configured to accommodate a part of the agricultural implement and/or one or more holes for accommodating bolts for bolting the implement to the bracket.

In another embodiment the means for mounting said second end of said first hydraulic actuator comprises two elements extending in a forward direction from said transversal beam and each comprising a hole for accommodating a bolt.

These embodiments provide for a simple and inexpensive, and yet sturdy bracket for allowing easy and fast connecting the second end of said first hydraulic actuator to the agricultural implement.

In a second aspect the present invention relates to a tractor comprising a coupling mechanism according to the first aspect of the present invention.
In a third aspect the present invention relates to an agricultural system comprising a tractor according to the second aspect in combination with an agricultural implement, wherein said second hydraulic actuator is being mounted on said agricultural implement and being configured to allow hydraulic adjustment of the working depth of a rear part of said agricultural implement.

In one embodiment of the agricultural system of the third aspect of the present invention the implement being a soil conditioning implement such as a plough or a harrow.

In a fourth aspect the present invention relates to a use of a coupling mechanism according to the first aspect of the present invention or of a tractor according to the second aspect of the present invention or of an agricultural system according to the third aspect of the present invention for a soil conditioning purpose.

In one embodiment of the use according to the fourth aspect of the present invention the soil conditioning purpose is being ploughing or harrowing.

In a fifth aspect the present invention relates to a kit for installing on a tractor for improving the control of the working depth of a soil conditioning agricultural implement to be towed behind said tractor, said kit comprising:

a first hydraulic actuator, said hydraulic actuator is having a first end configured to be pivotally mounted at a rear end of a tractor, and a second end configured to be pivotally connected to a three point linkage of an agricultural implement;

a hydraulic control valve comprising an inlet and an outlet for pressurized hydraulic fluid; one or more primary outlets for supplying pressurized hydraulic fluid to said first hydraulic actuator; and one or more secondary outlets for supplying pressurized hydraulic fluid to a second hydraulic actuator being located on said implement to be moved by said tractor;

wherein said hydraulic control valve comprising one or more individual valves for controlling the flow of hydraulic fluid from the inlet for pressurized hydraulic fluid to the first hydraulic actuator and the second hydraulic actuator, respectively.

In one embodiment of the kit according to the fifth aspect of the present invention the kit further comprising one or more features as defined in respect of the embodiments of the first aspect of the present invention.

Referring now in details to the drawings for the purpose of illustrating preferred embodiments of the present invention, Fig. 1 illustrates the principle of a conventional and traditional design of a lifting hitch on a tractor. The lifting hitch is arranged on a rear part of the tractor and allows lifting and lowering agricultural tools or agricultural implements to be towed or moved behind the tractor.

Fig. 1 is a plan view as seen sideways from between the rear wheels of the tractor. Fig. 1 shows a traditional and conventional coupling mechanism 100 in the form three point hitch of the rear end of a tractor. The hitch comprises a top link 2 having a front end 4 and a rear end
8. The front end 4 of the top link 2 is pivotally mounted at a point on the tractor itself. The opposite rear end 6 of the top link 2 is pivotally mounted on a three point linkage of an agricultural implement 200 (not shown in fig. 1). The implement 200 may be an implement for cultivating soil or crops.

Below the top link are arranged first lift arm 12 and a second lift arm 14. The front end 16 of the lift arm 12, 14 is pivotally mounted on the tractor itself. The rear end 18 of the lift arm 12, 14 is pivotally mounted on the three point linkage of the agricultural implement 200.

The lift arms 12, 14 is being connected to a hydraulic actuator 54 in such a way that the height of the lift arms 12, 14 may be adjusted by providing hydraulic pressure to said actuator.

The top link 2 comprises a turnbuckle 40 for adjustment of the effective length thereof.

As mentioned above, the height of the coupling mechanism may be adjusted by hydraulic pressure to the hydraulic actuator 54. The hydraulic pressure may be provided by using the hydraulic system of the tractor.

Hence, providing hydraulic pressure to the hydraulic actuator implies lifting or lowering of the lift arms 12, 14. If an agricultural implement was connected to the three point hitch, the front end of the implement may be raised or lowered in this way.

However, the prior art coupling mechanism 100 in the form three point hitch outlined in fig. 1 does not allow for adjustment of a rear part of the implement 200 connected to the three point hitch.

Fig. 2 illustrates schematically a coupling mechanism according to the first aspect of the present invention for improving working depth of an agricultural implement 200 in the form of a plough.

In fig. 2 the coupling mechanisms of the present invention comprises the conventional and traditional tree point hitch illustrated in fig. 1 to which additional elements have been added.

Accordingly, fig. 2 is a plan view as seen sideways from between the rear wheels of the tractor. The coupling mechanism of fig. 2 comprises a top link 2 having a front end 4 and a rear end 8. The front end 4 of the top link 2 is pivotally mounted at a point on the tractor itself. The opposite rear end 6 of the top link 2 is pivotally mounted on an three point linkage of an agricultural implement 200 in the form of a plough comprising five plough bodies 66, 66′, 66″, 66‴, 66⁗. However, other implements comprising soil working tools may be used with the present invention as well.

The three point linkage of the agricultural implement is connected to the frame 64 of the agricultural implement. The plough schematically illustrated in fig. 2 comprises a rear wheel 68 which is pivotally connected to the frame 64 via a suspension 70. The suspension 70 is connected to the frame 64 of the plough by a second hydraulic actuator 36. The rear wheel is configured to roll on top of the soil surface 60.
The second hydraulic actuator allows adjustment of the working depth of the rear part of the plough 200.

Below the top link are arranged first lift arm 12 and a second lift arm 14. The front end 16 of the lift arm 12,14 is pivotally mounted on the tractor itself. The rear end 18 of the lift arm 12, 14 is pivotally mounted on the three pint linkage 10 of the agricultural implement 200.

A hydraulic actuator 54 is pivotally connected to the lift arms 12,14 in such a way that the height of the lift arms 12,14 may be adjusted by providing hydraulic pressure to said actuator.

The top link 2 comprises a turnbuckle 40 for adjustment of the effective length thereof.

In addition to the prior art three point linkage illustrated in fig. 1, the coupling mechanism 100 illustrated in fig. 2 further comprises a first hydraulic actuator 22. The first hydraulic actuator is having a first end 24 pivotally at a rear point of the tractor; and a second end 26 pivotally connected to the three point linkage of the agricultural implement 200.

Furthermore, the coupling mechanism of the present invention illustrated in fig. 2 comprises a hydraulic control valve 28. The hydraulic control valve comprises an inlet 30 and an outlet 32 for pressurized hydraulic fluid, one or more primary outlets 32 for supplying pressurized hydraulic fluid to said first hydraulic actuator 22, and one or more secondary outlets 34 for supplying pressurized hydraulic fluid to a second hydraulic actuator 36 being located on said implement 200 to be towed by said tractor 300.

The hydraulic control valve 28 is being fed with pressurized hydraulic fluid from a hydraulic pump or reservoir 37 for pressurized hydraulic fluid. Such pressurized hydraulic fluid is readily accessible on most tractors in the form of a hydraulic outlet and inlet on the tractor's hydraulic system. Such hydraulic pressures may be used without interfering with the individual tractor manufacturer's proprietary control systems for controlling the hydraulic systems of the individual tractor.

The hydraulic control valve 28 comprises a number of individual valves for controlling the flow of hydraulic fluid from the inlet 30 for pressurized hydraulic fluid to the first hydraulic actuator 22 and the second hydraulic actuator 36, respectively via the hoses 38 connecting the hydraulic control valve with the first hydraulic actuator 22 and the second hydraulic actuator 36, respectively.

This will allow individual adjustment of the first hydraulic actuator as well as the second hydraulic actuator.

Accordingly, using the coupling mechanism shown in fig. 2 for coupling an agricultural implement having its own hydraulic actuator for height adjustment of a rear part thereof, and hence also adjustment of the working depth of the plough bodies 66,66',66'',66''',66''' into the soil 58, it will be possible to obtain an individual adjustment of the working depth of both a front part as well as a rear part of the tools of the agricultural implement.
In use the tractor’s own hydraulic mechanism for raising and lowering of the lift arms 12,14, in
this case the hydraulic actuator 54 will be set into “floating mode” in which mode the
hydraulic actuator 54 essentially is freely movable.

The kit according to the fifth aspect of the present invention will accordingly be well suited as
an add-on to existing implements equipped with a hydraulic actuator for adjustment of
working depth of the front and rear part of that implement.

Fig. 3 schematically illustrates an embodiment of the means for controlling the coupling
mechanism 100 according to the present invention.

Fig. 3 shows the hydraulic control valve 28 comprising an inlet 30 and outlet 30’ for
pressurized hydraulic fluid from a hydraulic pump or reservoir. The hydraulic control valve
comprises two primary outlets 32 for supplying pressurized hydraulic fluid to said first
hydraulic actuator 22, and two secondary outlets 34 for supplying pressurized hydraulic fluid
to a second hydraulic actuator 36 intended to be located on an agricultural implement 200 to
be towed by a tractor.

The hydraulic control valve 28 in its inner comprises one or more individual valves for
controlling the flow of hydraulic fluid from the inlet 30 for pressurized hydraulic fluid to the
first hydraulic actuator 22 and the second hydraulic actuator 36, respectively via the hoses 38.

A control unit 42 for controlling the individual valves of the hydraulic control valve 28 is also
shown.

The control unit 42 comprises input means 44 in the form of an alphanumerical keyboard for
allowing a user to provide instructions to the control unit with the view to control said
hydraulic control valve 28.

Furthermore, the control unit 42 comprising display means 46, such as a monitor, for
displaying to a user the settings and/or status of the coupling mechanism or parts thereof.

Hence, using the keyboard 44 and the monitor 46 it will be possible to control the hydraulic
valve and accordingly also to control the first hydraulic actuator 26 and the second hydraulic
actuator 36, thereby allowing full and individual control of the working depth of a front end
and a rear end of a soil conditioning implement to be towed behind a tractor.

Fig. 4 is a perspective view of a bracket to be used with the coupling mechanism according to
the first aspect of the present invention.

Fig. 4 shows the bracket 80 for mounting on an agricultural implement 200. The bracket
comprising a transversal beam 82, a first longitudinal side wing 84 and a second longitudinal
side wing 86.

The first longitudinal side wing 84 and said second longitudinal side wing 86 each comprises
means 88 for mounting on an agricultural implement. These means 88 are in the form of an
opening 92 in the side wings which opening is being configured to accommodate a part of the
agricultural implement 200. Furthermore, these means 88 comprises a number of holes 94 for accommodating bolts for bolting the implement to the bracket.

Furthermore, the bracket comprises means 90 for mounting the second end 26 of said first hydraulic actuator. The means 90 for mounting said second end 26 of said first hydraulic actuator comprises two elements 96 extending in a forward direction from said transversal beam 82 and each comprising a hole for accommodating a bolt.

The bracket may be used for mounting on an agricultural implement having a universal three point linkage. By mounting the bracket on the agricultural implement the implement will be prepared for receiving and fastening the first hydraulic actuator 22 according to the coupling system of the first aspect according to the present invention.
List of reference numerals

2  Top link
4  Front end of top link
6  Rear end of tractor
5 8  Rear end of top link
10 Three point linkage of agricultural implement
12 First lift arm
14 Second lift arm
16 Front end of lift arm
10 18 Rear end of lift arm
20 Common pivot axis of two lift arms
22 First hydraulic actuator
24 First end of first hydraulic actuator
26 Second end of first hydraulic actuator
15 28 Hydraulic control valve
30 Inlet for pressurized hydraulic fluid
30’ Outlet for pressurized hydraulic fluid
32 Primary outlet for pressurized hydraulic fluid
34 Secondary outlet for pressurized hydraulic fluid
20 36 Second hydraulic actuator
37 Hydraulic pump or reservoir for pressurized hydraulic fluid
38 Hydraulic hose
40 Tumbuckle
42 Control unit
25 44 Input means
46 Display means
48 Rear part of agricultural implement
<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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<tbody>
<tr>
<td>50</td>
<td>Three point linkage of tractor</td>
</tr>
<tr>
<td>52</td>
<td>Rear wheel of tractor</td>
</tr>
<tr>
<td>54</td>
<td>Hydraulic actuator</td>
</tr>
<tr>
<td>58</td>
<td>Soil</td>
</tr>
<tr>
<td>60</td>
<td>Surface of soil</td>
</tr>
<tr>
<td>64</td>
<td>Frame of agricultural implement</td>
</tr>
<tr>
<td>66,66',66''</td>
<td>Plough shear of implement</td>
</tr>
<tr>
<td>66'',66''''</td>
<td>Plough shear of implement</td>
</tr>
<tr>
<td>68</td>
<td>Rear wheel of agricultural implement</td>
</tr>
<tr>
<td>70</td>
<td>Rear wheel suspension of implement</td>
</tr>
<tr>
<td>80</td>
<td>Bracket</td>
</tr>
<tr>
<td>82</td>
<td>Transversal beam of bracket</td>
</tr>
<tr>
<td>84</td>
<td>First longitudinal side wing</td>
</tr>
<tr>
<td>86</td>
<td>Second longitudinal side wing</td>
</tr>
<tr>
<td>88</td>
<td>Mounting means of side wing of bracket</td>
</tr>
<tr>
<td>90</td>
<td>Mounting means of transversal beam of bracket</td>
</tr>
<tr>
<td>92</td>
<td>Opening in side wing of bracket</td>
</tr>
<tr>
<td>94</td>
<td>Hole</td>
</tr>
<tr>
<td>96</td>
<td>Forwardly extending elements</td>
</tr>
<tr>
<td>100</td>
<td>Coupling mechanism</td>
</tr>
<tr>
<td>200</td>
<td>Agricultural implement</td>
</tr>
<tr>
<td>300</td>
<td>Tractor</td>
</tr>
<tr>
<td>400</td>
<td>Agricultural system</td>
</tr>
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Claims

1. A coupling mechanism (100) for coupling an agricultural implement (200) to a tractor (300), said coupling mechanism comprising:

a top link (2), said top link is having a front end (4) configured to be pivotally mounted on a rear end (6) of a tractor; and said top link is having an opposite rear end (8) configured to be pivotally mounted on a three point linkage (10) of an agricultural implement;

a first lift arm (12) and a second lift arm (14); said first lift arm and said second lift arm each having a front end (16) configured to be pivotally mounted on a rear end of a tractor and an opposite rear end (18) configured to be pivotally mounted on a three point linkage of an agricultural implement; said two front ends of the first and second lift arm, at their points of mounting, are configured to share a common pivot axis (20);

wherein said first and second lift arms being adapted to be arranged below the top link;

a first hydraulic actuator (22); said hydraulic actuator is having a first end (24) configured to be pivotally mounted at a rear end of a tractor; and a second end (26) configured to be pivotally connected to a three point linkage of an agricultural implement;

a hydraulic control valve (28) comprising an inlet (30) and an outlet (30') for pressurized hydraulic fluid; one or more primary outlets (32) for supplying pressurized hydraulic fluid to said first hydraulic actuator (22), and one or more secondary outlets (34) for supplying pressurized hydraulic fluid to a second hydraulic actuator (36) being located on said implement (200) to be moved by said tractor (300);

wherein said hydraulic control valve (28) comprising one or more individual valves for controlling the flow of hydraulic fluid from the inlet (30) for pressurized hydraulic fluid to the first hydraulic actuator (22) and the second hydraulic actuator (36), respectively.

2. A coupling mechanism (100) according to claim 1 furthermore comprising a hydraulic hose (38) for connecting the inlet (30) for pressurized hydraulic fluid of the hydraulic control valve (28) and/or comprising a hydraulic hose (38) for connecting the outlet (30') for pressurized hydraulic fluid of the hydraulic control valve (28) to a hydraulic pump or a reservoir (37) for pressurized hydraulic fluid on a tractor and/or furthermore comprising hydraulic hoses (38) for connecting the hydraulic control valve (28) to the first hydraulic actuator (22) and the second hydraulic actuator (36), respectively.

3. A coupling mechanism (100) according to claim 1 or 2, wherein said top link (2) comprises means, such as a turnbuckle (40) for adjusting the effective length of said top link.

4. A coupling mechanism (100) according to any of the claims 1 – 3 furthermore comprising a control unit (42) for controlling the individual valves of the hydraulic control valve (28).
5. A coupling mechanism (100) according to claim 4, wherein said control unit (42) comprising input means (44), such as an alphanumerical keyboard, for allowing a user to provide instructions to said control unit with the view to control said hydraulic control valve (28).

6. A coupling mechanism (100) according to claim 4 or 5, wherein said control unit (42) furthermore comprising display means (46), such as a monitor or a user interface (UI), for displaying to a user the settings and/or status of the coupling mechanism or parts thereof.

7. A coupling mechanism (100) according to any of the claims 4 – 6, wherein said control unit (42) comprises means for providing a calibration relating to the general degree of movement of the first hydraulic actuator (22) relative to the second hydraulic actuator (36).

8. A coupling mechanism (100) according to any of the claims 1 – 7 wherein one or both of said hydraulic actuators (22,36) is/are being double acting hydraulic actuator(s).

9. A coupling mechanism (100) according to any of the claims 1 – 8 wherein one or both of said hydraulic actuators (22,36) is/are being a pair of oppositely arranged single acting hydraulic actuators.

10. A coupling mechanism (100) according to any of the claims 1 – 9 wherein the coupling mechanism is configured to allow operation of the first actuator (22) and the second actuator (36), respectively, independently from any hydraulic control system of said tractor.

11. A coupling mechanism (100) according to any of the claims 1 – 10 further comprising a bracket (80) for mounting on an agricultural implement (200), said bracket comprising a transversal beam (82), a first longitudinal side wing (84) and a second longitudinal side wing (86); wherein said first longitudinal side wing and said second longitudinal side wing each comprises means (88) for mounting on an agricultural implement; and wherein said transversal beam comprises means (90) for mounting said second end (26) of said first hydraulic actuator.

12. A coupling mechanism (100) according to claim 11, wherein the means (88) for mounting on an agricultural implement comprises an opening (92) configured to accommodate a part of the agricultural implement (200) and/or one or more holes (94) for accommodating bolts for bolting the implement to the bracket.

13. A coupling mechanism (100) according to claim 11 or 12, wherein said means (90) for mounting said second end (26) of said first hydraulic actuator comprises two elements (96) extending in a forward direction from said transversal beam (82) and each comprising a hole for accommodating a bolt.

13a. A coupling mechanism (100) according to any of the claims 1 – 13, wherein said coupling mechanism (100) is for a soil conditioning implement.

13b. A coupling mechanism (100) according to claim 13a, wherein said coupling mechanism (100) thereby allows adjustment of the working depth at two opposite ends of said implement,
such as an easy and fast adjustment of the working depth at two opposite ends of said implement.

13c. A coupling mechanism (100) according to any of the claims 1 – 13b, wherein said coupling mechanism further comprises a first sensor for sensing the extension of the first hydraulic actuator, and a second sensor for sensing the extension of the second hydraulic actuator.

13d. A coupling mechanism (100) according to claim 4 and 13c wherein said control unit is being configured to receive signals form said first sensor and/or from said second sensor, said signals relating to the extension of said first hydraulic actuator and/or said second hydraulic actuator, respectively, wherein said control units is being configured to adjust the extension of said first hydraulic actuator and/or said second hydraulic actuator, respectively based on said signals and based on a predetermined setting of a desired extension of said first hydraulic actuator and/or said second hydraulic actuator, respectively.

13e. A coupling mechanism (100) according to any of the claims 1 – 13d, wherein said hydraulic control valve is being configured for providing step less control of the extension of the said first hydraulic actuator and/or said second hydraulic actuator, respectively.

13f. A coupling mechanism (100) according to any of the claims 1 – 13e, wherein said coupling mechanism is configured for adjustment of the working depth at two opposite ends of said implement in an automatic mode, based on a predetermined setting of desired working depths at said two opposite ends.

14. A tractor (300) comprising a coupling mechanism (100) according to any of the claims 1 – 13.

15. An agricultural system (400) comprising a tractor (300) according to claim 14 in combination with an agricultural implement (200), wherein said second hydraulic actuator is being mounted on said agricultural implement and being configured to allow hydraulic adjustment of the working depth of a rear part (48) of said agricultural implement (200).

16. An agricultural system (400) according to claim 15, wherein said implement being a soil conditioning implement such as a plough or a harrow.

17. Use of a coupling mechanism (100) according to any of the claims 1 – 13 or of a tractor (300) according to claim 14 or of an agricultural system (400) according to claim 15 or 16 for a soil conditioning purpose.

18. Use according to claim 17, wherein the soil conditioning purpose being ploughing or harrowing.

19. A kit (500) for installing on a tractor (300) for improving the control of the working depth of a soil conditioning agricultural implement (200) to be towed behind said tractor, said kit comprising:
a first hydraulic actuator (22), said hydraulic actuator is having a first end (24) configured to be pivotally mounted at a rear end of a tractor, and a second end (26) configured to be pivotally connected to a three point linkage of an agricultural implement;

a hydraulic control valve (28) comprising an inlet (30) and an outlet (30') for pressurized hydraulic fluid; one or more primary outlets (32) for supplying pressurized hydraulic fluid to said first hydraulic actuator (22), and one or more secondary outlets (34) for supplying pressurized hydraulic fluid to a second hydraulic actuator (36) being located on said implement (200) to be moved by said tractor (300),

wherein said hydraulic control valve (28) comprising one or more individual valves for controlling the flow of hydraulic fluid from the inlet (30) for pressurized hydraulic fluid to the first hydraulic actuator (22) and the second hydraulic actuator (36), respectively.

20. A kit (500) according to claim 19 further comprising one or more features as defined in any of the claims 1 – 13.
# INTERNATIONAL SEARCH REPORT

**International application No**

PCT/DK2016/050436

## A. CLASSIFICATION OF SUBJECT MATTER

**INV. A01B63/114**

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

A01B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

## EPO-Internal, WPI Data

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
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<th>Relevant to claim No.</th>
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<td>X</td>
<td>US 4 817 730 A (WINTER DAVID C [US]) 4 April 1989 [1989-04-04] column 3, line 32 - column 6, line 3; Figures 1,2</td>
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### Further documents are listed in the continuation of Box C.

### See patent family annex.

* "A" document defining the general state of the art which is not considered to be of particular relevance
* "E" earlier application or patent published on or after the international filing date
* "L" document which may throw doubts on priority claimed or which is cited to establish the publication date of another invention or other special reason (as specified)
* "O" document referred to as oral disclosure, see, exhibition or other means
* "P" document published prior to the international filing date but later than the priority date claimed

**Date of the actual completion of the international search**

24 March 2017

**Date of mailing of the international search report**

06/04/2017

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Lucchesi-Palli, C

Form PCT/ISA/210 (second sheet) (April 2006)
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**Information on patent family members**

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4. Appendix / Patent C – A system for damping oscillations between a tractor and an agricultural implement during transport thereof
(12) International Application Status Report

Received at International Bureau: 16 December 2016 (16.12.2016)
Information valid as of: 02 May 2017 (02.05.2017)
Report generated on: 03 August 2017 (03.08.2017)

(10) Publication number: (43) Publication date: (26) Publication language:
WO2017101932 22 June 2017 (22.06.2017) English (EN)

(21) Application Number: (22) Filing Date: (25) Filing language:

(31) Priority number(s): (31) Priority date(s): (31) Priority status:
PA 2015 00814 (DK) 17 December 2015 (17.12.2015) Priority document received (in compliance
with PCT Rule 17.1)

(51) International Patent Classification:
A01B 59/06 (2006.01); A01B 63/10 (2006.01)

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(54) Title (EN): A SYSTEM FOR DAMPING OSCILLATIONS BETWEEN A TRACTOR AND AN AGRICULTURAL IMPLEMENT DURING TRANSPORT THEREOF

(54) Title (FR): SYSTÈME PERMETTANT D'AMORTIR LES OSCILLATIONS ENTRE UN TRACTEUR ET UNE MACHINE AGRICOLE PENDANT SON TRANSPORT

(57) Abstract:
(EN): The invention relates to a coupling mechanism (100) for damping oscillations between a tractor (300) and an agricultural implement during transport thereof; said coupling mechanism comprising: a top link, said top link is having a front end (4) configured to be pivotally mounted on a rear end (6) of a tractor; and said top link is having an opposite rear end (8) configured to be pivotally mounted on three point linkage (10) of an agricultural implement; wherein said top link is comprising a hydraulic actuator (38), said hydraulic actuator is having a front end (40) and a rear end (42); said hydraulic actuator is being arranged between the front end and the rear end of said top link so as to allow altering the effective distance between the front end and the rear end of said top link; a first lift arm (12) and a second lift arm (14); said first lift arm and said second lift arm (12, 14) each having a front end (16) configured to be pivotally mounted on a rear side of a tractor and an opposite rear end (18) configured to be pivotally mounted on a three point linkage of an agricultural implement; said two rear ends of the first and second lift arm, at their points of mounting, are configured to share a common pivot axis (20); wherein said first and second lift arms (12, 14) being adapted to be arranged below the top link (2); a transducer (44); said transducer being configured to sense the load exerted between the front end (40) and the rear end (42) of said hydraulic actuator; a hydraulic valve (46) comprising one or more outlets and being configured to supply pressurized hydraulic fluid to said hydraulic actuator in response to instructions (50) received by said hydraulic valve; a control unit (52) configured to receive a signal (54) provided by said transducer, and being configured to translate this signal into instructions (50) to be supplied to said hydraulic valve according to a predetermined protocol in order to suppress any oscillations encountered between a tractor and an agricultural implement during transport thereof.

(FR): L'invention concerne un mécanisme de couplage (100) permettant d'amortir les oscillations entre un tracteur (300) et une machine agricole pendant son transport; dit mécanisme de couplage comprenant : une liaison supérieure, ladite liaison supérieure ayant une extrémité avant (4) conçue pour être montée pivotante sur une extrémité arrière (6) d'un tracteur; et ladite liaison supérieure ayant une extrémité arrière opposée (8) conçue pour être montée pivotante sur un ancrage trois points (10) d'une machine agricole; ladite liaison supérieure comprenant un actionneur hydraulique (38), dit actionneur hydraulique ayant une
extrémité avant (40) et une extrémité arrière (42); ledit actionneur hydraulique étant placé entre l'extrémité avant et l'extrémité arrière de ladite liaison supérieure de façon à altérer la distance effective entre l'extrémité avant et l'extrémité arrière de ladite liaison supérieure; un premier bras de levage (12) et un second bras de levage (14); ledit premier bras de levage et ledit second bras de levage (12, 14) ayant chacun une extrémité (avant (16) ou arrière (16)) conçue pour être montée pivotante sur l'extrémité arrière d'un tracteur et une extrémité arrière opposée (18) conçue pour être montée pivotante sur un attelage trois points d'une machine agricole; ledites deux extrémités arrière des premiers et seconds bras, au niveau de leurs points de montage, étant conçues pour partager un axe de pivotement commun (20); ledits premiers et seconds bras de levage (12, 14) étant conçus pour être placés sous la liaison supérieure (2); un transducteur (44); ledit transducteur étant conçu pour détecter la charge exercée entre l'extrémité avant (40) et l'extrémité arrière (42) du ledit actionneur hydraulique; une soupape hydraulique (46) comprenant une ou plusieurs sorties de refoulement et étant conçue pour fournir un fluide hydraulique sous pression à un ledit actionneur hydraulique en réponse à des instructions (50) reçus par ladite soupape hydraulique; une unité de commande (52) conçue pour recevoir un signal (54) fourni par ledit transducteur, et conçue pour traduire ce signal en instructions (50) devant être fournies à ladite soupape hydraulique selon un protocole prédéfini afin de supprimer toute oscillation rencontrée entre un tracteur et une machine agricole pendant son transport.

International search report:
Received at International Bureau: 11 April 2017 (11.04.2017) [EP]

International Report on Patentability (IPRP) Chapter II of the PCT:
Not available

(81) Designated States:

European Patent Office (EPO) : AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR


Eurasian Patent Organization (EAPO) : AM, AZ, BY, KG, KZ, RU, TJ, TM
(54) Title: A SYSTEM FOR DAMPING OSCILLATIONS BETWEEN A TRACTOR AND AN AGRICULTURAL IMPLEMENT DURING TRANSPORT THEREOF

(57) Abstract: The invention relates to a coupling mechanism (100) for damping oscillations between a tractor (300) and an agricultural implement during transport thereof; said coupling mechanism comprising: a top link (100), said top link is having a front end (40) configured to be pivotally mounted on a rear end (60) of a tractor; and said top link is having an opposite rear end (80) configured to be pivotally mounted on three point linkage (100) of an agricultural implement; wherein said top link is comprising a hydraulic actuator (30), said hydraulic actuator is having a front end (40) and a rear end (60); said hydraulic actuator is being arranged between the front end and the rear end of said top link so as to allow altering the effective distance between the front end and the rear end of said top link; a first lift arm (12) and a second lift arm (14); said first lift arm and said second lift arm (12, 14) each having a front end (16) configured to be pivotally mounted on a rear side of a tractor and an opposite rear end (18) configured to be pivotally mounted on a three point linkage of an agricultural implement; said two rear ends of the first and second lift arm, at their points of mounting, are configured to share a common pivot axis (20); wherein said first and second lift arms (12, 14) being adapted to be arranged below the top link (20); a transducer (44); said transducer being configured to sense the load exerted between the front end (40) and the rear end (42) of said hydraulic actuator; a hydraulic valve (40) comprising one or more outlets and being configured to supply pressurized hydraulic fluid to said hydraulic actuator in response to instructions (50) received by said hydraulic valve; a control unit (52) configured to receive a signal (54) provided by said transducer, and being configured to translate this signal into instructions (50) to be supplied to said hydraulic valve according to a predetermined protocol in order to suppress any oscillations encountered between a tractor and an agricultural implement during transport thereof.
before the expiration of the time limit for amending the
claims and to be republished in the event of receipt of
amendments (Rule 48.2(b))
A system for damping oscillations between a tractor and an agricultural implement during transport thereof

Field of the invention

The present invention relates to the field of agriculture. More specifically, the present invention relates in a first aspect to a coupling mechanism for damping oscillations between a tractor and an agricultural implement during transport thereof.

In a second aspect the present invention relates to a tractor comprising a coupling mechanism according to the first aspect of the present invention.

In a third aspect the present invention relates to a use of a coupling mechanism according to the first aspect or of a tractor according to the second aspect of the present invention for damping oscillations between a tractor and an agricultural implement during transport thereof.

In a fourth aspect the present invention relates to a kit for installation on a three point linkage for an agricultural implement for damping oscillations between a tractor and an agricultural implement during transport thereof.

Background of the invention

In the field of agriculture it has for centuries been acknowledged that in order to obtain a good yield of crops in terms of quantity and quality it will be necessary at regular intervals to provide a conditioning of the soil in which the crops are to be grown.

Such conditioning may relate to ploughing, cultivation, harrowing etc. The conditioning serves the purpose of aerating the soil, destroy the rooting of weed and to bury residues of last year’s crops.

Conditionings like ploughing, cultivation and harrowing are typically performed by lift mounting an agricultural tool or implement behind a tractor.

With an ever increasing focus on optimizing efficiency of modern farming such agricultural implements tend to be designed in ever increasing sizes.
The implements to be used with a tractor are in a working situation usually towed or pulled or carried behind the tractor. The implement is connected to the tractor via the front end three point linkage of the implement. This three point linkage is connected to a coupling mechanism in the form of a three point hitch on a rear end of the tractor.

A three point hitch comprises two lower lift arms attached to the tractor's hydraulic system enabling hydraulic lift for elevating and lowering of these two lift arm. Additionally a three point hitch comprises normally an upper rigid top link, which length may be manually adjustable by turning a turnbuckle having two oppositely threaded inner threads connecting two oppositely threaded end bars.

In a non-working, transport situation, for example during transportation of the tractor the implement is usually lifted by the three point hitch in such a way that no part of the implement itself touches the ground. Accordingly, during transportation of an agricultural implement it is inevitably that oscillations of the implement being suspended on the three point hitch of the tractor will result. These oscillations will be induced by accelerations and decelerations of the tractor, by uneven road surfaces, by wind effects, by small or larger turns of the tractor and by the resilient nature of the inflated tires of the tractor, all of which may result in oscillations of the tractor in a downward/upward direction.

As most agricultural implements are having a significant weight, the lifting of an agricultural implement during a transport situation on public or private road may occasionally lead to vigorous oscillations which may be prone to positive feedback leading to oscillations with increasing amplitude during certain periods of time. The most extreme situation being in situations in which natural oscillations are obtained.

The oscillations may be directed in a forward-rear-direction of may be directed in a transverse direction, in a vertical direction or may be directed in a combination of a forward-rear-direction and vertical direction in relation to the direction of movement of the tractor.

It is self-evident that oscillations may pose a hazard in relation to traffic safety, because transportation by a tractor of an oscillating implement may have the effect of making it difficult to control the tractor. Furthermore, in case the oscillation take place in a forward-rear direction a pulsating altering weight distribution on the four wheels of the tractor may be encountered, which may lead to an insufficient and/or pulsating weight distribution on the steering front wheels of the tractor during intervals of this pulsation.
Furthermore, carrying an oscillating implement in a tractor will impart great discomfort to the driver driving the tractor.

Finally, an oscillating implement may during transport thereof result in weakening and/or breaking of essential parts of the suspension system carrying the implement, thereby imparting further hazards in a transport situation on public roads.

Accordingly, there exists a need for improving transportation safety during transport of an agricultural implement.

It is an objective of the present invention to provide a solution to the above stated problem in order to reduce oscillations between a tractor and an implement being carried thereby in a transport situation.

Brief description of the invention

This objective is attained with the present invention in its first, second, third, fourth, and fifth aspect, respectively.

Accordingly, the present invention relates in a first aspect to a coupling mechanism for damping oscillations between a tractor and an agricultural implement during transport thereof; said coupling mechanism comprising:

a top link, said top link is having a front end configured to be pivotally mounted on a rear end of a tractor, and said top link is having an opposite rear end configured to be pivotally mounted on a three point linkage of an agricultural implement;

wherein said top link is comprising a hydraulic actuator, said hydraulic actuator is having a front end and a rear end; said hydraulic actuator is being arranged between the front end and the rear end of said top link so as to allow altering the effective distance between the front end and the rear end of said top link;

a first lift arm and a second lift arm; said first lift arm and said second lift arm each having a front end configured to be pivotally mounted on a rear side of a tractor and an opposite rear end configured to be pivotally mounted on a three point linkage of an agricultural implement; said two rear ends of the first and second lift arm, at their points of mounting, are configured to share a common pivot axis;
wherein said first and second lift arms being adapted to be arranged below the top link;

a transducer; said transducer being configured to sense the load exerted between the front end and the rear end of said hydraulic actuator;

a hydraulic valve comprising one or more outlets and being configured to supply pressurized hydraulic fluid to said hydraulic actuator in response to instructions received by said hydraulic valve;

a control unit configured to receive a signal provided by said transducer, and being configured to translate this signal into instructions to be supplied to said hydraulic valve according to a predetermined protocol in order to suppress any oscillations encountered between a tractor and an agricultural implement during transport thereof.

In a second aspect the present invention relates to a tractor comprising a coupling mechanism according to the first aspect of the present invention.

In a third aspect the present invention relates to a use of a coupling mechanism according to the first aspect of the present invention or of a tractor according to the second aspect of the present invention for damping oscillations between a tractor and an agricultural implement during transport thereof.

In a fourth aspect the present invention relates to a kit for installation on a three point linkage for an agricultural implement for damping oscillations between a tractor and that agricultural implement during transport thereof, said kit comprising:

a top link, said top link configured to be mounted between a rear part of a tractor and a three point linkage of an agricultural implement; said top link is having a front end configured to be pivotally mounted on the rear end of said tractor; and said top link is having an opposite rear end configured to be pivotally mounted on an three point hitch of an agricultural implement;

wherein said top link is comprising a hydraulic actuator, said hydraulic actuator is having a front end and a rear end; said hydraulic actuator is being arranged between the front end and the rear end of said top link so as to allow altering of the effective distance between the front end and the rear end of said top link;

a transducer; said transducer being configured to sense the load exerted between the front end and the rear end of said hydraulic actuator;
a hydraulic valve comprising one or more outlets and being configured to supply pressurized hydraulic fluid to said hydraulic actuator in response to instructions received by said hydraulic valve;

a control unit configured to receive a signal provided by said transducer, and being configured to translate this signal into instructions to be supplied to said hydraulic valve according to a predetermined protocol in order to suppress any oscillations encountered between a tractor and an agricultural implement during transport thereof.

The present invention in its various aspects provides for improved comfort and safety in a transport situation in which an agricultural implement is transported by a tractor.

The improved safety is due to improved damping and control of any oscillations between a tractor and an agricultural implement during transport thereof.

Furthermore, the present invention allows minimizing unnecessary stress and wear of the mechanical and hydraulic system, and thereby minimizing the risk of material breakage.

**Brief description of the figures**

Fig. 1 illustrates schematically a prior art three point hitch for connecting a tractor to an agricultural implement.

Fig. 2 illustrates schematically coupling mechanism according to the present invention for damping oscillations between a tractor and an agricultural implement during transport thereof.

Fig. 3 illustrates schematically an embodiment of a control system for controlling the coupling mechanism of the present invention.

**Detailed description of the invention**

The present invention relates in a first aspect to a coupling mechanism for damping oscillations between a tractor and an agricultural implement during transport thereof; said coupling mechanism comprising:
a top link, said top link is having a front end configured to be pivotally mounted on a rear end of a tractor; and said top link is having an opposite rear end configured to be pivotally mounted on a three point linkage of an agricultural implement;

wherein said top link is comprising a hydraulic actuator, said hydraulic actuator is having a front end and a rear end; said hydraulic actuator is being arranged between the front end and the rear end of said top link so as to allow altering the effective distance between the front end and the rear end of said top link;

a first lift arm and a second lift arm; said first lift arm and said second lift arm each having a front end configured to be pivotally mounted on a rear side of a tractor and an opposite rear end configured to be pivotally mounted on a three point linkage of an agricultural implement;

said two rear ends of the first and second lift arm, at their points of mounting, are configured to share a common pivot axis;

wherein said first and second lift arms being adapted to be arranged below the top link;

a transducer; said transducer being configured to sense the load exerted between the front end and the rear end of said hydraulic actuator;

a hydraulic valve comprising one or more outlets and being configured to supply pressurized hydraulic fluid to said hydraulic actuator in response to instructions received by said hydraulic valve;

a control unit configured to receive a signal provided by said transducer, and being configured to translate this signal into instructions to be supplied to said hydraulic valve according to a predetermined protocol in order to suppress any oscillations encountered between a tractor and an agricultural implement during transport thereof.

In the present description the term “load” shall be construed to mean physical parameters encountered by the hydraulic actuator, selected from the group comprising: force or pressure acting between the actuator’s two ends, or displacement or stress taking place between the actuator’s two ends.

In the present description and in the appended claims the term “protocol” shall be construed to mean that specific algorithm or set of directions or instructions according to which the control unit translates the signal, received by it from the transducer, is translated and subsequently supplied to the hydraulic valve in order to suppress any oscillation encountered.
In one embodiment of the first aspect of the present invention, the coupling mechanism furthermore comprising one or more hydraulic hoses connecting the hydraulic valve to said hydraulic actuator.

In one embodiment of the first aspect of the present invention, the top link comprises length adjustment means, such as a turnbuckle for adjusting the effective length of said top link.

Such means allows for fine tuning the settings of the coupling mechanism.

In one embodiment of the first aspect of the present invention, the control unit comprising input means, such as an alphanumerical keyboard, for allowing a user to provide information of said predetermined protocol to said control unit.

In one embodiment of the first aspect of the present invention the control unit comprising display means, such as a monitor or a user interface (UI), for displaying to a user the settings and/or status of the coupling mechanism or parts thereof.

In one embodiment of the first aspect of the present invention the input means and/or said display means is/are being in the form of a human machine interface (HMI).

Such means allows for controlling and communicating with the control unit.

In one embodiment of the first aspect of the present invention the hydraulic actuator is being a double acting hydraulic actuator.

In one embodiment of the first aspect of the present invention the hydraulic actuator comprises a pair of single acting hydraulic actuators.

In one embodiment of the first aspect of the present invention hydraulic actuator and said transducer are being an integral unit.

In one embodiment of the first aspect of the present invention the hydraulic actuator and said transducer are being separate units.

In one embodiment of the first aspect of the present invention the hydraulic actuator comprises a barrel, housing a hydraulic piston having a piston rod.
In one embodiment of the first aspect of the present invention the coupling mechanism further comprising safety means for avoiding lowering of the coupling mechanism to more than a predefined extend in case of malfunction of the hydraulic system relating to the top link.

In one embodiment of this embodiment the safety means comprising wires, chains or the like for connecting a rear end of the top link to the tractor itself; or wherein said safety means comprising a maximum possible expansion of the hydraulic actuator of 300 mm or less, such as 250 mm or less, for example 200 mm or less, such as 150 mm or less, such as 100 mm or less or 50 mm or less; or said safety means comprising a hydraulic safety valve being integrated with said hydraulic actuator and being configured to block outlet of hydraulic liquid from said hydraulic actuator.

Such means add additional safety in a transport situation.

In one embodiment of the first aspect of the present invention, said protocol is configured to follow the algorithm:

i) at time $T_1$, allow the transducer (44) to determine the degree of extension of the hydraulic actuator (38);

ii) at later time $T_1 + \delta T$ allow the transducer (44) to determine the degree of extension of the hydraulic actuator (38);

iia) optionally repeat the steps i) and ii) a number $N$ times until time $T_2$;

iii) in a case the degree of extension of the hydraulic actuator (38) from time $T_1$ to $T_1 + \delta T$, or from time $T_1$ to $T_2$, as the case may be, represents an expansion of the hydraulic actuator, instruct the hydraulic valve (46) to retract the hydraulic actuator (38) a distance $D_{re}$;

iv) in a case the degree of extension of the hydraulic actuator (38) from time $T_1$ to $T_1 + \delta T$, or from time $T_1$ to $T_2$, as the case may be, represents an retraction of the hydraulic actuator, instruct the hydraulic valve (46) to expand the hydraulic actuator (38) a distance $D_{ex}$;

v) define a new time $T_1$ and repeat steps i) – iv).

This protocol allows control based on sensing of exact positions of the actuator.

In one embodiment of the first aspect of the present invention, said protocol is configured so as to follow the algorithm:
i) at time $T_1$, allow the transducer (44) to determine the actual relative displacement between the front end (40) and the rear end (42) of the \textit{hydraulic actuator} (38);

ii) in case the actual movement determined in step i) represents an expansion of the hydraulic actuator (38), instruct the hydraulic valve (46) to retract the hydraulic actuator a distance $D_{ns}$;

iii) in case the actual movement determined in step i) represents a retraction of the hydraulic actuator (38), instruct the hydraulic valve (46) to expand the hydraulic actuator a distance $D_{ns}$;

iv) define a new time $T_1$;

v) repeat steps i) – iv).

This protocol allows control based on sensing of exact movements of the actuator.

In one embodiment of the first aspect of the present invention, said protocol is configured to follow the algorithm:

i) at time $T_1$, determine the direction and magnitude of the force or pressure sensed by the transducer (44);

ii) at later time $T_1 + \delta T$, determine the direction and magnitude of the force or pressure sensed by the transducer (44);

iii) optionally repeat the steps i) and ii) a number $N$ times until time $T_2$;

iii) in case the sum of direction and magnitude of the force or pressure sensed by the transducer (44) from time $T_1$ to $T_1 + \delta T$, or from time $T_1$ to $T_2$, as the case may be, represents an expansion of the hydraulic actuator, instruct the hydraulic valve (46) to retract the hydraulic actuator (38) a distance $D_{ns}$;

iv) in case the sum of direction and magnitude of the force or pressure sensed by the transducer (44) from time $T_1$ to $T_1 + \delta T$, or from time $T_1$ to $T_2$, as the case may be, represents a retraction of the hydraulic actuator, instruct the hydraulic valve (46) to expand the hydraulic actuator (38) a distance $D_{ns}$;

v) define a new time $T_1$ and repeat steps i) – iv).

This protocol allows control based on sensing of force or pressure by the transducer.
In one embodiment of the first aspect of the present invention, the time interval between repetition of the steps i) - v) is independently being selected from the ranges 0.001 - 5 sec; such as 0.005 - 4 sec, such as 0.01 - 2 sec, e.g. 0.05 - 1 sec, such as 0.1 - 0.5 sec.

In one embodiment of the first aspect of the present invention the distances $D_s$ and $D_p$, independently being selected from the ranges 0.01 - 100 mm, such as 0.05 - 50 mm, for example 0.1 - 25 mm, such as 0.5 - 15 mm, for example 1.0 - 10 mm, such as 2 - 9 mm, for example 3 - 8 mm, such as 4 - 7 mm or 5 - 6 mm.

In one embodiment of the first aspect of the present invention the period of time $\delta T$, is being selected from the ranges 0.001 - 5 sec; such as 0.005 - 1 sec, such as 0.01 - 0.5 sec., for example 0.05 - 0.1 sec.

In one embodiment of the first aspect of the present invention the number $N$ of repetition of steps of the algorithm is being selected from the range of 2 - 55, such as 5 - 50, for example 10 - 45, such as 15 - 40, e.g. 20 - 35 or 25 - 30.

The present invention relates in a second aspect to a tractor comprising a coupling mechanism according to the first aspect of the present invention.

The present invention relates in a third aspect to a use of a coupling mechanism according to the first aspect of the present invention or of a tractor according to the second aspect of the present invention for damping oscillations between a tractor and an agricultural implement during transport thereof.

In one embodiment of the third aspect of the present invention the agricultural implement being a plough, a harrow, a cultivator, a seeder, an irrigator or a spreader.

The present invention relates in a fourth aspect to a kit for installation on a three point linkage for an agricultural implement for damping oscillations between a tractor and that agricultural implement during transport thereof, said kit comprising:

25 a top link, said top link configured to be mounted between a rear part of a tractor and three point linkage of an agricultural implement; said top link is having a front end configured to be pivotally mounted on the rear end of said tractor; and said top link is having an opposite rear end configured to be pivotally mounted on an three point hitch of an agricultural implement;
wherein said top link is comprising a hydraulic actuator, said hydraulic actuator is having a front end and a rear end; said hydraulic actuator is being arranged between the front end and the rear end of said top link so as to allow altering of the effective distance between the front end and the rear end of said top link;

5 a transducer; said transducer being configured to sense the load exerted between the front end and the rear end of said hydraulic actuator;

a hydraulic valve comprising one or more outlets and being configured to supply pressurized hydraulic fluid to said hydraulic actuator in response to instructions received by said hydraulic valve;

10 a control unit configured to receive a signal provided by said transducer, and being configured to translate this signal into instructions to be supplied to said hydraulic valve according to a predetermined protocol in order to suppress any oscillations encountered between a tractor and an agricultural implement during transport thereof.

In one embodiment of the fourth aspect of the present invention, the kit further comprising one or more features as defined in respect of the first aspect.

Referring now in details to the drawings for the purpose of illustrating preferred embodiments of the present invention, Fig. 1 illustrates the principle of a conventional and traditional design of a lifting hitch on a tractor. The lifting hitch is arranged on a rear part of the tractor and allows lifting and lowering agricultural tools or agricultural implements to be lift-mounted behind the tractor.

Fig. 1 is a plan view as seen sideways from between the rear wheels 26 of the tractor resting on the surface 32 of the soil 30. Fig. 1 shows a traditional and conventional coupling mechanism 24 in the form three point hitch of the rear end of a tractor. The hitch comprises a top link 2 having a front end 4 and a rear end 8. The front end 4 of the top link 2 is pivotally mounted at a point on the tractor itself. The opposite rear end 8 of the top link 2 is pivotally mounted on a three point linkage of an agricultural implement (not shown in fig. 1). The implement may be an implement for cultivating soil or crops for fertilizing or for irrigating the soil or may be any other type of agricultural implement.
Below the top link are arranged first lift arm 12 and a second lift arm 14. The front end 16 of the lift arm 12,14 is pivotally mounted on the tractor itself. The rear end 18 of the lift arm 12, 14 is pivotally mounted on the three point hitch of the agricultural implement.

The lift arms 12,14 are connected to a hydraulic actuator 28.

5  The top link 2 comprises a turnbuckle 22 for adjustment of the effective length thereof.

The height of the coupling mechanism may be adjusted in height by activating the hydraulic actuator 28 either upward or downward. The actuator of the hydraulic actuator 28 is brought about by using the hydraulic system of the tractor.

Hence, actuating the hydraulic actuator 28 affects movement of the lift arms 12,14. If an agricultural implement is connected to the three point hitch, the front end of the implement may be raised or lowered in this way.

As the prior art three point hitch provides a rather rigid suspension of an agricultural implement, the weight of such an implement during transport thereof, which takes place in a lifted configuration where no part of the implement touches the ground, will easily result in oscillation of the implement. Such an oscillation implies hazards in terms of traffic safety.

Fig. 2 illustrates schematically a coupling mechanism according to the first aspect of the present invention for damping oscillations between a tractor and an agricultural implement during transport thereof.

Fig. 2 is a plan view as seen sideways from between the rear wheels of the tractor. The coupling mechanism 100 of fig. 2 comprises a top link 2 having a front end 4 and a rear end 8. The front end 4 of the top link 2 is pivotally mounted at a point on the tractor itself. The opposite rear end 8 of the top link 2 is pivotally mounted on an three point linkage 10 of an agricultural implement (not shown in fig. 2).

Below the top link are arranged first lift arm 12 and a second lift arm 14. The front end 16 of the lift arm 12,14 is pivotally mounted on the tractor itself. The rear end 18 of the lift arm 12, 14 is pivotally mounted on the three point linkage 10 of an agricultural implement.

The lift arms 12,14 are connected to a hydraulic actuator 28
In addition to the prior art three point hitch illustrated in fig. 1, the coupling mechanism 100 illustrated in fig. 2 further comprises a hydraulic actuator 38 which is being part of the top link 2. The hydraulic actuator 38 is having a first (front) end 40 and a second (rear) end 42.

The hydraulic actuator 38 is being coupled to a transducer 44 which is configured to sense physical parameters of the hydraulic actuator 38, such as force or pressure or load acting between the actuator’s two ends, or such as displacement or stress taking place between the actuator’s two ends.

By sensing such physical parameters by the transducer 44, it will be possible to use the hydraulic actuator 38 for counteracting any oscillations taking part between the tractor and an implement being lift-mounted by said tractor in a transport situation thereof.

Accordingly, in the coupling mechanism according to the first aspect of the present invention, the transducer 44 and the actuator 38 will be configured in a feed-back mode.

This is further illustrated in fig. 3.

Fig. 3 schematically illustrates an embodiment of the means for controlling the coupling mechanism 100 of the coupling mechanism according to the present invention.

Fig. 3 shows the hydraulic valve 46 comprising an inlet 64 and outlet 64' for pressurized hydraulic fluid from a hydraulic pump or reservoir 62. The hydraulic pump or reservoir may preferably be a hydraulic outlet of the hydraulic system of a tractor, i.e. the tractor’s hydraulic supply system. The hydraulic valve 46 comprises two outlets 48 for supplying pressurized hydraulic fluid to a hydraulic actuator 38 intended to be part of a top link for a coupling mechanism of the present invention for carrying an agricultural implement to be towed or pulled or carried by a tractor.

The hydraulic valve 46 in its interior comprises one or more individual valves for controlling the flow of hydraulic fluid from the inlet 64 for pressurized hydraulic fluid to the hydraulic actuator 38 via hoses 56.

These valves are controlled by instructions 50 being sent from the control unit 52.

The control unit in turn comprises means for receiving a signal 54 from a transducer 44. The transducer is configured to be able to sense various parameters of the hydraulic actuator 38.
Such parameters may relate to pressure or force acting between the actuator's two ends, or displacement or stress taking place between the actuator's two ends.

The control unit 52 is connected to input means 58 in the form of an alphanumeric keyboard for allowing a user to provide instructions to the control unit with the view to control said hydraulic valve 46.

Furthermore, the control unit 52 is connected to display means 60, such as a monitor or a user interface (UI), for displaying to a user the settings and/or status of the coupling mechanism or parts thereof.

The input means 58 and/or the display means 60 may be in the form of an HMI (Human Machine Interface).

Hence, using the keyboard 58 and the monitor 60, optionally in the form of an HMI, it will be possible to control the working mode of hydraulic valve and the hydraulic actuator 26 on the basis of the signal 54 provided by the transducer.

The controlling of the control unit 32 may relate to loading and activating one or more algorithms which a user wishes the control unit to follow in the control of the hydraulic actuator.

The control valve 46, the hydraulic actuator 38, the transducer 44 and also the control unit 52 are per se individually available at manufacturers and suppliers of hydraulic equipment and control units.

The present invention relates in a fifth aspect also to a kit. This kit will accordingly be well suited as an add-on to existing coupling mechanisms of tractors.
<table>
<thead>
<tr>
<th>Number</th>
<th>Description</th>
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<tbody>
<tr>
<td>2</td>
<td>Top link</td>
</tr>
<tr>
<td>4</td>
<td>Front end of top link</td>
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<tr>
<td>6</td>
<td>Rear end of tractor</td>
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<tr>
<td>5</td>
<td>Rear end of top link</td>
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<tr>
<td>10</td>
<td>Three point linkage of agricultural implement</td>
</tr>
<tr>
<td>12</td>
<td>First lift arm</td>
</tr>
<tr>
<td>14</td>
<td>Second lift arm</td>
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<tr>
<td>16</td>
<td>Front end of lift arm</td>
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<td>10</td>
<td>Rear end of lift arm</td>
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<td>20</td>
<td>Common pivot axis of two lift arms</td>
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<td>22</td>
<td>Turnbuckle</td>
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<td>Three point hitch of tractor</td>
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<tr>
<td>26</td>
<td>Rear wheel of tractor</td>
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<tr>
<td>15</td>
<td>Hydraulic lifting cylinder</td>
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<tr>
<td>30</td>
<td>Soil</td>
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<td>20</td>
<td>Rear end of hydraulic actuator</td>
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<tr>
<td>42</td>
<td>Transducer</td>
</tr>
<tr>
<td>46</td>
<td>Hydraulic valve</td>
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<tr>
<td>48</td>
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SUBSTITUTE SHEET (RULE 25)
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<td>Control unit</td>
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<td>54</td>
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<td>58</td>
<td>Input means</td>
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<td>60</td>
<td>Display means</td>
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<tr>
<td>62</td>
<td>Hydraulic pump or reservoir for pressurized hydraulic fluid</td>
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<tr>
<td>64</td>
<td>Inlet for pressurized hydraulic fluid</td>
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<td>64'</td>
<td>Outlet for pressurized hydraulic fluid</td>
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<tr>
<td>100</td>
<td>Coupling mechanism</td>
</tr>
</tbody>
</table>
Claims

1. A coupling mechanism (100) for damping oscillations between a tractor and an agricultural implement during transport thereof; said coupling mechanism comprising:

a top link (2), said top link is having a front end (4) configured to be pivotally mounted on a rear end (6) of a tractor; and said top link is having an opposite rear end (8) configured to be pivotally mounted on three point linkage (10) of an agricultural implement;

wherein said top link is comprising a hydraulic actuator (38), said hydraulic actuator is having a front end (40) and a rear end (42); said hydraulic actuator is being arranged between the front end and the rear end of said top link so as to allow altering the effective distance between the front end and the rear end of said top link;

a first lift arm (12) and a second lift arm (14); said first lift arm and said second lift arm (12, 14) each having a front end (16) configured to be pivotally mounted on a rear side of a tractor and an opposite rear end (18) configured to be pivotally mounted on a three point linkage of an agricultural implement; said two rear ends of the first and second lift arm, at their points of mounting, are configured to share a common pivot axis (20);

wherein said first and second lift arms (12, 14) being adapted to be arranged below the top link (2);

a transducer (44); said transducer being configured to sense the load exerted between the front end (40) and the rear end (42) of said hydraulic actuator;

a hydraulic valve (46) comprising one or more outlets and being configured to supply pressurized hydraulic fluid to said hydraulic actuator in response to instructions (50) received by said hydraulic valve;

a control unit (52) configured to receive a signal (54) provided by said transducer, and being configured to translate this signal into instructions (50) to be supplied to said hydraulic valve according to a predetermined protocol in order to suppress any oscillations encountered between a tractor and an agricultural implement during transport thereof.

2. A coupling mechanism (100) according to claim 1 furthermore comprising one or more hydraulic hoses (56) connecting the hydraulic valve (46) to said hydraulic actuator (38).
3. A coupling mechanism (100) according to claim 1 or 2, wherein said top link comprises length adjustment means (22), such as a turnbuckle for adjusting the effective length of said top link.

4. A coupling mechanism (100) according to any of the claims 1-3, wherein said control unit (52) comprising input means (58), such as an alphanumerical keyboard, for allowing a user to provide information of said predetermined protocol to said control unit (52).

5. A coupling mechanism (100) according to any of the claims 1-4, wherein said control unit (52) comprising display means (60), such as a monitor or a user interface (UI), for displaying to a user the settings and/or status of the coupling mechanism or parts thereof.

6. A coupling mechanism (100) according to claim 4 or 5, wherein said input means (58) and/or said display means (60) is/are being in the form of a human machine interface (HMI).

7. A coupling mechanism (100) according to any of the claims 1-6 wherein said hydraulic actuator (38) is being a double acting hydraulic actuator.

8. A coupling mechanism (100) according to any of the claims 1-6 wherein said hydraulic actuator (38) comprises a pair of single acting hydraulic actuators.

9. A coupling mechanism (100) according to any of the claims 1-8 wherein said hydraulic actuator (38) and said transducer (44) are being an integral unit.

10. A coupling mechanism (100) according to any of the claims 1-8 wherein said hydraulic actuator (38) and said transducer (44) are being separate units.

11. A coupling mechanism (100) according to any of the claims 1-10 wherein the hydraulic actuator (38) comprises a barrel, housing a hydraulic piston having a piston rod.

12. A coupling mechanism (100) according to any of the claims 1-11 further comprising safety means for avoiding lowering of the coupling mechanism to more than a predefined extend in case of malfunction of the hydraulic system relating to the top link.

13. A coupling mechanism (100) according to claim 12, wherein said safety means comprising wires, chains or the like for connecting a rear end of the top link to the tractor itself; or wherein said safety means comprising a maximum possible expansion of the hydraulic actuator of 300 mm or less, such as 250 mm or less, for example 200 mm or less, such as 150 mm or less, such as 100 mm or less or 50 mm or less; or wherein said safety
means comprising a hydraulic safety valve being integrated with said hydraulic actuator and being configured to block outlet of hydraulic liquid from said hydraulic actuator.

14. A coupling mechanism (100) according to any of the claims 1 – 13 wherein said protocol is configured to follow the algorithm:

i) at time $T_1$, allow the transducer (44) to determine the degree of extension of the hydraulic actuator (38);

ii) at later time $T_1 + \delta T$ allow the transducer (44) to determine the degree of extension of the hydraulic actuator (38);

iii) optionally repeat the steps i) and ii) a number N times until time $T_2$;

iii) in a case the degree of extension of the hydraulic actuator (38) from time $T_1$ to $T_1 + \delta T$, or from time $T_1$ to $T_2$, as the case may be, represents an expansion of the hydraulic actuator, instruct the hydraulic valve (46) to retract the hydraulic actuator (38) a distance $D_{in}$;

iv) in a case the degree of extension of the hydraulic actuator (38) from time $T_1$ to $T_1 + \delta T$, or from time $T_1$ to $T_2$, as the case may be, represents a retraction of the hydraulic actuator, instruct the hydraulic valve (46) to expand the hydraulic actuator (38) a distance $D_{out}$;

v) define a new time $T_1$ and repeat steps i) – iv).

15. A coupling mechanism (100) according to any of the claims 1 – 13 wherein said protocol is configured so as to follow the algorithm:

i) at time $T$, allow the transducer (44) to determine the actual relative displacement between the front end (40) and the rear end (42) of the hydraulic actuator (38);

ii) in case the actual movement determined in step i) represents an expansion of the hydraulic actuator (38), instruct the hydraulic valve (46) to retract the hydraulic actuator a distance $D_{in}$;

iii) in case the actual movement determined in step i) represents a retraction of the hydraulic actuator (38), instruct the hydraulic valve (46) to expand the hydraulic actuator a distance $D_{out}$;

iv) define a new time $T$;

v) repeat steps i) – iv).
16. A coupling mechanism (100) according to any of the claims 1 – 13 wherein said protocol is configured to follow the algorithm:

i) at time $T_1$, determine the direction and magnitude of the force or pressure sensed by the transducer (44);

ii) at later time $T_1 + \delta T$ determine the direction and magnitude of the force or pressure sensed by the transducer (44);

iii) optionally repeat the steps i) and ii) a number $N$ times until time $T_2$;

iv) in a case the sum of direction and magnitude of the force or pressure sensed by the transducer (44) from time $T_1$ to $T_1 + \delta T$, or from time $T_1$ to $T_2$, as the case may be, represents an expansion of the hydraulic actuator, instruct the hydraulic valve (46) to retract the hydraulic actuator (38) a distance $D_{\text{act}}$;

v) in a case the sum of direction and magnitude of the force or pressure sensed by the transducer (44) from time $T_1$ to $T_1 + \delta T$, or from time $T_1$ to $T_2$, as the case may be, represents a retraction of the hydraulic actuator, instruct the hydraulic valve (46) to expand the hydraulic actuator (38) a distance $D_{\text{act}}$;

vi) define a new time $T_1$ and repeat steps i) – iv).

17. A coupling mechanism (100) according to any of the claims 14 – 16 wherein the time interval between repeating steps i) – vi) independently being selected from the ranges 0.001 – 5 sec; such as 0.005 – 4 sec, such as 0.01 – 2 sec, e.g. 0.05 – 1 sec, such as 0.1 – 0.5 sec.

18. A coupling mechanism (100) according to any of the claims 14 – 17 wherein the distances $D_{\text{act}}$ and $D_{\text{act}}$ independently being selected from the ranges 0.01 – 100 mm, such as 0.05 – 50 mm, for example 0.1 – 25 mm, such as 0.5 – 15 mm, for example 1.0 – 10 mm, such as 2 – 9 mm, for example 3 – 8 mm, such as 4 – 7 mm or 5 – 6 mm.

19. A coupling mechanism (100) according to claim 14 or 16, wherein the period of time $\delta T$, is being selected from the ranges 0.001 – 5 sec; such as 0.005 – 1 sec, such as 0.01 – 0.5 sec, for example 0.05 – 0.1 sec.

20. A coupling mechanism (100) according to claim 14 or 16, wherein $N$ is being selected from the range of 2 – 55, such as 5 – 50, for example 10 – 45, such as 15 – 40, e.g. 20 – 35 or 25 – 30.
21. A tractor (300) comprising a coupling mechanism (100) according to any of the claims 1 – 13.

22. Use of a coupling mechanism (100) according to any of the claims 1 – 20 or of a tractor (300) according to claim 21 for damping oscillations between a tractor and an agricultural implement during transport thereof.

23. Use according to claim 22, wherein the agricultural implement being a plough, a harrow, a cultivator, a seeder, an irrigator or a spreader.

24. A kit for installation on a three point linkage for an agricultural implement (300) for damping oscillations between a tractor and an agricultural implement during transport thereof, said kit comprising:

   a top link (2), said top link configured to be mounted between a rear part (6) of a tractor and an three point linkage (10) of an agricultural implement; said top link is having a front end (4) configured to be pivotally mounted on the rear end of said tractor; and said top link is having an opposite rear end (8) configured to be pivotally mounted on an three point linkage (10) of an agricultural implement;

   wherein said top link (2) is comprising a hydraulic actuator (38), said hydraulic actuator is having a front end (40) and a rear end (42); said hydraulic actuator is being arranged between the front end (4) and the rear end (8) of said top link so as to allow altering of the effective distance between the front end and the rear end of said top link;

   a transducer (44); said transducer being configured to sense the loads exerted between the front end (40) and the rear end (42) of said hydraulic actuator (38);

   a hydraulic valve (46) comprising one or more outlets (48) and being configured to supply pressurized hydraulic fluid to said hydraulic actuator (38) in response to instructions (50) received by said hydraulic valve;

   a control unit (52) configured to receive a signal (54) provided by said transducer (44), and being configured to translate this signal into instructions (50) to be supplied to said hydraulic valve (46) according to a predetermined protocol in order to suppress any oscillations encountered between a tractor and an agricultural implement during transport thereof.
25. A kit according to claim 24 further comprising one or more features as defined in any of the claims 1–25.
**INTERNATIONAL SEARCH REPORT**

(PCT Article 18 and Rules 43 and 44)

<table>
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**International application No.**

PCT/DK2016/059438

**International filing date (day/month/year)**

15 December 2016 (15-12-2016)

**(Earliest) Priority Date (day/month/year)**

17 December 2015 (17-12-2015)

**Applicant**

AGRO INTELLIGENCE APS

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This international search report has been prepared by the International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This international search report consists of a total of 4 sheets.

It is also accompanied by a copy of each prior art document cited in this report.

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1. **Basis of the report**
   
   a. With regard to the **language**, the international search was carried out on the basis of:
      
      - the international application in the language in which it was filed

   b. This international search report has been established taking into account the rectification of an obvious mistake authorized by or notified to this Authority under Rule 91 (Rule 43.53(a)).

   c. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, see Box No. I.

2. **Certain claims were found unsearchable** (See Box No. II)

3. **Unity of invention is lacking** (see Box No. III)

4. **With regard to the title,**
   
   - the title is approved as submitted by the applicant
   - the title has been established by this Authority to read as follows:

5. **With regard to the abstract,**
   
   - the abstract is approved as submitted by the applicant
   - the abstract has been established, according to Rule 38.2, by this Authority as it appears in Box No. IV. The applicant may, within one month from the date of mailing of this international search report, submit comments to this Authority

6. **With regard to the drawings,**
   
   a. the figure of the drawings to be published with the abstract is Figure No. 2
      
      - as suggested by the applicant
      - as selected by this Authority, because the applicant failed to suggest a figure
      - as selected by this Authority, because this figure better characterizes the invention
   
   b. none of the figures is to be published with the abstract

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Form PCT/ISA/210 (1st sheet) (January 2015)
### INTERNATIONAL SEARCH REPORT

**International application No**

PCT/DK2016/050438

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**A. CLASSIFICATION OF SUBJECT MATTER**

INV. A01B59/05 A01B63/10

ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

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**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

A01B B62D B69D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

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**EPO-Internal, WIPO Data**

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**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

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**Date of the actual completion of the international search**

28 March 2017

**Date of mailing of the international search report**

13/04/2017

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**Name and mailing address of the ISA**

European Patent Office, P.B. 5818 Patentlaan 2
NL-2360 HV Rijswijk,
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**Authorized officer**

Lucchesi-Palli, C
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Form PCT405 (6/10) (patent family annex) (April 2006)
5. Appendix / Paper IV – Sensor and control for consistent seed drill coulter depth
Original papers

Sensor and control for consistent seed drill coulter depth

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ARTICLE INFO

Article history:
Received 30 December 2015
Received in revised form 7 July 2016
Accepted 23 July 2016

Keywords:
Seed drill coulter
Seed placement
Angle sensor
Coulter control systems

ABSTRACT

The consistent depth positioning of seeds is vital for achieving the optimum yield of agricultural crops. In state-of-the-art seeding machines, the depth of drill coulters will vary with changes in soil resistance. This paper presents the retrofitting of an angle sensor to the pivoting point of a drill coulter, providing sensor feedback to a control system that via an electro-hydraulic actuator delivers a consistent coulter depth. The results showed a strong correlation between the angle of the coulter and the coulter depth under static (R² = 1.00) and dynamic (R² = 0.99) operations, verified by a sub-millimeter accurate positioning system (GPS, Nikon Metrology NV, Belgium) mounted on the drill coulter. At a drill coulter depth of 75 mm and controlled by an ordinary fixed spring loaded down force, the change in soil resistance reduced the mean depth by 23 mm. By dynamically controlling the spring loaded down force based on the angle sensor, the mean depth was independent of the seeded resistance change as shown from tests in soils ranging from sand to gravel. The PID controller was most effective because it provided a mean depth deviation from the target depth of −0.17 mm and ±0.08 mm for sand and gravel, respectively. The most cost-efficient control function was found to be the three-position control system, resulting in a mean depth deviation from the target depth of −0.08 mm and ±1.18 mm for sand and gravel, respectively. A Fast Fourier Transform (FFT) analysis of the coulter depth measurements showed that the control system also provided a damping effect on the coulter depth variations. The research showed that it is possible to minimize the low-frequency drill coulter depth variations and provide a consistent coulter depth independent of soil conditions by using the developed sensor system and control system.

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1. Introduction

A consistent seeding depth is vital for achieving the optimum yield of agricultural crops. In conventional seeding, the seedbed is prepared through the tillage operations, which ensure the correct ratio between temperature and moisture content to accelerate the seed germination (Forbes and Watson, 1992). The primary tillage can be executed by ploughing or deep harrowing (low-4E) to an approx. 20-25 cm depth, and thereby removing residues and loosening the soil (Hákansson et al., 2002). Secondly, as part of the tillage for seedbed preparation, the seedbed is slightly compacted, and the top soil is loosened to a depth defined by the seed size and crop species, which in all creates a smooth and loose top soil horizon with the required aggregate size (Henriksen, 1989; Hákansson et al., 2002). Following the tillage, the objective is to place the seeds evenly and exactly at the bottom of the created seedbed in order to provide the optimal conditions for a quick germination (Hákansson et al., 2002; Karayel, 2008). By this placement, the seeds are able to absorb moisture from the compacted soil below, and independently of weather conditions and heat from above, which is transferable through the loose top horizon (Chang et al., 2004; Forbes and Watson, 1992). Research has shown that the seeding depth has a significant effect on germination and that the yield decreases with inaccurate seeding depth (Brennan and Leop, 2014; Kinzer et al., 1993; Morrison and Gerrit, 1985). Crop emergence decreases with increased depth variations and a delay in germination generates the adverse effect of the crop having to compete with the other plants or weeds (Brennan and Leop, 2014). Different machines for drilling seeds in a variation of sowed conditions have been studied and the conclusion is that large depth variations persist (Brennan and Leop, 2014; Morrison and Gerrit, 1985). A seedbed most often inhabits irregular and inconsistent soil resistance, which causes drill coulters to generate vibrations and inconsistent seeding depths due to the static coulter down force. In this study, it was assumed that the correct tillage operations have been performed as the focus was on the seeding operation and the development of a
system to control and maintain a consistent drill coulter depth, independently of irregularities in the seedbed and variations in soil resistance. However, a depth control system is also highly relevant for direct seeding.

The state-of-the-art seed drill depth control concept has been based on concept for weight for decades, creating a static down force. The springs are usually adjusted before seeding and no sensor feedback exists. Depth guide wheels in the proximity of the drill coulter avoid seed placements that is too deep but do not prevent the overly shallow seedling and depth variations of more than ±10 mm (SD) that are experienced (Hörner and Pütz, 2013). Recent innovations consist of sensors constantly measuring the pressure on the depth guide wheels, if the pressure on the depth guide wheels changes because of a change in speed or soil resistance, the automatic coulter pressure system responds immediately. The central hydraulic coulter pressure adjustment is used to ensure that the consolidation pressure of the depth-guide wheel always is constant, provided that the depth wheel is designed to always stay on top of the seedbed (Lenten GmbH & Co., Germany). Coulter with or without depth guide wheel are affected by irregularities in the soil and operation speed (Hörner and Pütz, 2013). In addition, the design of the coulters has different influence on the seed trajectory depending on seed shape, velocity, angle and soil conditions/movements immediately after the seed is released from the coulter, which also leads to a undesirable inconsistent seed placement and emergence (Dulmon et al., 1974). Recent studies of a coulter depth control system was developed and tested using multiple sensing inputs, detecting the soil surface and coulter position (Sjöström and Olofsson, 2015). The technology was able to maintain the desired working depth within a tolerance ±10 mm (SD) at a driving speed of 10 km/h.

The aim of this study was to demonstrate and evaluate the performance of concept for an applicable low-cost depth control system for a seed drill coulter. The first objective was to examine and analyse the depth variations and vibrations by detecting the angle of the Suffolk drill coulter. The second objective was to design and implement a control system to manage coulter depth adjustments. The hypothesis was that angle detection of the drill coulter and a known seeder frame depth can be used for control and thereby maintain an even coulter depth, reducing the low-frequency vibrations, independently of soil resistance.

2. Materials and methods

The research was carried out at Research Centre Foulum in Denmark (9°34.40.22'E, 56°29.47.61'N), using a rotating soil bin. The instrumentation for the experiments is shown in Fig. 1. The setup consists of a CompactRio as an embedded controller (National Instruments Ltd., USA), programmed in LabVIEW interfaced by a laptop. For the reference positioning of the coulter position, the high-accuracy independent IGPS system was used (Nikon Metrology, Belgium). The prototype seeder system is framed, consisting of a hydraulic system with a spring mounted on the coulter for the down force adjustments combined with an angle sensor (Phi sensor and controls, Spain) mounted at the pivot point of a Suffolk coulter (Fig. 1).

2.1. Experimental setup

A Suffolk drill coulter and parts from Kongskilde's Masterline drill seeder (Kongskilde Industries A/S, Denmark) was retrofitted with an angle sensor and an electro-hydraulic actuator system (Fig. 2) as the key components of the experiments. The prototype seeder was constructed with one drill coulter having a diameter of 38 mm, a wall thickness of 3 mm and a straight length of 960 mm (Fig. 2). For deriving the correlation of the angle to the coulter position, the sub-millimetre accurate positioning IGPS system was used.

Different experiments including static, dynamic sensing and dynamic control were carried out. For the static experiments (Section 2.3), the soil bin was not in rotation and the drill coulter was manually loaded and thereby elevated to correlate the angle to the measured reference position (Fig. 2). For the dynamic sensing experiments (Section 2.4), the rotation speed of the soil bin was 4 km/h, and the bin contained uniform soil and mixed non-uniform soil, separated with 2 solid pipes and also acting as stone simulators. For the control experiments (Section 2.5), the speed was 6 km/h, and to keep the soil uniform and level, a narrow line first loosened the soil and then, a 30° angled iron blade compacted and levelled the different seedbeds. The bin had a soil depth level of 300 mm, a tracks diameter of 3200 mm with 500 mm soil on each side of the coulter. The objective of the control experiments was to test the control systems performance and response to variations in seedbed resistance. The control experiments were performed individually with considerable different seedbed materials using sand and gravel. It was expected that the sand and gravel generated significant different penetration resistances and impacting the coulter depth. To verify the expected depth change, an experiment was carried out analysing the coulter depth change with fixed coulter down force but as a function of the seedbed change from sand to gravel. The sand had a particle sizes of (D = 0–8 mm, μ = 1.6 t/m³) and the gravel of (D = 0–32 mm, μ = 1.7 t/m³). In addition, the gravel simulating soil with aggregates up to 32 mm, which approximately did not change size or shape during the repetitions. To simulate additional compaction in the gravel, the narrow line was removed during the control experiments. In order to achieve a static compacted gravel seedbed, a considerable number of rotations were carried out before initiating the experiments.

Fig. 1. Instrumentation for the experimental setup with communication interfaces, consisting of a GUI on a laptop connected to the controller using flash storage. A prototype drill coulter with an angle sensor and a hydraulic valve with a cylinder are embedded. Reference system (IGPS, GUI) on a laptop, Wi-Fi connected to the sensors.
The angle sensor for the coulter detection was a PST 36D [Pher sensors and controls, Spala], which specifies a robust, dust and water protected sensor type, (IP67) with a 12-bit resolution. The sensor operates using the Hall Effect technology with a linearity of ±0.5% and a frequency of 500 Hz.

The actuator for the adjustments of the spring loaded down force was a hydraulic cylinder with a 4/3 proportional electro-hydraulic direction valve PVEH2 (Danfoss A/S, Denmark), combined with a small mobile hydraulic pump station (5 l/min, 90 bar). The control module of the valve was a proportional high-performance solenoid, PVEH 3-9 V (Danfoss A/S, Denmark). The module had a delay of 250 ms and to minimise the neutral position, which generated a static error, a mathematical function was implemented to skip the hydraulic dead zone from 5.4 V to 8.6 V while still maintaining the proportionality.

For real-time control, a Compact RIO 9032 (cRIO) was used (National Instruments Ltd., USA). For the I/O modules for the sensor and actuator, the digital N9401 IWM and analogue N9629 module were selected. The cRIO with modules were configured and the control programs were developed from scratch for each experiment using the LabVIEW environment.

For the drill coulter position reference detection, the submillimetre accurate positioning IGPS system was used. The system has an accuracy of ±50 µm for static conditions and a measuring frequency of 40 Hz (Depenthal, 2009). For dynamic conditions, the deviation is below ±500 µm until an angle velocity of 1 m/s (Depenthal, 2009), and it is a preferred system for dynamic positioning according to Depenthal (2010). IGPS is used in complex production processes and has not been used for studying coulter positions before.

For the real-time depth control, three control algorithms were tested: three-position, proportional (P) and proportional-integral-derivative (PID).

The simple three-position control was used to adjust the hydraulic flow of the valve. The control was based on stepping statements defining the interval limits for the three-position control (Eq. (1)).

\[
\begin{align*}
    u &= -100\% \quad \text{for} \quad e(t) > e_u \\
    u &= 0\% \quad \text{for} \quad \left| e(t) \right| \leq \theta_1 \\
    u &= 100\% \quad \text{for} \quad e(t) < \theta_2
\end{align*}
\]

where \( e_t \) is the limits of the error interval, \( e \) is the error, \( u \) is the control output and \( t \) is the sample time.

The traditional P control combined with a proportional hydraulic valve generates the oil flow proportional to the error (Eq. (2)).

\[
\theta(t) = K_e e(t)
\]

where \( K_e \) is the proportional gain and \( \theta(t) \) is the control output. The PID control is a well-known method used in more than 95% of industrial applications with great performance (Kara et al., 2009). It predicts and generates a damping effect by the derivative control and removes static errors by the integral control (Eq. (3)).

\[
\theta(t) = K_e e(t) + \frac{1}{T_d} \int_0^t e(\tau) d\tau + T_i \frac{d \theta(t)}{dt}
\]

where \( T_d \) is the derivative time, \( T_i \) is the integral time and \( \theta(t) \) is the control output.

To respond to adverse fast oscillations, the derivative filter was implemented. The oscillations depend on the derivative action, proportional gain and sampling time. The filter reduces the bandwidth and thereby the instability (Eq. (4)). The magnitude of the damping time constant \( \tau \) is normalised between 0 and 1 and set to 0.94 using the trial and error method in the initial experiments.

\[
\theta(t) = K_e e(t) + \frac{T_i}{T_d} \frac{d \theta(t)}{dt}
\]

where \( \theta(t) \) is the control output from the PID control, is extracted.

To ensure that the system did not induce the windup problem due to increasing error integration, it was adjusted using the anti-windup algorithm based on defining limitations at ±100% (Eq. (5)).

\[
\theta(t) = \lim_{u(t)} - \theta_u(t) \quad \text{for} \quad \left| \theta_u(t) +\theta(t) \right| > \left| \lim u(t) \right|
\]

Due to mechanical constraints (valve saturation), the output limit \( u \) was defined at ±100% (Eq. (6)).

\[
\begin{align*}
    \theta(t) &= \theta_u(t) \quad \text{for} \quad \theta_u(t) > \theta_u(t) \\
    \theta(t) &= \theta_u(t) \quad \text{for} \quad \theta_u(t) < \theta_u(t)
\end{align*}
\]

2.2. Data processing and statistical analysis

For data processing, the cRIO controller with LabVIEW was used (National Instruments, USA). To carry out the data analysis, R-studio (RStudio, USA) and MATLAB (MathWorks, USA) were used for computation and visualisation.

2.3. Static measurements

The objective of the static experiment was to derive a mathematical model able to correlate the coulter angle to the respective coulter position defined as the vertical distance to the machine frame. To carry out the experiment, the down force actuator was fixed in the centre position. The IGPS sensor was mounted on the
soil bin frame and on the drill coulter to obtain the coulter position (Fig. 2). By the specific placement of GPS sensors, the structural deflection of the drill coulter was included in the measurements. The drill coulter was loaded/elevated at even vertical intervals of 5 mm as validated by rulers.

To detect and remove outliers, Chauvenet's Criterion was used to calculate the ratio of maximum acceptable deviation $f_i$ (Eq. (7)) [Holman, 2011].

$$|e_i| \leq \frac{C_i \cdot k}{1 - \frac{1}{N}}$$

(7)

where $C_i$ is the obtained mean value, $k$ is the obtained value and $N$ the standard deviation.

The null hypothesis was defined as the data obtained from a population with a normal distribution with the Chi-square probability of 0.05 (Eq. (7)).

$$\chi^2 = \sum_{i=1}^{N} (O_i - E_i)^2 / E_i$$

(8)

where $\chi^2$ is the chi-square variable, $O_i$ is the observed value and $E_i$ is the expected value from the normal distribution.

2.4. Dynamic measurements

To verify the dynamic performance of the Instrumentation developed in static condition, the system was tested when operating dynamically as derived from rapid coulter depth vibrations. To correlate the vertical distance measurement in the developed system with the measurement in the GPS reference system, the system hardware were interconnected by using a digital signal from the controller to the GPS system as a trigger function (Fig. 1). The trigger signal was manually started and sent every second to ensure the systems were time synchronised, and verified every second. Thereby, it was possible to subsequently synchronise the two measurement systems.

To carry out the experiment, the prototype seeder frame was elevated above the soil bin until the bin was rotating in a steady state (4 rpm). The frame was then lowered into the soil for testing and elevated for a total of 60 s. The stone stimulator (pipes) separated the bin for creating the uniform soil and mixed soil parts.

To analyse the performance of the developed sensing system; the data was cross-correlated with the GPS reference system for dynamic sensing experiment (Eq. (9)).

$$\frac{c_{e}}{c_{m}} = \frac{\sum (d_{m} - d_{e})}{\sqrt{\sum (d_{m} - d_{e})^2 \cdot \sqrt{\sum (d_{m} - d_{e})^2}}}$$

(9)

where the indices $m$ specifies the data model obtained, $n$ specifies the model mean, $C_{e}$ is the GPS obtained and $C_{m}$ specifies the GPS mean.

To determine the magnitude and distribution of the data frequencies, the Fast Fourier Transform (FFT) was used to analyse the mathematic model of distance data and for the configuration of the process variable filter as well as for analysing the PID control performance.

2.5. Dynamic control experiments

For the control experiments, all of the applied instrumentation was used (Fig. 1). The objectives of the experiments were to test the performances of the prototype control system with the three different control systems: P, PID and three-position. The same prototype seeder was used for all experiments, but for the three-position control, the hydraulic system was used without the flow proportionality and thereby operating as an ordinary 4/3 direction valve (Eq. (1)). Furthermore, no filtration was used to keep the three-position control at a low cost. For the PID and PID control, the algorithms Eq. (2)–(6) were used. During the initial experiments, noise was located, which had an adverse impact, especially on the derivative part. The anti-windup (Eq. (5)) was implemented to ensure additional stability, a derivative filter (Eq. (6)) was used to eliminate high-frequency noise. Additionally, a Butterworth filter was used for equalising the process variable (PV) with a cut-off frequency at 1 Hz, and based on the FFT analysis.

To determine the dead time and response time for the control system, step analyses were performed at elevated conditions. The dead time was related to the hydraulic, specifically the PVIFS solenoid combined with the PVIFS at 250 mm as stated in the data sheet (Danfoss A/S, Denmark). Due to the hydraulic viscosity change (deflection resistance), the test was performed for cold conditions at approx. 5 °C and when the hydraulic system was at its operating temperature of approx. 70 °C. The analysis was carried out with an output step from 0% to 100%, which makes the valve saturate and the hydraulic system integrate.

The practical, well-known closed loop Ziegler-Nichols tuning method was selected for controller parameter determination [Jannrup and Særensen, 2004]. For the three-position control, the intervals were set to the depth interval of 3 mm, based on initial experiments.

The coulter precision and accuracy were determined and used to compare the different control algorithms for minimising the coulter depth variations and vibrations. The accuracy defines how exact the systems reach the set-point (SP) depth and the precision defines the depth variation/distribution. Steady set-point and precision analyses were based on 3000 measurements for 40 s with a logging frequency of 75 Hz, and corresponding to a travelled length of 34 m (3 repetitions). In addition, SP step experiments were carried out to simulate change in soil resistance to analyse the response and settling time for the control system. The step was changed from 55 mm to 44 mm in depth. Both the experiments were carried out in sand and gravel to simulate significant variations in the seedbed. The mean depth variations without coulter control (fixed actuator) were also analysed to indicate the need for control due to the changes in soil resistance.

2.6. Error propagation

The linearity of the angle sensor and structural stress deflection of the coulter were the two sources of error for the precision arising when correlating the coulter angle to the vertical distance between the coulter and the frame. The impact of the sensor linearity was mathematically correlated to the precision $d_{c}$ of the distance between the coulter and the frame (Eq. (10)).

$$d_{c} = f \cdot \cos(\theta_{\text{max}}) - f \cdot \cos(\theta_{\text{max}}) = \frac{d_{c}}{\theta_{\text{max}}}$$

(10)

where $\theta_{\text{max}}$ is the maximal output, $\theta_{\text{max}}$ is the linearity in percent, $\theta_{\text{max}}$ is the operation angle, $\alpha$ is the vertical distance, $f$ is the length of the drill coulter, and $d_{c}$ the distance precision.

The structural stress and deflection of the drill coulter was analysed using the Finite Element Method (FEM) drawn and computed in SolidWorks (Dassault Systemes SolidWorks Corp., USA). The reverse longitudinal load of 100 N was used, and as determined by initial experiments and verified to be larger than the forces located in the dynamic experiments.

3. Results and discussion

For the coulter depth sensing, the sensor's non-linearity of ±0.5% did not generate a considerable impact on the precision.
even though it was the most dominating precision error in the system. It was determined in the error propagation (Eq. (10)) that the theoretical vertical distance precision ($d_v$) for the long and short coulter resulted in ±3.3 mm and ±2.1 mm, respectively. This precision can be minimised by changing the sensor pre-determined sensitivity operating interval from 30° to 15°, which would halve the precision to ±1.7 mm and ±1.0 mm for the long and short coulters, respectively. The variation between the true coulter depth and the angle sensor readings at the pivot point was also influenced by material deflection relative to the coulter length. From the FEM, it was theoretically concluded that most of the material stress was generated below the spring mounting at the ‘S’ shape of the coulter pipe. For the long coulter pipe measuring a straight length of 1230 mm, the deflection caused a vertical depth displacement of 1.9 mm using the horizontal force of 100 N acting on the coulter. The short drill coulter pipe of 980 mm created less vertical displacement, 1.0 mm.

3.1 Static measurements

The data for each of the 22 static experiments used to create the model contained 1795 angle measurements and one sample was remeasured as an outlier for the experiments no. 2, 5, 6, 9 and 19 based on Chauvenet’s criterion (Eq. (7)). The Chi-square goodness-of-fit statistic test verified that the data fitted a normal distribution with a 0.05 significance level (Eq. (8)). Skewness analysis indicated an insignificant skewness varying between -0.086° and 0.06°. The standard deviations were stable and all below 0.079°. In summary, the data were considered reliable data and suitable for the further analysis.

3.1.1 Mathematical modelling of the correlation between angle and coulter depth

The static data were used for mathematical modelling to correlate the angle measurements of the drill coulter to the measured reference vertical distance, defined as distance from the frame to the coulter point, using the IGPS. The model was based on 2nd-degree polynomial regression and the least-squares method (Eq. (11)). The input for the model was the angle measurements $P_v$, and the output is the vertical distance $d_v$ between the frame and coulter. The model had a RMS of 1.26 mm and $R^2$ of 0.9999.

$$d_v = 0.011 \cdot P_v^2 + 1.450 \cdot P_v - 918 \quad (11)$$

The model was verified by an experimental precision test using the same approach, but the static experiments were carried out by lowering the coulter, as opposed to elevating (Eq. (12)).

$$d_{ew} = 0.012 \cdot P_v^2 + 1.380 \cdot P_v - 919 \quad (12)$$

The model $d_{ew}$ had a similar RMS of 1.15 mm and $R^2$ of 0.9999. In the precision test, a very small imperfection was identified. The difference was up to 3.25 mm in vertical distance between the model peaks at an angle of 15°, which was half the sensor operation span. The non-linearity was caused by the angle sensor non-linearity, infinitesimal mechanical play, and structural deflection in the coulter and construction. The angle sensor had ±0.5% non-linearity, and corresponding to a vertical distance of ±2.1 mm. The sensor non-linearity, infinitesimal mechanical play, and deflection were additive, but the small deviation was considered reasonable.

3.2 Verification of the mathematical model under dynamic condition

To verify the static developed model as based on the angle sensor, it was compared with the IGPS for different dynamic conditions using the non-uniformed mixed soil, uniform sand and the stone simulators. The developed model (100 Hz) detected the rapid coulter variations efficiently, while the IGPS (40 Hz) slowed occasional poor detection caused by the complex environment where the view between the sensors and the sensors for some of the coulter positions were partly blocked. This issue generated some unexpected data in the form of a few missing and fluctuating measurements. However, the majority of the measurements were still usable.

The IGPS measurements and mathematically modelled distance data from the experiment are represented by the blue and black dots, respectively (Fig. 3). The clamped pipe (stone simulator) created the peaks and separated the bin into the non-uniformed mixed soil and uniform sand.

As mentioned, the IGPS measurements created a few unexpected fluctuating measurements when the drill coulter was static at the start and end, which should have made the coulter easy to detect (Fig. 3). The vertical distance, defined as the distance from frame to coulter, varied significantly more in the non-uniformed mixed soil, than in the uniform sand (Fig. 3). The soil, from 21.2 s to 16.3 s, had a large vertical distance variation of 48.5 mm. The sand, from 16.4 s to 20.6 s, varied 9.7 mm. The uniformed soil was slightly smoothed out and not compacted ideally with the levelling rubber blade during the 6 repetitions. The experiment showed an increased depth in the sand of 21.6 mm from 8 s to 42 s (Fig. 3). The rapid depth variations occurring when the drill coulter was dragged over the pipes and then penetrated into the sand were only detected by the angle sensor. The IGPS system did not record any measurements or retained the last accurate measurement due to poor accuracy. The accuracy of the IGPS system decreases as the sensing velocity increases (Depenhal, 2009). Due to the insufficient remote detection accuracy and using the same reference system, an independent validation was not achieved. However, the measurements were still usable for dynamic verification of the developed system.

The cross-correlation factor was found to be 0.931 for all data, which indicated correlation but with a small inaccuracy (Eq. (19)). To accommodate the undetected rapid depth variation, when the coulter was dragged over the pipes, 0.4 s of data were removed from 29 s (Figs. 3 and 4). A new cross-correlation was then calculated at 0.987, and thereby the verification of the data similarity was performed with the 6 repetitions. By comparing the absolute distance measurements (Figs. 3 and 4) and the great cross-correlation of the two systems, it can be concluded that the static developed system operated well for dynamic condition.

In addition, the system was examined individually in the sand and soil (Fig. 4), to test the system under different dynamic conditions. The cross-correlation for sand in the time interval 26 s to 29 s was calculated at 0.956 with a mean error of 5.95 mm, for the soil from 29.4 s to 12.4 s, the cross-correlation was 0.957 with a mean error of 8.23 mm. When the coulter was dragged over the pipe from 29 s to 29.4 s, the cross-correlation was at a very low of 0.708 as a result of missing accurate measurements, and this again supported the removal of data. The calculated cross-correlations in sand and soil showed that the developed system operated similarly for the dynamic conditions.

The Fast Fourier Transform (FFT) used on the mathematically modelled vertical distance from the angle sensor was performed for the drill coulter in the uniform sand and the non-uniformed mixed soil. From the frequency response in sand, the natural frequency was determined to be 0.26 Hz (Fig. 5), and it was 0.44 Hz in soil (Fig. 6). The FFT analyses have identified that the natural frequencies have the greatest magnitudes below 1 Hz, which means that mainly slower coulter depth variations occurred. The result was used to determine the method of filtration to handle the PV signal and to create the control system. In addition, it can be concluded that frequencies higher than 1 Hz were mainly related to high fre-
frequency noise (coulter depth vibrations). However, the sensitivity to depth variations and the normal frequencies depends on the speed, coulter mass and design, combined with the spring characteristics.

3.3. Drill coulter depth control

The static and dynamic sensing have been analysed (Section 3.1 and 3.2), and the PI, PID and the three-position (on/off) control systems have been examined in dynamic conditions in sand and gravel at 6 km/h. The vertical distance between the coulter and the frame was related to the soil surface and thereby recalculated to correspond with the coulter sampling depth.

3.3.1. Response and filter analysis
To test the dead time and response time, the SP step opened the PVEH valve 100%. The coulter (PV) was measured as feedback enabling an analysis of the entire system. It was essential that the experiments were carried out when the hydraulic system was at operating temperature of approx. 70 °C. A sensitivity analysis of oil viscosity showed that the dead time decreased from 527 ms in cold condition at approx. 5 °C to 182 ms. The response time constant, τ (PV at 63.3%) was 588 ms and related to the limited pump oil flow. The 182 ms dead time for the entire system was lower than the individual PVEH dead time at 250 ms as stated by the datasheet. Due to the dead time, fast depth vibrations greater than 1 Hz were not considered controllable.

The Butterworth filter operated properly by equalising the PV signal for the PI and PID control systems without a substantial delay (Fig. 7). The insignificant small delay was related to the controller computation power and was not impacting the experiments.

3.3.2. Depth variations and frequency
An FFT analysis of the PV signal in the sand, when using the PID control system, showed that the control system was able to react and minimise the low frequency depth variations below 1 Hz (Fig. 8). The controlled depth did not have a normal frequency and did not increase asymptotically towards 0 Hz, and that was in contrast to the uncontrolled depth (Fig. 5). Due to the filter and dead time of 182 ms, the system was only able to minimise more consistent depth variations below 1 Hz.

3.3.3. Depth variations in sand and gravel
The integrated control systems were examined in the sand and the gravel over 5 m and corresponding to 5 repetitions with 3000 measurements. The depth was manually set to approx. 55 mm in the sand with a fixed actuator and for testing the control systems it was changed in a step to 44 mm (Table 1). The first experiment
The depth was manually set to be approximately 55 mm without control. The real mean depth from the data was calculated to be 51.66 mm. The mean depth was not directly comparable to the controlled mean depth, but it was used to compare the uncontrolled depth in the experiment with gravel. Due to the undefined set-point, it was not possible to determine the accuracy of the uncontrolled seeding depth. The standard deviation describes the outer depth variations, which was slightly larger than the controlled variations.

Duncan's Multiple Range Tests were used to compare the different systems with each other, with a significant level (x = 0.05) and it was concluded that differences between control systems were significantly different. When the depth was changed to 44 mm in the sand, the three-position was significantly different from P control and PID control. For the depth of 55 mm in gravel seeded, the three-position control was also significantly different from P control and PID control. For the reduced depth of 44 mm, the three-position was still significantly different from the P control and the PID control.

The significant differences between the control systems were found as a result of the relative high number of measurements. Therefore, the Duncan's Multiple Range Test indicated a significantly different even though the absolute difference in depth was very low (Table 1). Compared with the potentially error caused by the non-linearity of the sensor, all the control systems were within the calculated error up to (±3.3 mm). However, all system means were very close to the set point (less than 1.2 mm) and therefore be considered as appropriate systems for controlling the down force and achieving the specified SP depth. The three-position control was the most inaccurate, in respect to the mean, and due to the deadband level, but it was still considered as an appropriate system for fast response and minimal hydraulic adjustments. Even through there were significantly differences between the control systems it cannot be definitely concluded that one of the systems was the best due to the small differences, which also were impacted by very small variations in the seedbeds.

A Bartlett Test of homogeneity of variances showed significantly differences between all the control systems with significance level (x = 0.05) except for P control and PID control in the gravel for 44 mm depth. The three-position had the highest precision but also the poorest precision when the depth was decreased (Table 1). However, slightly different structure of the stones in the seedbed impacted the results.

The three-position control was able to reach the set-point depth by a mean error value of 0.89 mm, due to the control interval. However, the three-position control had the best precision with a standard deviation of 1.08 mm, but for the reduced depth, it had the worst precision with a standard deviation of 2.16 mm. The deviation was caused by the decreased damping effect from the sand due to the lower depth. The P control was very accurate, but it was less accurate than the three-position control due to random depth fluctuations around the set-point because a proportional control contains a small static error by not being able to make an infinitesimal degree of opening in the hydraulic valve. The PID control should theoretically be the most accurate, but with a mean error of -0.17 mm and even greater for the reduced depth that was not the case. The standard deviation was slightly worse but the highest for the reduced depth.

In the gravel without control, the actuator was fixed in the same position as in the sand experiment (Table 1). The depth decreased by 23 mm when the seedbed was changed from sand to gravel due to the greater seedbed resistance acting on the drill coulter. This large depth change verified the expected penetration resistance change, due to change in seedbed material. This depth change generated the anticipated condition for testing the control system and adjusting the down force regarding the change in soil resistance. The force variation to generate the measured depth change was manually measured in static conditions as amounting to 28 N in reverse to longitudinal direction. Additional experiments in a real seedbed with a real machine are needed to verify the significant depth change. The data without control had a standard deviation of 2.78 mm (Table 1). The depth distribution without control was not directly comparable to the control systems due to the different seedbeds, which resulted in the smaller damping effect from the seedbed. However, all control systems were able to find

| Table 1: Statistical indicators for seeding depth variations in sand and gravel over 54 m travelling length. |

<table>
<thead>
<tr>
<th>Control</th>
<th>Mean depth (mm)</th>
<th>Mean error to SP (accuracy) (mm)</th>
<th>Standard deviation to SP (precision) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>55</td>
<td>44</td>
<td>55</td>
</tr>
<tr>
<td>No control (sand)</td>
<td>51.66</td>
<td></td>
<td>1.53</td>
</tr>
<tr>
<td>Three-position (sand)</td>
<td>55.89</td>
<td>44.04</td>
<td>0.90</td>
</tr>
<tr>
<td>P control (sand)</td>
<td>55.08</td>
<td>43.49</td>
<td>0.60</td>
</tr>
<tr>
<td>PID control (sand)</td>
<td>55.17</td>
<td>43.02</td>
<td>0.61</td>
</tr>
<tr>
<td>No control (gravel)</td>
<td>28.57</td>
<td></td>
<td>1.45</td>
</tr>
<tr>
<td>Three-position (gravel)</td>
<td>50.18</td>
<td>44.04</td>
<td>1.18</td>
</tr>
<tr>
<td>P control (gravel)</td>
<td>54.09</td>
<td>43.49</td>
<td>0.11</td>
</tr>
<tr>
<td>PID control (gravel)</td>
<td>54.02</td>
<td>43.06</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Page 184 of 266
the set-point depth within an acceptable range. The three-position control had a similar accuracy (~1.18 mm) as in the sand, but for the reduced depth, there was a very high accuracy of ~0.04 mm. The precision was high for the three-position control, but it was considerably poor for the decreased depth. This was related to the reduced damping effect from the spring and the decreased down force from the springs. The P control was more accurate than the three-position control. As expected, the PID control was the most accurate in the experiment for both depths, and the P and PID control had a similar precision.

Based on the statistics, it can be concluded that all control systems tend to minimise the depth variations and find the desired depth, despite the large change in rootled resistance from sand to gravel. The minor distribution variations between the controlled systems were mainly related to randomness. The control systems cannot be shown to minimise vibrations (greater than 1 Hz). Furthermore, the depth distributions are not comparable between the different control systems and the system without control. To minimise the more rapid depth vibrations, the dead time and response time of the actuator system must be optimised.

3.3.4. Control step analysis in sand and gravel

The analyses of the controllers' reactions and performances due to variations in the control-force acting on the drill coulter were conducted. To simulate reedbed material change, a step in set-point depth was carried out and ranging from 55 mm to 44 mm in depth. The set-point depth changes with depth measurements based on the angle and control output are illustrated for sand and gravel and tested with the three-position, P, and PID control systems (Fig. 9).

The three-position control in sand operated as intended by momentarily opening the hydraulic valve 100% when a step in the set-point was involved (Fig. 9c). The difference between the measured depth and the set-point depth was the control error and when the error became smaller than the selected 3 mm deadband limit, the hydraulic valve closed momentarily. Due to the noisy measured signal, some valve on/off switching occurred in order for the depth to settle at the set-point. However, the settling time was rapidly performed after 0.9 s due to the momentarily opening of the hydraulic valve, which was kept open until the depth was settled.

The three-position control operated similarly in the gravel (Fig. 9b). The system reacted rapidly and settled after 0.7 s. Due to the noisy signal from the gravel, even more valve switching occurred due to the response of the depth variations. The three-position control opened on the errors at 1.4 s and 2.2 s.

The P control in sand had a smoother settling, but the settling time was slower at 1.7 s due to the lower opening degree of the valve (Fig. 9c). The smaller opening degree of the valve operates properly for the P control, and the control output decreased proportionally to the error. The error was additionally minimised compared to the three-position control because of the proportionality. However, the control system showed a minor tendency to exhibit static error.

The P control in gravel reacted properly by the proportional output to the error (Fig. 9d). The settling time was slower and approximated 2.2 s. The smaller opening degree of the valve induced that the system did not minimise the depth variations as rapidly as the three-position control.

The PID control in sand had a faster settling time than the P control, but slower than the three-position control (Fig. 9a). The control output increased more than the P control due to the D action. The PID control settling time was 0.9 s. However, the PID control had the set-point depth more accurate than the three-position control due to the I action.

The PID control in gravel had a slightly faster settling time than the P control but still slower than the three-position control (Fig. 9f). The control output increased more than the P control at the start, due to the D action. The P and I actions kept the output steady at 0.9 % until 1 s. The PID control settling time was approx. 2.1 s, and the integral action was slow initially and reached a higher degree of accuracy only after the illustrated 3 s (Fig. 9f).

However, over a longer period and as also determined from the depth variation section, the PID control became more accurate, than the three-position control but it used significantly longer time for settling.

3.3.5. Controller selection

None of the applied systems were able to eliminate the rapid depth vibrations caused by the inappropriate hydraulic dead time and the response time as caused by the valve opening degree and the limited oil flow supply (3 l/min). However, all control systems

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![Figure 9](image-url)
were able to nearly eliminate depth variations less than 1 Hz, which corresponded to more consistently changes in the seedbed. The three-position control was the most rapid control system for settling because of the full opening degree; however, the 0.7 s settling time in the gravel corresponded to 1.17 m. Alternatively, the three-position control was shown to be more stable when the seedbed counterforce was extraordinary low (sloped at the top part of the seedbed). This issue is solvable by increasing the control deadband limits or using the Butterworth filter at the PV signal. Increasing the control deadband limits induces more inaccuracy but less hydraulic switching which has to be a trade-off with depth accuracy versus the allowed valve switching frequency. An ordinary 4/3 direction valve is sufficient for the three-position control, which is also considerably cheaper and does not require the additional oil filtration. The PID control was the most stable and accurate control system, but it was important that the D control was inhibited with the filter because it tends to generate instability. The PID control was more rapid than the P control, but considerably slower than the three-position control. However, the PID and P were remarkably more accurate than the three-position control. If the set-point depth change was larger, all controls momentarily adjust the output to 100%, making them equally fast until the P and afterwards the PID control reduced the output level due to the proportion action. In general, all control systems were able to handle soil consistent changes in seedbed conditions.

In the experimental environment, the seedbed was reproduced in the soil bin, but the sand, soil and gravel was not directly trans-ferable to a real seedbed in a field. A real seedbed differs in the field depending on the respective soil, water content and tillage operation intensity. The seedbed moisture content was not measured, but all the control experiments were carried out the same day in order to achieve similar conditions. However, the structure in the seedbed changed slightly during the repetitions and for the gravel experiments, a small tendency of soil compaction was observed due to the non-ideal tillage system. This seedbed change slightly affects the soil resistance. Field experiments are needed to validate the selection of the best commercial low-cost depth control system. Compared to the study (Weatherly, 1997), the coulter depth controlled based on front disc sensing, where the proposed depth control system ensured a constant coulter depth. The study (Sønndal and Oskarson, 2015) was developing and presenting a sensing system controlled using multiple sensor inputs, and the presented coulter depth in this study was significantly more accurate than comparable systems. However, systems in real field conditions do not have a fixed frame as in the soil bin, which gives rise to additional accuracy challenges. In real seeding operations, the coulters are influenced by forces and movements of the entire seeding machine. However, based on this study, the three-position control was the best low-cost solution using only one sensing input and similar concept or study has not been shown before. For subsequent field experiments, the following improvements can be considered.

- Three-position control can be considered with a fuzzy control method in partial membership in quantitatively defined linguistic terms.
- P control can be considered with lag and/or lead compensator to improve low and high frequency control (Jannergaard and Sørensen, 2004).
- PID can be improved with a cascade or adaptive control for taking changes/disturbances into account. However, additional physical sensing is needed.
- If greater depth precision is required, the hydraulic dead time at 182 ms of the actuator system has to be additionally to eliminate the rapid vibrations.

4. Conclusion

A novel coulter depth control system for maintaining a consistent grain coulter depth independent of soil resistance was developed and examined in a soil bin. By the ordinary fixed down force spring, the mean depth decreased by 23 mm due to change in soil resistance, when the seedbed was changed from sand to gravel. The dynamic down force control system of the coulter showed significant improvement, and achieving the desired coulter depth independently of the soil resistance. The system requires accurate information of the transverse frame distance of the seeding machine relative to the soil surface.

A three-position control system for automatic adjustments of the coulter depth was found to be the best cost-efficient solution for a proof-of-concept of the researched technology. It provided a mean depth variation from the desired coulter depth of –0.089 mm (SD = 1.08) and –1.18 mm (SD = 1.55) for sand and gravel, respectively.

Acknowledgements

The authors acknowledge financial support from Aarhus University, Faculty of Science and Technology, Department of Engineering for the research presented. Thanks to Jens Kristian Kristensen and Peter Storegaard Nielsen for practical guidance and support during the experimental sessions. Thanks to the engineers at the Kongskilde R&D department and Agro Intelligence A/S for technical discussions.

References

6. Appendix / Patent D – A sowing apparatus for sensor based depth control of seeding
(12) International Application Status Report

Received at International Bureau: 15 May 2015 (15.05.2015)
Information valid as of: 07 September 2016 (07.09.2016)

(10) Publication number: WO2015/169323
(13) Publication date: 12 November 2015 (12.11.2015)
(26) Publication language: English (EN)

(21) Application Number: PCT/DK2015/050119
(22) Filing Date: 08 May 2015 (08.05.2015)
(25) Filing language: English (EN)

(31) Priority number(s): PA 2014 00255 (DK)
(31) Priority date(s): 09 May 2014 (09.05.2014)
(31) Priority status: Priority document received (in compliance with PCT Rule 17.1)

(51) International Patent Classification:
A01C 7/20 (2006.01)

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(54) Title (EN): A SOWING APPARATUS FOR SENSOR-BASED DEPTH CONTROL OF SEEDING
(54) Title (FR): APPAREIL D'ENSEMBEMENT PERMETTANT DE CONTRÔLER LA PROFONDEUR D'ENSEMBEMENT À L'AIDE D'UN CAPTEUR

(57) Abstract:
(EN): The apparatus relates to a sowing apparatus (100), said sowing apparatus comprises: a frame (2) comprising a front end (4) and a rear end (6), as seen in relation of the intended direction of movement; said intended direction of movement defining a longitudinal direction (X) of the apparatus; wherein said frame is having an extension in a transverse direction (Y), said transverse direction being perpendicular to the longitudinal direction (X); wherein said frame comprising one or more shear carriers (8), said shear carriers each having a first end (10) and a second end (12); wherein said one or more shear carriers (8) at its first end being pivotally suspended onto said frame in a suspension (14); wherein said shear carrier at its second end (12) comprising one or more shear (16) adapted to be at least partially submerged into the soil (18); wherein in respect of one or more of said one or more shear carriers (8), said frame comprising seed conveying means (20) for conveying seeds into the soil at a position corresponding to one or more of said one or more shear; wherein in respect of one or more of said one or more shear carriers (8), said apparatus comprises a sensor (22) for detecting the position of said shear carrier in relation to the frame; said sensor (22) being configured to provide an output signal representing a sensed position of said shear carrier (8); wherein in respect of one or more of said one or more shear carriers said apparatus comprises an actuator (24) for altering the position of the shear carrier in relation to the frame; wherein said apparatus comprises a control unit (25) configured to receive said output signal from said sensor; wherein said control unit is configured to provide an output signal for controlling said actuator; wherein said control unit is connected to an input device (28), said input device being configured to allow an operator to provide said control unit with instruction relating to the desired response of the actuator, based on the input signal of said sensor.

(FR): La présente invention concerne un appareil d'ensemencement (100), ledit appareil d'ensemencement comprenant : un bâti (2) comportant une extrémité avant (4) et une extrémité arrière (6) comme on le voit par rapport au mouvement de direction fixe, ladite direction de déplacement prévue définissant la direction longitudinale (X) de l'appareil. Ledit bâti présentant une extension dans la direction transversale (Y), ladite direction transversale étant perpendiculaire à la direction longitudinale (X).
Ph.D. Thesis

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(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)
(19) World Intellectual Property Organization
International Bureau
(43) International Publication Date 12 November 2015 (12.11.2015)
(10) International Publication Number WO 2015/169323 A1

(51) International Patent Classification:
A01C 7/20 (2006.01)

(21) International Application Number:
PCT/DK2015/050119

(22) International Filing Date:
8 May 2015 (08.05.2015)

(25) Filing Language:
English

(26) Publication Language:
English

(30) Priority Data:
PA 2014 00255 9 May 2014 (09.05.2014) DK

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Published:
with international search report (Art. 21(1))

(54) Title: A SOWING APPARATUS FOR SENSOR BASED DEPTH CONTROL OF SEEDING

(57) Abstract: The apparatus relates to a sowing apparatus (100), said sowing apparatus comprises: a frame (2) comprising a front end (4) and a rear end (6), as seen in relation of the intended direction of movement; said intended direction of movement defining a longitudinal direction (X) of the apparatus; wherein said frame is having an extension in a transverse direction (Y), said transverse direction being perpendicular to the longitudinal direction (X); wherein said frame comprises one or more sheer carriers (8), said sheer carriers each having a first end (10) and a second end (12); wherein said one or more sheer carriers (8) at its first end being pivotally suspended onto said frame in a suspension (14); wherein said sheer carrier at its second end (12) comprising one or more sheer carriers (10) adapted to be at least partially submerged into the soil (18) wherein in respect of one or more of said one or more sheer carriers (8), said frame comprising seed conveying means (20) for conveying seeds into the soil at a position corresponding to one or more of said one or more sheer carriers, wherein in respect of one or more of said one or more sheer carriers (8), said apparatus comprises a sensor (22) for detecting the position of said sheer carrier in relation to the frame; said sensor (22) being configured to provide an output signal representing a sensed position of said sheer carrier (8), wherein in respect of one or more of said one or more sheer carriers (8) said apparatus comprises a control means (24) for altering the position of the sheer carrier in relation

(Continued on next page)
to the flame; wherein said apparatus comprises a control unit (26) configured to receive said output signal from said sensor; wherein said control unit is configured to provide an output signal for controlling said actuator; wherein said control unit is connected to an input device (28), said input device being configured to allow an operator to provide said control unit with instruction relating to the desired response of the actuator, based on the input signal of said sensor.
A sowing apparatus for sensor based depth control of seeding

Field of the invention

The present invention relates generally to sowing technology in the field of agriculture. More specifically, the present invention relates in a first aspect to a sowing apparatus and in a second aspect to use of such a sowing apparatus for sowing seeds.

Background of the invention

Within the field of agriculture, when culturing crops it is common practice to grow crops in vast areas of land for the purpose of harvesting desired parts of the crop or the whole crop itself. Due to the extremely large areas of land involved, it is preferred to use a sowing apparatus when sowing the crop seeds making the sowing process as efficient and as little time consuming as possible.

A prior art sowing apparatus is configured to be towed behind a tractor or the like, and it comprises a frame suspending on a couple of wheels. On the frame is pivotally suspended one or more shear carriers. The opposite end of each shear carrier is located near the ground and comprises a shear that during use at least is partially suspended into the soil. When towing the sowing apparatus the shears will each create a furrow in the soil, extending a relatively small distance into the soil. A seed conveyor is arranged in respect of each shear on the frame in such a way that the shear carrier allows dispensing seeds into the furrows created by the shears. By slightly angling the shears in relation to the direction of movement of the sowing apparatus, it is possible to make the shears create a furrow on the one hand, and on the other hand, immediately subsequent to dispensing and sowing a seed, to make the shears cover that furrow with soil. The covering of the furrow is made by either a second time/share pushing soil into the furrow and/or compacting the furrow sides with a small wheel to compress soil into the furrow and make a light soil compaction around the seed to improve germination and water availability.

By burying the seeds it may be possible to establish optimum growth conditions for the seeds during the seeding stage due to the better accessibility of nutrients and water at a certain depth in the soil. Furthermore, losses of seeds to small foraging animals may be minimized and also
losses due to blowing winds removing the seeds from the sowing site are avoided in this way as are detrimental effects of UV radiation originating from the sun.

Each species of crop has its own optimum conditions in relation to the initial seeding growth stage and thus also in relation to the seeding depth. Generally, the smaller the seed, the less depth of seeding desired. Furthermore, as a general rule, the smaller the seed, the more sensitive the seed will be in relation to deviations to the optimum seeding depth. Accordingly, optimum growth depth for wheat seeds is 2 – 6 cm; optimum growth depth for maize/corn seeds is 7 – 8 cm; and optimum growth depth for rape seeds is 1.5 – 2.5 cm.

When sowing a crop seed, in case a relatively large part of the seeds is seeded in a non-optimum seeding depth, a non-optimum germination of the crop will result. Due to a lower germination rate, the result will be a weaker competition against weeds and poor utilization of nutrient per area unit.

Accordingly, it is of paramount importance for the farmer’s economy that the seeds will be seeded at a seeding depth which is optimum for the specific plant species.

To this end, the prior art sowing apparatus is provided with a depth controlling device for attempting to secure that the seeds being seeded will be seeded at a depth which corresponds to the optimum seeing depth of the crop species in question. Such a depth controlling device comprises a spring load for spring loading the pivotally suspended shear carrier. In this way the shear carrier will not be freely movable in the pivotally suspension and it will not be rigidly suspended onto the frame of the sowing apparatus. Rather the pivotally suspended shear carriers will be pivotally suspended and forced into the soil by the force posed by the spring loading. The depth controlling device additionally comprises adjustment means for adjusting the tension of the spring, thus allowing the pivotally suspended shear carriers to be forced into the soil by a predetermined force as determined by the tension of the spring.

However, although this type of prior art sowing technology provides a somewhat improved technique for sowing the crop seeds in the soil at an approximate sowing depth compared to a non-suspension system, there exist a number of disadvantages associated with this technology.

One major disadvantage becomes apparent when using the prior art sowing apparatus in soil having a varying soil texture. Accordingly, when applying the prior art sowing apparatus in
areas comprising parts of sandy soil and other parts of clayed soil, possible with areas of presence of rocks or gravel, the spring loaded shear carrier with its pre-adjusted spring tension will not be able to cope with these varying nature of soil constituents in the sense that the spring loaded shear carrier having a constant and predetermined spring tension when operating in sand, which is relatively soft, will imply that the shear will be pressed a relative deep distance into the soil, whereas when operating in clayed or rocky soil, which is relatively hard, the shear (having the same spring loading) will be pressed only a relative shallow distance into the soil.

The consequence is that the seeds are not being sown at constant depths irrespective of the nature of the soil. Hence, a non-optimum growth of crops will result.

Furthermore, as the spring load is also calibrated to a specific speed and resulting soil resistance, if the speed is varying then also the seeding depth will vary, as the soil resistance will increase commensurate with increasing speed. Especially in the case of going up and down hill, the speed can easily vary 20–40%.

Another type of depth controlling sowing machine relies on measuring the distance over ground by use of a sensor sensing the distance to the surface of the ground. The sensor may be a sonic or an optical sensor, such as an ultrasonic sensor or an IR sensor which is arranged on the sowing machine itself. In these machines the sowing depth is controlled by a control unit which regulates the sowing depth of the seeds to be sown by changing the depth of a shear submerged into the soil in response to the distance sensed by the sensor.

Although these machines in theory could provide for a precise sowing depths of seeds, these machines in practice suffers from some drawbacks.

These drawbacks relate to the fact that optical and sonic sensing in general will be inaccurate and provide false reading due to temperature variation, presence of moist in the air, presence of crop residues or weed at the soil surface. Also presence of small areas of water surfaces at the upper layer of the soil may pose false readings by the sensor. Accordingly, complicated computing and noise filtering will be needed in the processing of the data originating from optical and sonic sensing.
Moreover, irregular surfaces of the field may present challenges in relation to providing the correct feedback, viz. the depth of a shear submerged into the soil in response to the distance sensed by the sensor.

Furthermore, dust and dirt depositing on the sensing surface of the sensor will require frequent cleaning of the sensors. Additionally, dust in the field of view might generate poor detection, impacting the sensing accuracy of optical sensing.

Finally, optical and sonic sensors are delicate equipment that needs careful maintenance in order to function properly.

Accordingly, a need persists for an improved sowing apparatus which will alleviate or even eliminate the above mentioned disadvantages.

**Brief description of the invention**

The object of the present invention is to alleviate or even eliminate the above mentioned disadvantages of the prior art sowing apparatus.

The object of the present invention is achieved by a sowing apparatus according to claim 1 and by the use of such a sowing apparatus according to claim 20.

Preferred embodiments of the invention are defined in the dependent claims 2 – 19.

Accordingly, the present invention relates in a first aspect to a sowing apparatus, said sowing apparatus comprises:

- a frame comprising a front end and a rear end, as seen in relation to the intended direction of movement; said intended direction of movement defining a longitudinal direction X of the apparatus; wherein said frame is having an extension in a transverse direction Y, said transverse direction being perpendicular to the longitudinal direction X.

  wherein said frame comprising one or more shear carriers, said shear carriers each having a first end and a second end;

  wherein said one or more shear carriers at its first end being pivotally suspended onto said frame in a suspension;
wherein said shear carrier at its second end comprising one or more shears adapted to be at least partially submerged into the soil;

wherein in respect of one or more of said one or more shear carriers, said frame comprising seed conveying means for conveying seeds into the soil at a position corresponding to one or more of said one or more shears;

wherein in respect of one or more of said one or more shear carriers, said apparatus comprises a sensor for detecting the position of said shear carrier in relation to the frame; said sensor being configured to provide an output signal representing a sensed position of said shear carrier;

wherein in respect of one or more of said one or more shear carriers said apparatus comprises an actuator for altering the position of the shear carrier in relation to the frame;

wherein said apparatus comprises a control unit configured to receive said output signal from said sensor;

wherein said control unit is configured to provide an output signal for controlling said actuator;

wherein said control unit is connected to an input device, said input device being configured to allow an operator to provide said control unit with instruction relating to the desired response of the actuator, based the input signal of said sensor.

The present invention relates in a second aspect to use of a sowing apparatus according to the first aspect for sowing seeds.

The present invention in its first and second aspect provides for sowing crop seeds at a preferred optimum sowing depth, irrespective of the nature of the soil. Hence, more optimum growth of crops will result. The optimum sowing depth has the consequence that the crop will be more competitive against weeds and resistant towards attack from fungi in early stage and thus imply improved yield of crops. Furthermore, when sowed at an optimum depth, the crop will be more robust towards variations in weather condition.

**Brief description of the figures**

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Detailed description of the invention

The first aspect of the present invention

The present invention relates in a first aspect to a sowing apparatus 100, said sowing apparatus comprises:

- a frame 2 comprising a front end 4 and a rear end 6, as seen in relation of the intended direction of movement; said intended direction of movement defining a longitudinal direction X of the apparatus; wherein said frame is having an extension in a transverse direction Y, said transverse direction being perpendicular to the longitudinal direction X;

- wherein said frame comprising one or more shear carriers 8, said shear carriers each having a first end 10 and a second end 12;

- wherein said one or more shear carriers 8 at its first end being pivotally suspended onto said frame in a suspension 14;

- wherein said shear carrier at its second end 12 comprising one or more shears 16 adapted to be at least partially submerged into the soil 18;

- wherein in respect of one or more of said one or more shear carriers 8, said frame comprising seed conveying means 20 for conveying seeds into the soil at a position corresponding to one or more of said one or more shears;

- wherein in respect of one or more of said one or more shear carriers 8, said apparatus comprises a sensor 22 for detecting the position of said shear carrier in relation to the frame; said sensor 22 being configured to provide an output signal representing a sensed position of said shear carrier 8;
wherein in respect of one or more of said one or more shear carriers said apparatus comprises an actuator 24 for altering the position of the shear carrier in relation to the frame;

wherein said apparatus comprises a control unit 26 configured to receive said output signal from said sensor;

wherein said control unit is configured to provide an output signal for controlling said actuator;

wherein said control unit is connected to an input device 28, said input device being configured to allow an operator to provide said control unit with instruction relating to the desired response of the actuator, based the input signal of said sensor.

In the present description and in the appended claims, the term “intended direction of movement” shall be construed to mean “the direction of movement of the sowing apparatus when used for sowing”, wherein the shears are usually positioned at a relatively rear position.

In the present description and in the appended claims, the term “the position of the shear carrier in relation to the frame” shall be construed to mean “the position of the shear carrier, in a vertical direction, in relation to the frame”.

In one embodiment of the first aspect of the present invention, in respect of one or more of said one or more shear carriers 8, said seed conveying means 20 for conveying seeds into the soil at a position corresponding to one or more of said one or more shears comprises a tube or pipe 21 having an extension in a vertical direction from an inlet opening 28 thereof to an outlet opening 30 thereof, said outlet opening 30 being arranged below said inlet opening 28.

In one embodiment of the first aspect of the present invention, in respect of one or more of said one or more shear carriers 8, said seed conveying means 20 for conveying seeds into the soil at a position corresponding to one or more of said one or more shears are configured to conveying seeds into the soil at a position corresponding to a rear part 32 of one or more of said one or more shears.

Such arrangements provide for a cost efficient and simple way of conveying seeds into the soil.

In one embodiment of the first aspect of the present invention in respect of one or more of said one or more shear carriers 8 said seed conveying means 20 for conveying seeds into the
soil at a position corresponding to one or more of said one or more shears is connected to a seed dispensing device 34 for dispensing seeds at a predetermined intervals.

This ensures an automated dispensing of seeds into the soil and thus may provide an accurate and constant mutual distance of sown seeds.

In one embodiment of the first aspect of the present invention said frame 2 comprises one or more wheels or carrier rollers 36 for providing support for said frame when towing the apparatus.

Providing the sowing apparatus with wheels or carrier rollers ensures less resistance when towing the apparatus behind a tractor. Furthermore, this may provide more accurately seeding seeds at a predetermined sowing depth.

In one embodiment of the first aspect of the present invention said sensor 22 and said actuator 24 is an integrated unit 38.

Such an arrangement provides a more simple design of the sowing apparatus.

In one embodiment of the first aspect of the present invention said control unit 26 is configured to receive instructions relating to a desired basis-depth of sowing, thus corresponding to a desired basis-position of the actuator relative to the frame.

Hereby is ensured that when sowing seeds, the seeds will as far as possible be sown at this predetermined basis-depth of sowing.

In the present description and in the appended claims, the term “basis-depth” shall be construed to mean a desired and optimum sowing depth associated with the specific crop species to be grown. The actual sowing depth may undesirably deviate from this basis-depth due to various types of errors or difficult soil conditions. However, the basis-depth is the depth at which it is desired that the seeds are to be sown.

In one embodiment of the first aspect of the present invention said sensor 22 being a sensor configured to sense a translational displacement; or wherein said sensor 22 being a sensor configured to sense an angular displacement.

These two types of sensors both will provide accurate sensing of the movement of the shear carriers in relation to the frame.
In one embodiment of the first aspect of the present invention the number of shear carriers is 5 – 180 or more, such as 10 – 175, e.g. 15 – 170, such as 20 – 165, e.g. 25 – 160, such as 30 – 155, e.g. 35 – 150, such as 40 – 145, such as 45 – 140, for example 50 – 135 or 55 – 130, such as 60 – 125, e.g. 65 – 120, such as 70 – 115, e.g. 75 – 110, for example 80 – 105, such as 85 – 100, such as 90 – 95.

Such numbers of shear carriers will provide for a fast and efficient sowing of crop seeds.

In one embodiment of the first aspect of the present invention, in respect of one or more of said one or more shear carriers said shear carrier may independently comprise one, two or three or more shears.

It may in certain cases not be necessary for each shear to have its own associated shear carrier. Providing one or more shear carriers with more shears provides for construction savings and a simpler design.

Likewise it may in certain cases not be necessary for each shear carrier to have its own associated actuator and/or have its own associated sensor. Accordingly, groups of two, three, four or more shear carriers, preferably shear carriers located in an immediate vicinity of each other, may be configured to forced synchronous movement, e.g. by being welded together, in a configuration where these groups of two, three, four or more shear carriers are sharing the same common actuator and/or the same common sensor.

Similarly, it is understood that within the meaning of the present description and the appended claims, the sowing apparatus of the first aspect of the present invention may one or more control units. Accordingly, one control unit may be configured to provide output signals for controlling all the actuators comprised in the sowing apparatus.

In one embodiment of the first aspect of the present invention the sowing apparatus being configured to be towed behind a tractor or the like.

In another embodiment of the first aspect of the present invention, the sowing apparatus being a self-propelled sowing apparatus.

In one embodiment of the first aspect of the present invention it is a requirement that in respect of one or more of said one or more shear carriers said apparatus comprises a spring, such as a pressure spring; said spring being suspended in serial configuration in relation to said actuator.
Hereby is achieved that shear carried being suspended in such a way that the actuator adjusts the tension of the spring load of the shear carrier.

In one embodiment of the first aspect of the present invention it is a requirement that in respect of one or more of said one or more shear carriers, said one or more shears being a drill shear or a disc shear.

Such types of shears are traditionally and conventionally used as shears in sowing apparatuses.

In one embodiment of the first aspect of the present invention, said sowing apparatus does not comprise a sonic or an optical sensor for remote sensing a distance.

In the present description and in the appended claims the term “remote sensing a distance” shall be interpreted as a situation in which a sensor senses a distance through the air. Hence, the term “remote sensing a distance” implies that the distance is sensed by the sensor without “touching”. In one embodiment of the first aspect of the present invention said sowing apparatus does not comprise an optical or a sonic sensor.

In one embodiment of the first aspect of the present invention said sowing apparatus does not comprise an optical or a sonic sensor for sensing a distance from said sensor to the surface of the ground.

In one embodiment of the first aspect of the present invention said sowing apparatus does not comprise an optical or a sonic sensor, such as an ultrasound sensor or an infrared sensor.

In one embodiment of the first aspect of the present invention it is a requirement that in respect of one or more of said one or more shear carriers, preferably all said shear carriers, said control unit is configured to dynamically regulating said output signal for controlling said actuator, solely in response to the output signal originating from said sensor.

In one embodiment of this embodiment of the first aspect of the present invention it is a requirement that in respect of one or more of said one or more shear carriers, preferably all said shear carriers, said control unit is configured to dynamically regulating said output signal for controlling said actuator; without receiving input from any other type of sensor as defined above.
These embodiments avoid the disadvantages associated with using optical or sonic sensors for sensing a distance of a frame of a sowing apparatus over the ground as set out in the introduction of the present application.

In the present description and the appended claims the term “dynamically regulating” shall be interpreted as a repeatedly adjustment of the position of the shear carrier in relation to the frame based on the position of the shear carrier as detected by the sensor.

Accordingly the term “dynamically regulating” is different from an initial setting of the control unit relating to a desired “basis depth” which in turn in most situations will be a single adjustment of the control unit and relating to a specific species of crop.

The second aspect of the present invention

The present invention relates in a second aspect to the use of a sowing apparatus according to the first aspect for sowing seeds.

Referring now in details to the drawings for the purpose of illustrating preferred embodiments of the present invention, fig. 1 illustrates schematically the principle of a prior art sowing apparatus. Fig. 1 shows the prior art sowing apparatus 200 comprising a frame 2 to be towed along a longitudinal direction X at a towing part (not shown in fig. 1). The frame is suspended on wheels or carrier rollers 36 which allow the frame to follow the surface of the soil 18 when being towed. On the frame 2 is pivotally suspended a shear carrier 8 having a first end 10 and a second end 12. The shear carrier is suspended onto the frame 2 at its first end 10 in a suspension 14. At the second end 12 of the shear carrier 8 is rotably mounted a shear 16. The shear carrier 8 is in relation to the frame 2 subjected to the action of a spring 202 which will force the shear carrier 8 downward in relation to the frame 2 by pivoting in the suspension 14. A spring tensioner 204 allows for adjusting the tension of the spring 202, thus resulting in varying the force with which the shear carrier 8 is forced downward, and thus varying the force with which the shear 16 is forced into the soil. This feature in turn results in allowing adjustment of the depth of the shear furrow, and thus ultimately the depth at which the seeds will be sowed. The seeds to be sown originates from a seed hopper (not shown in fig. 1) and passed a seed dispensing device 34 (also not shown in fig. 1) before it is allowed to be guided
into the soil via seed conveying means 20 in the form of a pipe 21 having an inlet opening 28 at an upper part and an outlet opening 30 at a lower part.

As it can easily be contemplated from the schematically outline of the principle of the prior art sowing apparatus of fig. 1, the apparatus when towed in use and upon being set with a predetermined spring tension by adjusting spring tensioner 204, will allow the shear carrier 8 to pivot around the suspension 14 at a varying angle, thus resulting in a varying shear depths D and thus varying sowing depth of the seeds.

Accordingly, the prior art apparatus as outlined in fig. 1 does not provide for optimum sowing depths of seeds, and consequently ultimately results in a non-optimum quantity and quality of harvested crops.

Parameters especially affecting the sowing depths of seeds with the prior art apparatus of fig. 1 are the texture or nature of the ground or soil, such as type of soil (e.g. soil constituents like clay, sand, gravel), moisture content of soil, presence of plant residues in the soil, presence of rocks in the soil.

The disadvantages of the prior art sowing apparatus of fig. 1 has been overcome with a sowing apparatus according to the present invention. Such an apparatus is shown in fig. 2.

Fig. 2 illustrates a sowing apparatus 100 according to a first aspect of the present invention. The sowing apparatus 100 comprising a frame 2 to be towed along a longitudinal direction X at a towing part (not shown in fig. 2). The frame is suspended on wheels or carrier rollers 36 which allow the frame to follow the surface of the soil 18 when being towed. On the frame 2 is pivotally suspended a shear carrier 8 having a first end 10 and a second end 12. The shear carrier is suspended onto the frame 2 at its first end 10 in a suspension 14. At the second end 12 of the shear carrier 8 is rotatably mounted a shear 16.

The seeds to be sown originates from a seed hopper (not shown in fig. 2) and passed a seed dispensing device 34 (also not shown in fig. 2) before it is allowed to be guided into the soil via seed conveying means 20 in the form of a pipe 21 having an inlet opening 28 at an upper part and an outlet opening 30 at a lower part.

Seed hoppers and seed dispensers suitable for use in the present invention are readily available on the marked and are thoroughly disclosed in the prior art. Examples of such
devices may be found by reference to the producers Kverneland Accord, Pöttinger, Kongskilde, Kuhn and Lemken.

Between the shear carrier 8 and the frame 2 is arranged a sensor 22, sensing the angle $\alpha$ between the shear carrier 8 and the frame 2. Alternatively, the sensor 22 may be configured for sensing not an angular displacement but rather a translational displacement between the shear carrier 8 and the frame 2. Also arranged between shear carrier 8 and the frame 2 is an actuator 24 for actuating or asserting a force between the shear carrier 8 and the frame 2. Such actuation will result in moving the pivotally suspended shear carrier 8 in relation to the frame 2 by rotational movement in the suspension 14. Accordingly, by means of the actuator 24, the shear carrier 8 may be lifted upward in a direction away from the ground or soil; or may be forced downward in a direction towards the ground or soil, thereby altering the angle $\alpha$ between the shear carrier 8 and the frame 2. The actuator 24 may e.g. be a hydraulic actuator, an electrical actuator or a mechanical actuator.

In this way the depth $D$ of the shear furrow created by the shear 16 may be adjusted.

Accordingly, ultimately this allows for adjustment of the depth at which the seeds will be sown.

The sowing apparatus according to the first aspect also comprises a control unit 26 (not shown in fig. 2). The control unit 26 is configured to receive input signal originating from the sensor 22. Furthermore, the control unit is configured to send instruction signals to the actuator.

Preferably, the control unit 26 comprises means, such as a data storage medium, comprising a computer program which provides instructions as to how the actuator 24 must react on the basis of input signals received form the sensor 22.

Preferably, the control unit 26 comprises input means for allowing an operator to input data relating to the desired behavior of the actuator 24 in response to signals received form the sensor 22. Such input means may be in the form of a keyboard. Additionally, the control unit 26 may include a monitor or the like for allowing an operator to monitor the settings of the control unit and/or the operation of the sowing apparatus.

In this way, the control unit 26 may be configured to receive instructions relating to a desired basis-depth of sowing, thus corresponding to a desired basis-position of the actuator relative
to the frame. The term “basis depth” shall in the present description and in the appended claims be construed to mean a predetermined sowing depth of a specific crop species which has shown to be optimum in respect of that crop species.

The sensor 22 and the actuator 24 may be in the form of an integrated unit 38. Such integrated units are commercially available. Accordingly, the producer Bliter manufactures hydraulic cylinders with build in electronic sensors.

Whether being separate units or an integrated unit it is desired that the actuator 24 is being suspended between the 2 frame and the shear carrier 8 in series with a spring, such as a pressure spring for providing a spring loaded shear carried in such a way that actuator 24 adjusts the tension of the spring load of the shear carrier.

In fig. 2 only principles of the sowing apparatus according to the first aspect of the invention have been depicted. It should be noted, however, that while fig. 2 only illustrates a sowing apparatus having one shear carrier 8 and one shear 16 and one seed conveying means 20, it will easily be contemplated that the inventive apparatus may comprise a number of such shear carriers, shears and seed conveying means. Such shear carriers, shears and seed conveying means will typically be arranged “in-line” in a transverse direction Y, perpendicular to the intended direction of movement of the sowing apparatus. For example, the inventive sowing apparatus may comprise 5 – 180 or more, such as 10 – 175, e.g. 15 – 170, such as 20 – 165, e.g. 25 – 160, such as 30 – 155, e.g. 35 – 150, such as 40 – 145, such as 45 – 140, for example 50 – 135 or 55 – 130, such as 60 – 125, e.g. 65 – 120, such as 70 – 115, e.g. 75 – 110, for example 80 – 105, such as 85 – 100, such as 90 – 95 shear carriers. Each shear carrier may comprise one, two or three or even more shears. The number of seed conveying means may typically be identical to the number of shears.

Accordingly, the inventive sowing apparatus as outlined in fig. 2 allows for providing optimum sowing depths of seeds, because the sensor 22 and the actuator 24 constantly will be sensing the depth of the shear and subsequently and immediately thereafter dynamically adjust the depth of the shear if that depth is deviating from a predetermined and desired depth of sowing, such as a “basis depth”.

Consequently, the inventive sowing apparatus provides for optimum quantity and quality of harvested crops. This is not at least the case when using the inventive sowing apparatus in soil having a varying texture or nature as to content, such as sand, clay, rocks, plant residues etc.
Fig. 3 illustrates the trigonometry involved in converting the angle \( \alpha \) between the frame 2 and the shear carrier 8 as outlined in fig. 2, to a sowing depth \( D \).

Fig. 3 illustrates a simplified way the frame part 2 of the sowing apparatus according to the first aspect of the present invention. The frame part 2 is oriented in a horizontal direction parallel to the longitudinal direction of the intended movement of the apparatus during use.

On the frame part 2 is in suspension 14 pivotally suspended the shear carrier 8 having the length \( L \) (between the pivot point 14 and the mounting point of the shear). The frame part 2 and its pivot point 14 is arranged at a height \( H \) above the surface of the ground.

The radius of the shear is \( R \), and the shear is at the angle \( \alpha \) between the frame 2 and the shear carrier 8 submerged the distance \( D \) into the soil.

One easily deduces that:

\[
\begin{align*}
    h &= L \times \sin(\alpha); \text{ and} \\
    h + R &= H + D;
\end{align*}
\]

which gives the correlation:

\[
D = L \times \sin(\alpha) + R - H;
\]

\( h \) being the vertical distance from the pivot point of the shear carrier to the mounting point of the shear.

Accordingly, knowing the radius \( R \) of the shear 16; the effective length \( L \) of the shear carrier 8; the height \( H \) above ground of the frame part 2 (or its pivot point 14); and the measured or sensed angle \( \alpha \), allow one to calculate the sowing depth \( D \).

These parameters may accordingly be useful in programming or setting the control unit 26 in order to obtain an optimum sowing depth.

In fig. 1, 2 and 3, the shear is depicted as a disc-type shear. However, any other type of conventional and/or traditional shear may be used with the sowing apparatus according to the first aspect of the present invention.
Above only a few embodiments of the invention have been described, however, it can easily be envisaged that several other embodiments are possible within the scope of the invention as defined in the claims.
<table>
<thead>
<tr>
<th>Reference Numeral</th>
<th>Description</th>
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<tbody>
<tr>
<td>2</td>
<td>Frame of sowing apparatus</td>
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<tr>
<td>4</td>
<td>Front end of frame</td>
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<tr>
<td>6</td>
<td>Rear end of frame</td>
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<tr>
<td>5 8</td>
<td>Shear carrier</td>
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<tr>
<td>10 18</td>
<td>Soil</td>
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<td>20 21 22 24 26</td>
<td>Seed conveying means</td>
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<td>Tube or pipe</td>
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<tr>
<td></td>
<td>Sensor</td>
</tr>
<tr>
<td></td>
<td>Actuator</td>
</tr>
<tr>
<td>15 28</td>
<td>Control unit</td>
</tr>
<tr>
<td>30 32 34 36 40</td>
<td>Outlet opening of tube or pipe</td>
</tr>
<tr>
<td></td>
<td>Rear part of shear</td>
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<td></td>
<td>Seed dispensing device</td>
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<td>Wheel or carrier roller of sowing apparatus</td>
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<td>Integrated sensor/actuator</td>
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<td>Input device</td>
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17
Vertical distance from pivot point of shear carrier to the mounting point of shear.

Height above ground of pivotally suspension of shear carrier

Radius of shear

Effective length L of shear carrier

Depth of shear furrow

Sensed angle between shear carrier and frame part

Sowing apparatus according to the present invention

Prior art sowing apparatus

Spring

Spring tensioner
Claims

1. A sowing apparatus (100), said sowing apparatus comprises:
a frame (2) comprising a front end (4) and a rear end (6), as seen in relation of the intended
direction of movement; said intended direction of movement defining a longitudinal direction
(X) of the apparatus; wherein said frame is having an extension in a transverse direction (Y),
said transverse direction being perpendicular to the longitudinal direction (X).

wherein said frame comprising one or more shear carriers (8), said shear carriers each having
a first end (10) and a second end (12);

wherein said one or more shear carriers (8) at its first end being pivotally suspended onto said
frame in a suspension (14);

wherein said shear carrier at its second end (12) comprising one or more shears (16) adapted
to be at least partially submerged into the soil (18);

wherein in respect of one or more of said one or more shear carriers (8), said frame
comprising seed conveying means (20) for conveying seeds into the soil at a position

 correponding to one or more of said one or more shears;

wherein in respect of one or more of said one or more shear carriers (8), said apparatus
comprises a sensor (22) for detecting the position of said shear carrier in relation to the frame;
said sensor (22) being configured to provide an output signal representing a sensed position of
said shear carrier (8);

wherein in respect of one or more of said one or more shear carriers said apparatus comprises
an actuator (24) for altering the position of the shear carrier in relation to the frame;

wherein said apparatus comprises a control unit configured to receive said output signal from
said sensor;

wherein said control unit is configured to provide an output signal for controlling said
actuator;

wherein said control unit is connected to an input device (40), said input device being
configured to allow an operator to provide said control unit with instruction relating to the
desired response of the actuator, based the input signal of said sensor.
2. A sowing apparatus according to claim 1, wherein in respect of one or more of said one or more shear carriers (8), said seed conveying means (20) for conveying seeds into the soil at a position corresponding to one or more of said one or more shears comprises a tube or pipe (21) having an extension in a vertical direction from an inlet opening (28) thereof to an outlet opening (30) thereof, said outlet opening (30) being arranged below said inlet opening (28).

3. A sowing apparatus according to claim 1 or 2, wherein in respect of one or more of said one or more shear carriers (8) said seed conveying means (20) for conveying seeds into the soil at a position corresponding to one or more of said one or more shears are configured to conveying seeds into the soil at a position corresponding a rear part (32) of one or more of said one or more shears

4. A sowing apparatus according to any of the claims 1 - 3, wherein in respect of one or more of said one or more shear carriers (8) said seed conveying means (20) for conveying seeds into the soil at a position corresponding to one or more of said one or more shears is connected to a seed dispensing device for dispensing seeds at a predetermined intervals.

5. A sowing apparatus according to any of the claims 1 – 4, wherein said frame (2) comprises one or more wheels or carrier rollers (36) for providing support for said frame when towing the apparatus.

6. A sowing apparatus according to any of the claims 1 – 5, wherein said sensor (22) and said actuator (24) is an integrated unit.

7. A sowing apparatus according to any of the claims 1 – 6, wherein said control unit is configured to receive instructions relating to a desired basis-depth of sowing, thus corresponding to a desired basis-position of the actuator relative to the frame.

8. A sowing apparatus according to any of the claims 1 – 7, wherein said sensor (22) being a sensor configured to sense a translational displacement; or wherein said sensor being a sensor configured to sense an angular displacement.

9. A sowing apparatus according to any of the claims 1 – 8, wherein the number of shear carriers (8) is 5 – 180 or more, such as 10 – 175, e.g. 15 – 170, such as 20 – 165, e.g. 25 – 160, such as 30 – 155, e.g. 35 – 150, such as 40 – 145, such as 45 – 140, for example 50 – 135 or 55 – 130, such as 60 – 125, e.g. 65 – 120, such as 70 – 115, e.g. 75 – 110, for example 80 – 105, such as 85 – 100, such as 90 – 95.
10. A sowing apparatus according to any of the claims 1 – 9, wherein in respect of one or more of said one or more shear carriers (8) said shear carrier comprises one, two or three or more shears.

11. A sowing apparatus according to any of the claims 1 – 10, wherein said sowing apparatus being configured to be towed behind a tractor or the like; or wherein said sowing apparatus being a self-propelled sowing apparatus.

12. A sowing apparatus according to any of the claims 1 – 11, wherein in respect of one or more of said one or more shear carriers said apparatus comprises a spring, such as a pressure spring; said spring being suspended in serial configuration in relation to said actuator (24).

13. A sowing apparatus according to any of the claims 1 – 12, wherein in respect of one or more of said one or more shear carriers, said one or more shears being a drill shear or a disc shear.

14. A sowing apparatus according to any of the claims 1 – 13, wherein said sowing apparatus does not comprise a sensor for remote sensing a distance.

15. A sowing apparatus according to any of the claims 1 – 14, wherein said sowing apparatus does not comprise an optical or sonic sensor.

16. A sowing apparatus according to any of the claims 1 – 15, wherein said sowing apparatus does not comprise an optical or sonic sensor for sensing a distance form said sensor to the surface of the ground.

17. A sowing apparatus according to any of the claims 1 – 16, wherein said sowing apparatus does not comprise an optical or sonic sensor, such as an ultrasound sensor or an infrared sensor.

18. A sowing apparatus according to any of the claims 1 – 17, wherein in respect of one or more of said one or more shear carriers, preferably all said shear carriers, said control unit is configured to dynamically regulating said output signal for controlling said actuator, solely in response to the output signal originating from said sensor (22).

19. A sowing apparatus according to claim 18, wherein in respect of one or more of said one or more shear carriers, preferably all said shear carriers, said control unit is configured to
dynamically regulating said output signal for controlling said actuator; without receiving input from any sensor as defined in any of the claims 14 – 17.

20. Use of a sowing apparatus (100) according to any of the claims 1 – 19, for sowing seeds.
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

INV. A01C7/20
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

A01C7 A01B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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A: document defining the general state of the art which is not considered to be of particular relevance
E: earlier application or patent but published on or after the international filing date
L: document which may throw doubts on priority claims or which is cited to establish the publication date of another invention or other special reason (as specified)
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**T** later document published after the international filing date or priority date and not in conflict with the application but used to understand the principle or theory underlying the invention

X: document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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Date of the actual completion of the international search

16 July 2015

Date of mailing of the international search report

24/07/2015

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Postfach 2
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Fax: (+31)-70 290-2016

Authorized officer

Oltra García, R

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7. Appendix / Paper V – Seed drill instrumentation for spatial coulter depth measurements
Seed drill instrumentation for spatial coulter depth measurements

Søren Kirkegaard Nielsen, Lars Juhl Munkholm, Mathieu Lamandé, Michael Norremark, Nick Skou-Nielsen, Gareth T.C. Edwards, Ole Green

Abstract

An even and correct depth placement of seeds is crucial for uniform crop germination and for obtaining the desired agricultural yield. On-state-of-the-art seed drills, the coulter down pressure is set manually by static springs or heavy weights, which entails that the coulter's seeding depth reacts to variations in soil resistance. The aim of the study was to develop and test an instrumentation concept installed on a low-cost, lightweight, three-meter wide, single-disc seed drill, for on-the-go measurements of spatial depth distributions of individual coulters under real field conditions. A field experiment was carried out to measure individual coulter depths at three different operational speeds. The targeted seeding depth was 0.5 cm, but shallower mean coulter depths were observed and the depth decreased slightly – although not significantly – with increasing speed, i.e., 0.4, 0.8, and 1.2 cm h⁻¹, respectively. The coulter depths ranged between 0.4 cm (below the surface) and 0.8 cm at all speeds, but the variation tended to decrease with decreasing speed. However, soil resistance influenced coulter depth as indicated by a significant block effect. The mean coulter depth varied up to 0.5 cm between the blocks. In addition, significant depth variations between the individual coulters were found. The mean depths varied between 0.4 and 0.8 cm for the six coulters. The mean shallower coulter depth (0.4 cm) was measured for the coulter running in the wheel track of the tractor. The power spectral density (distribution) of the coulter depth oscillation frequencies showed that the majority of oscillations occurred below 0.5 Hz without any natural vibration frequency. The study concluded that the instrumentation concept was functional for on-the-go spatial coulter depth measurements.

Keywords: Seed depth; Coulter depth sensors; Mapping; Operation speed; Spring barley.

1. Introduction

An even seed depth placement in the desired seedbed is crucial for the germination and even emergence of a crop (Henderson, 1989; Håkansson et al., 2002). The desired depth of seeding is at the bottom of a shallow loose soil layer and above a more compacted tilled or no-tilled layer (Chang et al., 2004; Håkansson et al., 2002). When preparing seedbeds, the tillage operation is chosen relative to the soil condition. Seedbed structure should be homogeneous, supporting an adequate combination of moisture and heat for optimal seed germination and emergence (Håkansson et al., 2002). An optimal seedbed is also expected to minimize evaporation, erosion and reduce the risk of pesticide leaching (Petersen et al., 2016). However, it has been shown that the risk of poor emergence depends more on the seeding depth than on the aggregate size and distribution in the seedbed (Håkansson et al., 2002). The sensitivity to suboptimal seeding depth differs between crop species. Small seeds with low energy content germinate faster, but tend to be more sensitive to depth variations (Håkansson et al., 2011). For instance, yellow clover yielded 87% germination success at 20 mm seeding depth but only 48% germination at 40 mm seeding depth (Ghadiri-Far et al., 2016). Seeding depth has generally a significant impact on the germination rate and emergence delay (Baskin and Baskin, 1988; Håkansson et al., 2011). Håkansson et al. (2011) showed that the period of delay for 50% barley emergence increased almost linearly with increasing seeding depth, within the range of 1 to 30 mm seeding depth at 20°C. The final emergence percentages were variable, at approximately 85, 100 and 95% for 10, 20 and 30 mm seeding depths, respectively. Another study showed...
that wheat emergence varied linearly as a parabola with the seeding depth, with an 80% emergence for 55 mm depth, decreasing to 70% when the depth was changed to 35 or 80 mm (Kinner et al., 1993). Any delay or reduction in emergence can have considerable negative effects on competitiveness against weeds, on plant development, and subsequently on the final crop yield. Therefore it is crucial to seed uniformly at the targeted depth (Boiffin et al., 1992; Depenthal, 2008; Håkansson et al., 2002; Kinner et al., 1993).

Achieving an uniform seed placement at the desired depth can be a challenging task for seed drills, due to variations in soil resistance affecting the coulter depth, which potentially results in considerable seeding depth variations (Brennan and Augs 2014; Garrido et al., 2011; Kinner et al., 1993). The coulter down pressure is determined manually at the beginning of the operation by adjusting the coulter spring’s tension. The spring adjustment is based on the operator experience (Kinner et al., 1993) and the producer’s recommendations, potentially evaluated according by carrying out random checks during initial test drives in the field. This means that the setting of the working depth depends primarily on the operator, which potentially causes errors. Furthermore, effects of spatial variations of soil resistance and operational speed on the coulter are not taken into account. Variations in soil penetration resistance depend on different factors such as texture, water content, bulk density (Dexter et al., 2007; Elaouet et al., 2014), but the soil resistance acting on the coulter is primarily affected by the tillage intensity before seeding and the applied soil compaction from the tractor wheels. Soil-coulter interaction varies with soil resistance composition and the operational speed. Multiple mechanical coulter designs are available to comply with the coulter depth variations. Some of these seeding methods have been compared by Herve (1993) and all tend to vary with respect to depth uniformity. The most common low-cost seed drill constructions are glide shoes, single or double-disc coulters, without pressure wheels. To our knowledge, none of the available seed drills are able to measure individual coulter depths.

Few studies have been published on electronic seeding depth control for arable crops. Weatherly and Bowes (1997) developed a hydraulically actuated seeding depth control system that planted the seeds based on the measured soil moisture conditions. The seeding depth was dynamically controlled based on a soil drying front sensor combined with monitoring, as moisture is considered significant for reliable germination. Conventional seedbeds are generated to a fixed depth, with the seed usually placed at the bottom of the seedbed (Håkansson et al., 2002). However, individual coulter depth measurements were not a part of the study. Recently, Saeidi and Glejeren (2015) developed a seed drill for depth control. The seed drill was with single disc, where each coulter had a wedge roller attached to the side and a common roller (12 rubber wheels) for compacting and levelling the soil. The system used multiple sensors, the surface was measured with two ultrasonic sensors combined with angle measurements of two installed soil gauge wheels running on the surface. Rotary sensors were used to measure the angle of three coulters. The system was able to maintain the desired depth within a tolerance of ±10 mm at 10 km h⁻¹.

Nielsen et al. (2016) developed a novel coulter depth sensing and control system, which was tested for one coulter in a soil box. The system measured the coulter position and controlled the coulter pressure with a hydraulic system. However, the sensing system needed additional development to be implemented on a full-scale seed drill operating in a real seedbed, where the seed drill lateral frame height can be unstable and the entire machine operates dynamically.

The aim of the present study was to evaluate the performance of the novel coulter depth measurement system developed by Nielsen et al. (2016) after further development and implementa-

The experimental setup consisted of a three meter Ecoline Kongskilde single disc seed drill (DK), modified with a sensing system to measure the individual coulter depths (Fig. 1).

For sensing the coulters' positions, linear position sensors were installed on every second coulter with 250 mm lateral distance of the three meter wide seed drill (i.e. eleven in total). The essential instrumentation is shown in a computer-aided design (CAD) drawing in Fig. 2 and in a front view picture of the seed drill in Fig. 3. The linear position sensors (“TX2” from Novotechnik, U.S., 1967, resolution at 0.01 mm and linearity up to 0.03%) measured the coulters’ positions in relation to the machine traverse frame (Figs. 2 and 3, 0). Two ultrasonic distance sensors (“VUS3” from PI. Sensors, IP65, D6, linearity error < 0.5%) were installed perpendicular to the traverse frame of the seed drill, in front of coulter 4 and 8, to measure the vertical frame height, relative to the soil surface (Figs. 2 and 3, 0). From these height measurements, the soil surface was dynamically estimated using linear interpolation between the sensors. As the machine was 3 m wide, two ultrasonic sensors were considered sufficient for prediction of the soil surface; however, additional sensors will include additional micro topography. By dynamically combining this height with the coulter position measurements, the system was able to include frame height variations, caused by variation in the wheel penetration of the seed drill. This variation could be caused by a change in soil resistance or a change in machine weight (i.e. seed quantity in the seed drill varies across the field).

For data processing and data logging a “B&R 920” controller was used (B&R Industrial Automation, AT, 12 bit A/D converter) with a flash memory, installed in a control box (Fig. 3, 3). The system was programmed to measure individually coulter depths and log the measurements with a frequency of 100 Hz. The controller was also connected to a GNSS unit (“RT-Q1000XT”, Qstarz, TW) to record the global position and log it with the coulter depth measurements. To study the impact of the wheel tracks from the tractor

Fig. 1. Experimental seed drill from Kongskilde modified with the coulter depth measurement system.
an coulter depth, wheel track radicarators (s-time) were installed in one side of the seed drill in front of coulter 10 (Fig. 3, O).

2.2. Sensor calibration and measurement accuracy

Static tests were carried out to analyse the similarity between the coulter position sensors. First, sensor voltage output was measured for two fixed positions and the coulter position sensor was manually measured using a vernier caliper. The coefficients describing the correlation of voltage per stroke length change of the individual sensors were calculated to vary from 0.453 to 0.462 V mm⁻¹ with a standard deviation at 0.0023 V mm⁻¹. This corresponded to an inter-couler variation of less than 1.9%. The difference was caused by small variations in sensor installation, machine construction, length of cables (voltage drop) and infinitesimal uncertainties in the reference length measuring equipment (vernier caliper). The linear position sensor was calibrated after installed on the seed drill, by correlating the measured coulter positions in the controller to the estimated seeding depth of the coulter. The calibrations were conducted by elevating the coulter depth in the interval from -85 mm to the theoretical soil surface, using regression. To comply with the small variations between the coulters, individually coulter biases were detected and taken account of in the software to ensure similarity in the coulter depth measurements. The impact of the sensor 0.05% non-linearity was recalculated to the coulters' kinematic coulter depth error and calculated to be smaller than ±0.55 mm.

Finally, the accumulated uncertainty for the individual coulter depth measurement system was tested in the range from -65 mm below the surface to 15 mm above the surface in a static validation experiment, ensuring the functionality of the sensors, wires and algorithms. These tests were conducted by manually elevating each coulter similar and then compare such coulter calculated coulter depth, to the actual measured coulter depth. The validation experiment concluded that the individual coulter depth measurements all operated within ±3 mm inaccuracy.

The ultrasonic sensors were chosen due to their robustness in irregular soil surface detection and soil particle sensitivity. Different studies have tested sensors in field environments, e.g. optical sensors (Lee et al., 1996) and ultrasonic sensors (Kiani, 2012; Wen et al., 2014), but the sensors' sensitivity to dust or aggregates in the field of view has not been determined in the studies. A complex, accurate, but less robust, method would be a 2D laser range surface scanner, which has been studied for detecting ploughing surface (Jensen et al., 2015). However, the cost, computation and especially the light beam are expected to be sensitive to dust and aggregates, which can create challenges in the detection of the soil surface in dry conditions during field operations. The ultrasonic height sensors were installed, tested and calibrated individually on the machine. The sensor non-linearity (±0.5%) was tested on the machine and found to be within ±1 mm uncertainty. Dust and soil aggregates in the field of view were not considered a problem, after initial experiments were conducted, involving soil dust and throwing soil aggregates through the sensor's field of view. Dust with low-density of aggregates (approximately 10 mm; diameter 0–25 mm) did not affect the measurements. Multiple tests showed that higher densities or greater aggregate sizes only slightly affected the measured distance. In addition, another study showed that a ultrasonic sensor can, to some extent, detect surface in spite of irregularity due to tillage, plant residue and stumbles (Kiani, 2012). The ultrasonic sensors were considered well suited to soil surface detection even though the environment includes; irregular surface, dust and aggregates in the sensor field of view.

2.3. Field experiment

The field experiment was conducted in Toekrump, Denmark, on 11 April 2016. The soil was a sandy loam. The topsoil texture of the field was determined to be relatively homogeneous based on 13 composite samples taken in the field. The soil organic matter content was determined to be 2.9 g 100 g⁻¹ (50 ± 0.5) and clay, silt and sand contents were 12.1 (50 ± 2.2), 16.7 (50 ± 2.3) and 68.4 g 100 g⁻¹ (50 ± 2.6), respectively. In addition, the field was measured in 2013 by the EM38 (Electromagnetic method) and the map was also compared with the seed drill coulter depth measurements. The field was relatively flat with a difference in elevation of 4 m across the 5.7 ha field. The mean gravimetric water content in the seedbed was 14.6 kg 100 kg⁻¹ at the time of seeding. Spring barley (Hordeum vulgare L.) was grown as it is a dominant cereal crop in Denmark. The experiment was organized as a randomized block experiment with six replicates (Fig. 4). Each strip trial was 3 m wide and 350 m long. In each trial eleven individual coulter sensors on the Kongsliide Ecoline seed drill obtained measurements with the lateral distance of 250 mm. The tested operational speeds were 4, 8 and 12 km h⁻¹ in each block (Fig. 4). A speed of between 5 and 8 km h⁻¹ is recommended for the Kongsliide Ecoline seed drill, but even higher speeds are often used in practice. Therefore, 8 km h⁻¹ was chosen and compared with the speeds outside the conventional range at 4 and 12 km h⁻¹, to test how the speeds impacted the coulter depths.

The tractor used for the experiment was a Fendt 710 with a front wheel load of 1550 kg and a rear wheel load of 2050 kg.
The front tyres were a size 600/60R28 and the rear tyres were 710/60R38. The load rated inflation pressure was adjusted to the required 40 kPa for all tyres to ensure a minimum impact from the wheel tracks. The tyre size on the seed drill was 7.00-12, loaded with 450 kg (±150 kg, depending on the seed quantity), and an inflation pressure of 120 kPa was used, as recommended for a constant loaded radius independent of variable seed quantity. The seedling dose rate was set to 155 kg ha⁻¹ which was verified by three repetitions. This corresponds to 200 seeds m⁻² at 95% emergence. Based on the soil and weather conditions at seeding, a seeding depth target of -30 mm was selected. Before starting the experiment, the farmer manually adjusted the coulter down pressure, based on his experience and observations from the actual seeding depth in the soil. After the conventional procedure for adjusting the coulter pressure, additional seed depth check samples were used to calibrate the coulter depth measurement system to the actual seeding depth to ensure the accuracy complying with the seed placement from the soil-coultor interaction.

2.4. Discrete Fourier transform of the coulter depth variations

The measured coulter depth data was analysed to find the frequency composition of the individual coulter depth variations. This analysis was done to search for dominating and normal frequencies for the different speeds and to test the variation between the coulters lateral placement on the machine. When analysing the data, normal and dominating frequencies are important to be considered, especially regarding signal filtration i.e. if a subsequently dynamic control should be developed. The computing of the discrete Fourier transform (DFT) was done in MatLab (Mathworks USA). The DFT of the data vector x of length N (Eq. (1)) was calculated accordingly (Eq. (6), Marchant, 2003).

$$X_{DFT}[k] = \sum_{n=0}^{N-1} x[n] \exp^{-\frac{2\pi i k n}{N}}$$

where i is the imaginary value. The variable [k] are the discrete frequency components of the data vector x. The variable, which is normalized to the sampling frequency fₛ, defined as fₛ = fₛ/N, k = 0, 1, ..., N. An additional explanation of the DFT function (Eq. (1)) with nomenclature can be found in Marchant (2003). To measure the power in each frequency component, the power spectral density (PSD) was calculated (Eq. (2)) according to Oprea (1999). The PSD was studied for all speeds, testing coulter 2, 8 and 10 which was in the wheel tracks, with and without track eactors and in between the wheel tracks (unaffected soil).

$$PSD(f[k]) = \frac{X_{DFT}[k]^2}{N}$$

To evaluate different combinations of coulters and speeds, the peaks values of each PSD function were compared, similar to Jeon et al. (2004).

2.5. Statistics

Less than 0.1% of the coulter depth measurements were regarded as outliers, and thus discarded from the dataset, as the measurements were 150 mm above the soil surface. Evaluation of the raw data was done by mean depth measurement subdivision to ensure valid data were obtained and to get an overview of the PSD function for the data before a more advanced and detailed data analysis. The differences in coulter depth according to the coulter's position, block, the operational speed and the effects of operational speed on each coulter (interaction Coulters x Speed) were tested at linear mixed model. Coulters, Speed, and their interaction were treated as fixed factors. Block, as well as the interaction effects between Block x Speed, Block x Coulters and Block x Speed x Coulters, were treated as random factors. Likelihood ratio tests were used to evaluate the significance of the fixed factors. Tukey's range test was used to group and compare coulter depths from A (deep) to E (narrow), as the method divide treatments into distinguishable groups with significant difference (Tukey, 1949). The data analysis and statistical calculations were carried out in R-studio (Rstudio, USA) and MatLab (Mathworks USA).

3. Results & discussion

3.1. Evaluation of coulter depth measurements

To create an overview of the data before presenting the statistical analysis, the mean depths of the eleven coulters were calculated. Henge (1993) found seed depth variations for drill seeding, with disc, shoe and packer-ring, to vary with a SD between 6 and 11 mm. In this study, a similar trend was found for single-disc drilling, but with greater coulter depth variations (SD from 16.5 to 18.0 mm). Table 1 presents the distribution of the mean coulter depth measurements in percentages for specific depth intervals at the three operational speeds. The magnitude of the coulter depth intervals tended to increase with speed (Table 1); however, this was not tested significant. Less than 25% of the mean coulter
depth was within ±5 mm from the targeted ~30 mm depth and the percentage decreased as increasing speeds (22.2, 20.7 and 19.0%, for 4, 8 and 12 km h⁻¹, respectively). The same trend of deviation was observed for ~60 to 0 mm interval (58.3, 88.5 and 85.5% for 4, 8 and 12 km h⁻¹, respectively). Therefore, a higher percentage of the mean coulter depth measurements closer to the targeted depth of ~30 mm were achieved when lowering the speed (Table 1).

Table 1: Mean coulter depth measurements at six depth intervals for the three operational speeds.

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Probability density functions (PDF) of the coulter depth measurements at the three operational speeds are shown in Fig. 5. The mean of the coulter depths tended to decrease slightly with increasing operational speed. The mean coulter depths between the speeds were ~22.1, ~20.9 and ~19.0 mm for a speed of 4, 8 and 12 km h⁻¹, respectively. This small increase in coulter depth means can be related to seedbed mechanical dynamic properties: deformation can occur at a given rate and increasing the operational speed will increasingly prevent coulter penetration. The differences between the PDF means comparing the speeds are therefore likely related to seedbed mechanical properties.

The targeted mean coulter depth of ~30 mm was not reached at any of the tested speeds (Fig. 5). Coulter depth larger than 0 mm indicated that the seeds were released above the soil surface, but might still be partially covered, due to the light post-seeding harrowing carried out by the seeder. The significance of the fixed terms in the mixed linear model: Coulter, Speed, and their interaction was tested using Likelihood ratio tests. Only the coulter position had significant effects on the coulter depth. According to this model analysis, operational speed had no significant effect on the coulter depth, which means all the coulters reacted approximately similarly to the increased operational speed. Taking speed as a continuous variable in the mixed linear model, a decrease of mean coulter depth by ~1.5 mm for an of 4 km h⁻¹ speed increment was found, although this was not tested significant.

The random effect factors could not be eliminated by the likelihood ratio test and a significant random block effect on coulter depth was found (P < 0.0001). The model residuals of the whole measuring system describing the variance of the coulter depth can be represented by the standard deviation (SD ≈ 15.7 mm). The SD from the model representing the random effect, Block: Speed:Coulter, was found to be ~2.6 mm (block effect for the individual coulter depth means in one trial compared to the modelled mean). The mean coulter depth for all coulter positions differed significantly between trials, with a SD of 5.1 mm, as determined by the random effect block: Speed (block effect for the individual trials depth means compared to the modelled mean).

Fig. 5. Probability density functions of the coulter depth measurements at three operational speeds. The desired depth was ~30 mm and the lines represent the means of the functions.
variation within the operational width of the machine has been found in the literature.

Coulter 10 was seeding in the loosened wheel track, which was the case for coulter 2. Shallow coulter depth in wheel tracks can be mitigated by the use of track radicators, as shown in this study, although it is important to avoid too intensive a loosening and thus risking a deeper coulter depth compared to the remaining coulters (Fig. 7). This finding shows the importance of seeding in well with an even seedbed structure, i.e., by uniform prepared seedbed and correct setting of track radicators or using a common front roller to evenly compact soil in the operational width. Alternatively, individually coulter pressure adjustment for the coulters running in the wheel tracks can be considered installed.

The effect of eliminating one to ten coulter sensors was determined by calculating the variation in the mean coulter depth of all the sensors and comparing the sensors to the mean of subgroups of sensors. To find the best subgroups of the sensors a brute force search method was performed with minimum variance in coulter depth as statement (Table 2).

When only using coulter sensors 3 and 9, the data can be explained with SD = 5.5 mm, which roughly describes the consistent trend of the coulter depth. However, wheel tracks are not included in the measurement and as expected, the variance decreased in general with increasing number of sensors (Table 2).

3.2. Power spectral densities of the coulter depth variations

Traces of the power spectral densities (PSD) for the coulter depth at the three tested operational speeds 4, 8 and 12 km h⁻¹ were analyzed from the raw sensor data for coulters 2, 6 and 10. The only other PSD analysis of coulter depths variations found in the literature was by Nielsen et al. (2016).

An illustrative example of the recorded coulter depth measurements for the coulter 2, at 8 km h⁻¹, with corresponding PSD is shown in Fig. 8. The coulter depths in time domain illustrate the data of the coulter depth for a full field trial, corresponding to 180 m (160 s). The PSD example shows that the majority of coulter depth variations were with low frequencies (peaks marked with circles, Fig. 8); however, this is only one example out of the 9 analyzed combinations of coulters versus speeds. To evaluate the remaining combinations of coulters versus speeds, a function was applied extracting the 15 greatest peaks values of each PSD function and plotting the values in one common graph (Fig. 9). These values represent the majority of the power magnitude (peaks) with their respective frequency, similar to Jeon et al. (2004). By this method the evaluation included and represents the 9 combinations of all the different speeds and coulters 2, 6 and 10.

The majority of coulter depth variation frequency band was from 0 to approximately 0.5 Hz, independent of speed (Fig. 9), similar to Nielsen et al. (2016). Some coulter depths oscillations with frequencies greater than 0.5 Hz was also observed; however, only with low power spectral density (Fig. 9). The frequency band of coulter depth oscillations increased slightly with increasing operational speed, however, without any considerable power magnitude. No clear natural frequencies were identified by the discrete Fourier transformations of the different coulter depth measurements.

Coulter 2 (in the wheel track) and coulter 6 (between the wheel tracks) showed approximately similar power spectral density of coulter depth oscillations. On the other hand, coulter 10 (in the wheel track with track radicators) oscillated with significantly less power magnitude for all operational speeds and was therefore the steadiest coulter (Fig. 9). No peaks with great power magnitude were observed and the majority was in the low frequency band (<0.5 Hz), but a few were also found up to 3 Hz (Fig. 9). This means that the track radicators had a damping influence on coulter depth vibrations.

Therefore, the majority of coulter vibrations were with a low frequency (<0.5 Hz) and a low pass filter can be considered if the measurement system subsequently should be used to provide an input signal for a dynamic coulter pressure control system.

3.3. Perspectives in the utilization of the instrumentation concept

In this study a generic high resolution coulter depth measurement system was developed for field application. Multiple
checks samples of seed depth in the field were used to calibrate the couler depth measurement system for the specific soil-couler interaction when placing the seed. Additional studies are needed to examine the relationship between couler depth and actual seeding depth for a range of couler designs at different soil conditions. However, the present couler depth measurement system was found to be functional with the initial seed placement calibration and can be utilized in a number of applications:

1. The system can be used for on-the-go monitoring of individually couler depth variations within the operational width and it can measure consistent couler depth variation, due to field variations. Such a system can be used to provide information for manual adjustment of the couler pressure while seeding in specific areas of the field, with variable seedbed conditions. The information on the variation between the coulers can be used to evaluate the influence of wheel tracks or performance of track eradicators. In addition, it can be used to monitor whether obstacles like stones and crop residues accumulate on the coulers and disturb the performance of the individual coulers.

2. If the seeding operation is carried out at a constant speed, a full field map of couler-soil resistance measured by couler depths can be generated, similar to other known field or soil mapping instruments (Godwin and Miller, 2003). Couler-soil resistance affecting the couler depth is comparable to other on-the-go soil measurement methods, e.g., vertical and horizontal penetration resistance (Garrido et al., 2011; Naderi-Boldaji et al., 2016). A couler depth map could subsequently be related to historical management information, which could be used for establishing site-specific management, e.g., choice of crop species, drainage modification, choice of field operations, or tillage operations targeting more homogeneous seedbed conditions.

3. Finally, the studied instrumentation concept can create the input signal for a full-scale dynamic couler pressure control system. Such a system should be able to operate site-specific and control the couler pressure, regarding variable seedbed condition. This could be based on previously generated couler depth maps from the previous operation or by using the dynamic on-the-go couler depth measurements signal. Such a control system should dynamically adjust the couler pressure and maintain the desired couler depth independent of variation in soil mechanical properties.
4. Conclusion

The low-cost seed drill was modified as a novel instrumentation concept and it was found functional for high-resolution on-the-go measurements of the individual cotter depth. The targeted mean cotter depth was not achieved at any of the tested speeds, as the cotter pressure manually was determined by the operator. The cotter depth varied between -60 mm to above soil surface and tended to decrease with increasing speed, although the effect was not found significant. The shallowest mean cotter depth (-14.2 mm) was measured for the cotter operating in the wheel track of the tractor. The largest mean depth (-25.0 mm) was measured for the cotter operating in the loosened wheel track. A block effect was found significant and the mean cotter depths varied by up to ±5 mm between the blocks, which likely was caused by differences in soil mechanical properties. The power spectral densities of the cotter depth oscillation frequencies showed that the majority of oscillations occurred below 0.5 Hz without any natural vibration frequency. The cotter depth measurement system can be used for mapping or on-the-go monitoring of the individual cotter depths. The system can be used for manual optimisation of the seeding operator, e.g. observing penetration, performance of track stabilisers or adjustment of the cotter pressure. Full potential of the studied cotter depth measurement system is expected when it is combined with an automatic cotter pressure control system to maintain the desired cotter depth.

Acknowledgement

We would like to thank Svend and Robert N. Poulsen for Spectrally for their help in carrying out the experiment. In addition, Peter Stroegaard Nielsen from Aarhus University and Thomas Schmidt from Simno have provided support in modifying the seed drill. A special acknowledgement should go to my colleagues from Agro science for their support, throughout the entire study. The work was financially supported by Innovation Fund Denmark through the project “Future Cropping”.

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Nadell, S, Sestig, B, Keller, M, 2010. Predicting the relative density then on the go is horizontal plot measurements at some available top soils in Northern Switzerland. Soil Tillage Res 105, 23-32.
8. Appendix / Patent E – A system for variable loosening of soil being compressed by a tractor’s wheels
**Patentansøgning**

Mottaget: 17-08-2017, 15:35:01 - Løbenc: 2192822
Betalingskort: Betalingskort (47448379)

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A system for controlling soil compaction caused by wheels

Field of the invention

The present invention in general relates to improvement in the field of agriculture.

More specifically, the present invention in a first aspect relates to a system for soil loosening of soil which has been compacted by wheels of an agricultural vehicle or an agricultural implement.

In a second aspect the present invention relates to an agricultural vehicle comprising such a system.

In a third aspect the present invention relates to an agricultural implement comprising a system according to the first aspect of the invention.

In a fourth aspect the present invention relates to the use of a system of the first aspect of the present invention or of an agricultural vehicle according to the second aspect of the present invention, or of an agricultural implement according to the third aspect of the invention for avoiding uneven crop growth between crops being or to be sown in and outside a wheel track, respectively.

Background of the invention

In order to prepare an agricultural field for sowing crop seeds a number of conditioning steps need to be performed so that optimum crop growth can be assured. These steps involve inter alia ploughing, and other types of seedbed preparations.

Such conditioning steps performed prior to the step of sowing the seeds, and the sowing operation itself are usually performed with the help of an implement configured to perform the intended purpose and these implements are usually being towed or carried by an agricultural vehicle, such as a tractor.

Upon driving a tractor on an agricultural field the areas of soil which have been subjected to the weight of the wheels, especially the rear wheels of the tractor will encounter a not insignificant degree of compaction in the soil.

If soil is being too compact an optimum growth of seeds may be prevented.

In order to alleviate this problem it is customary in harrowing and in sowing operations to provide for loosening the soil which has been just driven over by wheels of an agricultural vehicle or implement.

Accordingly, in prior art systems a soil loosening implement is provided behind the tractor. Such an implement comprises in respect of each rear wheel a group of tines or the like which
are configured to interact with the soil in the specific wheel track so as to loosening the soil of the track which has just been compacted by being overdriven by that wheel.

Each group of tines may be adjusted with respect to working depth. However, once set for a specific working depth, each group of tines is fixed and the working depth cannot be altered dynamically during operation of the vehicle.

In order to provide optimum growth of crops it is important that each crop seed to be sown is provided with equal growth condition. Especially, in the early stages of growth the crop seedlings will encounter a competition with neighboring seedlings in relation to access of a sufficient amount of water, sunlight and nutrients. Once a specific crop seedling has lost this competition caused by stronger growth of the neighboring seedlings, that specific crop seedling is likely not to be able to overcome this early growth suppression. The result will be that seedlings growing in soil which has been subjected to compaction by a wheel of an agricultural implement will encounter non-optimum growth conditions compared to seedlings growing in neighboring soil which has not encountered this type of compaction.

Even though the prior art soil loosening systems provide for soil loosening in wheel tracks which have encountered soil compaction, the prior art soil loosening systems suffer from certain disadvantages.

One of these disadvantages of the prior art soil loosening systems is that in case the field to be worked comprises different types of soil it will happen that different degrees of soil compaction results when the tractor's wheel drive the soil. For this reason these different types of soil need different degrees of soil loosen in order to obtain an even soil compaction in the field. In case no differentiation is made as to degree of soil loosening in respect of different types of soil, the result is that soil compaction varies in different areas of the field. Such variations in soil compaction throughout the field imply different growth conditions for the crop seeds.

The same variations may result in case the speed of the tractor working the field varies; a relative slow speed is expected to result in a relative high degree of soil compaction, whereas a relative high speed is expected to result in a relative low degree of soil compaction.

Degree of tire pressure and choice of type of tire will also affect the degree of soil compaction. A non-optimum choice of type of tire and/or tire pressure will lead to excessive soil compaction.

Furthermore, variations in degree of soil compaction will be encountered when an agricultural vehicle or implement substantially alters its weight during work, such as during a sowing operation or a fertilizing operation or a harvesting operation.

Accordingly, there exists a need for an improved track loosening system which to a higher degree will ensure a more homogeneous soil compaction of a field to be harrowed or sown by crop seed.
It is an objective of the present invention to provide systems, vehicles, implements and uses which meet this need.

Brief description of the invention

This objective is fulfilled with the present invention in its various aspects.

Accordingly, the present invention in its first aspect relates to a system for soil loosening of soil which has become compacted by wheels of an agricultural vehicle or an agricultural implement, said system comprises:

- one or more soil loosening devices for loosening soil in a wheel track;

- in respect of each soil loosening device, a sensing system which is configured for sensing a height difference between soil located in said wheel track and soil located outside said wheel track;

- a control unit;

wherein each of said one or more soil loosening devices comprises one or more soil loosening elements for loosening soil is said wheel track, and wherein each of said one or more soil loosening elements is/are mechanically connected to adjustment means for adjusting the degree of soil loosening provided by said one or more soil loosening elements;

wherein said sensing system being configured to provide one or more sensing signals representative of said sensed height difference of soil; and

wherein said control unit is configured to receive said one or more sensing signals provided by said sensing system and to provide a control signal on the basis thereof;

wherein said adjustment means is configured to receive said control signal, and on the basis thereof to adjust the degree of soil loosening of said one or more soil loosening elements of said one or more soil loosening devices.

The present invention relates in a second aspect to an agricultural vehicle comprising a system according to the first aspect.

In a third aspect the present invention relates to an agricultural implement comprising a system according to the first aspect of the present invention.

In a fourth aspect the present invention relates to the use of a soil loosening system according to the first aspect of the present invention, or of an agricultural vehicle according to according to the second aspect of the present invention, or of an agricultural implement according to the third aspect of the present invention during performance of an agricultural work operation in an agricultural field.
The present invention provides in its various aspects for reducing variance in soil compaction in a field to be sown by crop seeds, thereby avoiding uneven crop growth between crops being or to be sown in and outside a wheel track, respectively. This is due to the ability of the system to provide an even soil compaction of the soil, irrespective of whether the soil has been compacted by wheels or not, thereby also minimizing the potential of erosion of water, erosion of soil caused by the wind and reducing pesticide leaching potential.

Brief description of the figures

Fig. 1 is a side view diagrammatically illustrating the working mode of a prior art soil loosening system for an agricultural vehicle.

Fig. 2 is a side view diagrammatically illustrating the working mode of a soil loosening system for an agricultural vehicle according to the present invention.

Fig. 3 shows a diagram illustrating in more detail the various components of a soil loosening system according to the present invention and the mutual interactions between these components.

Fig. 4 is a top view illustrating possible positions of sensors, for use with the system of the invention, in relation to an agricultural implement.

Detailed description of the invention

The first aspect of the present invention

In the first aspect the present invention relates to a system for soil loosening of soil which has become compacted by wheels of an agricultural vehicle or an agricultural implement, said system comprises:

-one or more soil loosening devices for loosening soil in a wheel track;

-in respect of each soil loosening device, a sensing system which is configured for sensing a height difference between soil located in said wheel track and soil located outside said wheel track;

-a control unit;

wherein each of said one or more soil loosening devices comprises one or more soil loosening elements for loosening soil is said wheel track, and wherein each of said one or more soil loosening elements is/are mechanically connected to adjustment means for adjusting the degree of soil loosening provided by said one or more soil loosening elements;

wherein said sensing system being configured to provide one or more sensing signals representative of said sensed height difference of soil; and
wherein said control unit is configured to receive said one or more sensing signals provided by said sensing system and to provide a control signal on the basis thereof;

wherein said adjustment means is configured to receive said control signal, and on the basis thereof to adjust the degree of soil loosening of said one or more soil loosening elements of said one or more soil loosening devices.

The system according to the first aspect of the present invention is intended to be mounted on an agricultural vehicle or implement. The sensing system of the implement makes it possible to detect a soil compaction of soil imparted by wheels of that vehicle or the implement. Furthermore, on the basis of the sensed height differences, which are indicative of a soil compaction, the soil loosening device(s) with its soil loosening elements provides for loosening the soil that has been compacted by the wheels. Thereby the soil which has been compacted by the wheels of the vehicle or the implement is brought back to a condition in which the soil compaction is eliminated by the action of the soil loosening elements. With the system of the first aspect of the present invention, the degree of soil loosening may be adjusted to a degree which result in the same degree of compression as the surrounding soil which has not (immediately) been subjected to the compacting effect of the wheels of the vehicle or implement. This ultimately provides for a more even soil quality and hence an improved crop yield.

In the present description and in the appended claims the term “agricultural vehicle” shall be construed to mean a vehicle that is self-propelled.

In the present description and in the appended claims the term “agricultural implement” shall be construed to mean an implement which is not self-propelled.

In the present description and in the appended claims it shall be understood that the one or more soil loosening devices each are responsible for soil loosening of an individual wheel track created by one or more wheels of the vehicle or implement, such as a wheel track created by a carrying wheel of an implement or of a front wheel and a rear wheel of a tractor having the same lateral position.

By incorporating more soil loosening devices in the system it is thus possible to loose soil which has been compacted by more wheels of a tractor and/or an implement.

It should be noted though, that a common control unit may be used in respect of more than one soil loosening device. It should likewise be noted that a common control unit may be configured for receiving sensing signals from more than one sensing system corresponding to more than one soil loosening device.

In one embodiment of the system of the first aspect of the present invention said sensing system comprises one and only one sensor configured for sensing a height difference between soil located in said wheel track and soil located outside said wheel track.

This embodiment provides for a very simple set-up as only sensor is used.
In one embodiment of the system of the first aspect of the present invention said sensing system comprises two or more sensors, wherein one sensor is configured for sensing a height of soil located in said wheel track, and wherein an additional and optionally more sensors are configured for sensing a height of soil located outside said wheel track.

Hereby is ensured a more accurate determination of a height difference between soil located in a wheel track and soil located outside that wheel track.

In one embodiment of the system of the first aspect of the present invention said sensing system comprises a sensor which is configured for sensing a height of soil located in said wheel track before that soil is being subjected to soil loosening.

This embodiment allows a direct determination of soil compaction in that wheel track because the height of soil in that wheel track is measured before any soil loosening is performed.

In one embodiment of the system of the first aspect of the present invention said sensing system comprises a sensor which is configured for sensing a height of soil located in said wheel track after that soil is being subjected to soil loosening.

This embodiment allows a direct determination of the degree of soil loosening in the wheel track because the height of soil in that wheel track is measured after the soil loosening is performed.

In one embodiment of the system of the first aspect of the present invention said sensing system comprises a sensor which is configured for sensing a height of soil located in said wheel track before that soil is being subjected to soil loosening, and wherein said sensing system furthermore comprises a sensor which is configured for sensing a height of soil located in said wheel track after that soil is being subjected to soil loosening.

Hereby improved sensing is achieved. The one sensor may sense the degree of soil compaction immediately after the wheel track has been formed. On the basis of the measured height of the soil in this wheel track the control unit may send its feedback to the adjustment means. As a control the sensed height of soil located in said wheel track after that soil is being subjected to soil loosening is used. And on the basis of this sensed height an adjustment control signal may be sent to the adjustment means.

In one embodiment of the system of the first aspect of the present invention the number of soil loosening devices is 1 – 10, and being configured for soil loosening in a single or more wheel tracks, such as in the wheel tracks of one or both of the two rear wheels of an agricultural vehicle; or for soil loosening in the wheel tracks of four wheels of an agricultural vehicle; and/or for soil loosening in one or more wheel tracks of an agricultural implement being towed by an agricultural vehicle.

More soil loosening devices provides for being able to perform soil loosening in respect of more wheels on the vehicle and/or implement.
In one embodiment of the system of the first aspect of the present invention said soil loosening elements independently being tines or coulter blades.

These types of soil loosening elements provides for efficient soil loosening.

In one embodiment of the system of the first aspect of the present invention said and in respect of one or more of said soil loosening devices, the working width of said corresponding soil loosening elements independently being 20 – 200 cm, such as 30 – 180 cm, for example 40 – 170 cm, e.g. 50 – 160 cm, such as 60 – 150 cm, for example 70 – 140 cm, e.g. 80 – 130 cm, such as 90 – 120 cm or 100 – 110 cm.

Such working widths allow efficient soil loosening even in respect of the widest wheels used for agricultural implements and vehicles.

In one embodiment of the system of the first aspect of the present invention and in respect of one or more soil loosening devices, said adjustment means independently are configured to adjust the degree of soil loosening by altering the working depth of said one or more soil loosening elements; and/or by altering the angle of attack of said one or more soil loosening elements; and/or by altering a speed of movement of said one or more soil loosening elements, in a case said soil loosening provided by said one or more soil loosening elements is provided by mechanically driven soil loosening elements, and/or by movement of said one or more soil loosening elements by means of parallelogramic suspension means.

These types and directions of movements of the soil loosening elements provide for efficient soil loosening.

In one embodiment of the system of the first aspect of the present invention said control unit is configured for providing said control signal to said adjustment means of said one or more soil loosening devices on the basis of said one or more sensing signals in accordance with a predetermined algorithm.

Defining a predetermined algorithm allow for efficient control of the soil loosening system, thereby optimizing the quality of soil loosening.

In one embodiment of the system of the first aspect of the present invention said predetermined algorithm is configured in such a way that said control unit is configured to provide a control signal to said adjustment means so as to increase the degree of soil loosening of said one or more soil loosening devices in case said sensing system is sensing a higher soil height at a location outside a wheel track compared to the soil height of soil loosened soil at a location in said wheel track.

In one embodiment of the system of the first aspect of the present invention said predetermined algorithm is configured in such a way that said control unit is configured to provide a control signal to said adjustment means so as to decrease the degree of soil loosening of said one or more soil loosening devices in case said sensing system is sensing a higher soil height of soil loosened soil at a location in said wheel track, compared to the soil height at a location outside said wheel track.
Such an algorithm provides for efficient soil loosening.

In one embodiment of the system of the first aspect of the present invention said predetermined algorithm is configured in such a way that said control unit is configured to provide a control signal to said adjustment means on the basis of a sensed height of soil plus/minus a predetermined offset value.

Incorporating an offset value makes it possible to aim at a soil loosening, in which the height of soil which has been loosened is higher than the soil outside the wheel track. This is an advantage as soil loosened soil typically will be less compact immediately after soil loosening, compared to the surrounding soil outside the wheel track and also compared to the degree of compaction of soil in said wheel track after some time has passed.

In one embodiment of the system of the first aspect of the present invention said adjustment means of said one or more soil loosening devices independently comprises one or more hydraulic actuators, one or more pneumatic actuators, or one or more electric actuators for adjustment of said degree of soil loosening.

These types of actuators provides for efficient and fast regulation of the degree of soil loosening of the soil loosening elements of the adjustment means.

In one embodiment of the system of the first aspect of the present invention and in respect of one or more of said soil loosening devices, said soil loosening device comprises two or more soil loosening elements which are configured to move in concert.

Hereby is achieved soil loosening in a wider width compared to the situation in which only one soil loosening element is used per soil loosening device.

In one embodiment of the system of the first aspect of the present invention and in respect of one or more of said soil loosening devices, said one or more soil loosening elements independently are configured for being moved by said adjustment means by rotation around a rotational axis, such as an essentially horizontal rotational axis.

In one embodiment of the system of the first aspect of the present invention and in respect of one or more of said soil loosening devices, said one or more soil loosening elements independently are configured for being moved by said adjustment means by movement in an essential vertical direction.

In one embodiment of the system of the first aspect of the present invention and in respect of one or more of said soil loosening devices, said one or more soil loosening elements are suspended in a parallelogrammic suspension, thereby allowing said soil loosening elements to be moved by said adjustment means by movement in a direction having a vertical component and a horizontal component.

These three different ways of adjusting the degree of soil loosening provides for efficient soil loosening.
In one embodiment of the system of the first aspect of the present invention and in respect of one or more of said soil loosening devices said sensing system is configured for providing said one or more sensing signals via mechanical sensing means.

In one embodiment of the system of the first aspect of the present invention said sensing system is comprising a sensing wheel which is pivotally suspended and configured to follow the surface of soil in said wheel track, and also comprising one or more additionally sensing wheels which is/are pivotally suspended and configured to follow the surface of soil located outside said wheel track, wherein the height difference between soil loosened soil located in said wheel track and soil located outside said wheel track is determined on the basis of the respective sensed heights of said two or more sensing wheels.

Hereby is ensured, in a simple and reliable way, the sensing of the height of soil.

In one embodiment of the system of the first aspect of the present invention and in respect of one or more of said soil loosening devices said sensing system is configured for providing said one or more sensing signals via non-mechanical sensing means.

In one embodiment of the system of the first aspect of the present invention said sensing system comprising one or more transmitters configured to transmit electromagnetic radiation, and comprising one or more receivers which is/are configured to receive a reflected signal of said transmitted electromagnetic radiation, and wherein the height difference between soil located in said wheel track and soil located outside said wheel track is determined on the basis of detection of time-of-flight, frequency, wavelength, intensity/amplitude of the electromagnetic radiation involved, or a combination thereof.

In one embodiment of the system of the first aspect of the present invention said non-mechanical sensing system comprises a laser sensing system, an infrared sensing system or a laser range scanning sensing system.

In one embodiment of the system of the first aspect of the present invention and in respect of one or more of said soil loosening devices said sensing system is configured for providing said one or more sensing signals via sonic sensing means.

In one embodiment of the system of the first aspect of the present invention said sensing system comprising one or more transmitters configured to transmit a sonic radiation; and comprising one or more receivers which is/are configured to receive a reflected sonic signal of said transmitted sonic radiation; and wherein the height difference between soil located in said wheel track and soil located outside said wheel track is determined on the basis of detection of time-of-flight, frequency, wavelength, intensity/amplitude of the sonic radiation involved, or a combination thereof.

These non-mechanical sensing means provides sensing mechanisms which are less prone to mechanical wear and tear.

In one embodiment of the system of the first aspect of the present invention said control unit is configured in such a way that both in respect of soil in said wheel track and in respect of
soil outside said wheel track, a number of measurement samples of soil heights are made; and
wherein said control unit is configured for subsequently averaging these samples of soil
heights in said wheel track on the one hand and also for averaging these samples of soil
heights outside said wheel track on the other hand, and wherein said control signal is based on
the difference of said averaged samples of soil heights.

In one embodiment of the system of the first aspect of the present invention said control unit
is configured in such a way that the measurement samples of soil heights independently is
performed at a sampling rate of 1 – 200 Hz, such as 5 – 150 Hz, for example 10 – 100 Hz,
such as 25 – 80 Hz, e.g. 30 – 60 Hz, and/or wherein said control unit is configured in such a
way that said control signal independently is provided at a rate of 0.1 – 10 Hz, such as 0.5 – 9
Hz, e.g. 1 – 8 Hz, such as 2 – 7 Hz, e.g. 3 – 6 Hz or 4 – 5 Hz.

Control of the soil loosening system according to averaging procedures provides for efficient
sensing and feedback and thus for efficient soil loosening of the soil loosening system.

In one embodiment of the system of the first aspect of the present invention said control unit
is configured to perform a filtering, such as a low-pass filtering, of the sensed heights or
height differences prior to providing said control signal.

Filtration provides for better and more accurate description of the soil surfaces, and finally an
improved soil loosening operation.

In one embodiment of the system of the first aspect of the present invention said control unit
is configured to provide said control signal by means of a P (Proportional) control, PID
(Proportional Integration Differentiation) control, three position control, or a step control.

These ways of providing feedback provides for efficient soil loosening of the soil loosening
system.

In one embodiment of the system of the first aspect of the present invention one or more
of said sensors configured for sensing a height of soil located outside a wheel track
independent is/are configured for being arranged, in relation to the direction of movement, in
front of said wheel, and/or in a lateral position in relation to said wheel and/or behind said
wheel, or a combination thereof.

These locations are suitable locations for arranging some of the sensors.

In one embodiment of the system of the first aspect of the present invention said system
further comprising one or more mounting brackets configured for carrying one or more of
said soil loosening devices, or parts thereof, and for being mounted on an agricultural vehicle
or implement.

In one embodiment of the system of the first aspect of the present invention said system
further comprising one or more mounting brackets configured for carrying said sensing
system, or parts thereof, and for being mounted on an agricultural vehicle or implement.
In one embodiment of these embodiments of the present invention said mounting bracket configured for carrying one or more of said soil loosening devices and said mounting bracket configured for carrying said sensing system are the same bracket or are different brackets.

Providing the system with brackets provides for easy mounting on a vehicle or implement and further provides for easy adjustment.

In one embodiment of the system of the first aspect of the present invention said system further comprising a monitor and/or input means, wherein said monitor is configured for being coupled to said control unit so as to display to a user the settings and/or information relating to the operation of said system; and wherein said input means, e.g. in a form of a keyboard, is configured for being coupled to said control unit so as enable setting up and/or calibration of said system; said monitor and/or said input means optionally being in the form of an HMI (Human-Machine Interface) or a GUI (Graphical User Interface).

Such means provides for easy control of the soil loosening system and monitoring of the operation thereof.

In one embodiment of the system of the first aspect of the present invention said system further comprises a GNSS (Global Navigation Satellite System) receiver for providing information of the location on the field of said agricultural vehicle or said agricultural implement.

In a particular embodiment said control unit is configured to receive information from said GNSS receiver and also is being configured to have stored therein, data relating to characteristics of the soil at different locations of a field.

Such embodiments enables varying the degree of soil loosening, depending on the different types of soil in various areas of the field, such as sandy areas, muddy areas, areas of clay soil.

In one embodiment of the system of the first aspect of the present invention said sensing system comprises one or more force transducers which are configured for sensing a horizontally oriented force of one or more of said soil loosening elements, such as a strain gauge, or in the form of one or more sensors for sensing a hydraulic pressure in a hydraulic actuator which is configured for suspending one or more of said one or more soil loosening elements.

This provides for a simple way of providing the sensing system of the system of the invention.

In one embodiment of the system of the first aspect of the present invention said system furthermore comprises one or more axle or wheel load sensors for sensing the load on one or more axles or wheels of said agricultural vehicle or agricultural implement,

wherein said control unit is configured for receiving a load sensing signal from said one or more axle or wheel load sensors, and
wherein said control unit is configured for providing said control signal to said adjustment means in a way wherein said control signal is depending on the load as sensed by said one or more load sensors, thereby allowing the severity of the soil loosening provided by said soil loosening devices to be dependent of the axle or wheel load of said agricultural vehicle or said agricultural implement.

Hereby is attained that in a situation where the axle load during field work is not constant, for example during harvesting or spreading operations, the severity of the soil loosening is made depending on the load of the wheels or axle of the agricultural vehicle or implement.

Thereby an even better soil loosening quality be obtained.

This embodiment is especially preferably in a case where the control unit is configured to provide a control signal to the adjustment means on the basis of a sensed height of soil plus/minus a predetermined offset value.

In general the system according to the first aspect of the present invention in all its embodiments is preferably configured for automatic operation. Thereby soil loosening to a desired extent may automatically be achieved.

The second aspect of the present invention

In a second aspect the present invention relates to an agricultural vehicle comprising a system according to the first aspect.

The third aspect of the present invention

In a third aspect the present invention relates to an agricultural implement comprising a system according to the first aspect of the present invention.

In one embodiment of the implement of the third aspect of the present invention said implement is a tilling implement, such as a harrowing implement or a sowing implement for sowing crop seeds.

In one embodiment of the implement of the third aspect of the present invention said implement is a sowing implement, and wherein said sensing system comprises two or more sensors wherein one or more of said two or more sensors are configured to sense the working depth of one or more coulters on a sowing machine submerged in soil located in said wheel track; and wherein one or more of said two or more sensors are configured to sense the working depth of one or more coulters on a sowing machine submerged in soil located outside said wheel track.

This embodiment utilized mechanics already in existence on a sowing machine for providing sensing signals.
In one embodiment said implement said implement is a sowing implement, and wherein said sensing system comprises two or more sensors wherein one or more of said two or more sensors are configured to sense the depth of one or more seed drills on said sowing implement submerged in soil located in said wheel track; and wherein one or more of said two or more sensors are configured to sense the working depth of one or more seed drills on said sowing implement submerged in soil located outside said wheel track.

The fourth aspect of the present invention

In a fourth aspect the present invention relates to the use of a soil loosening system according to the first aspect of the present invention, or of an agricultural vehicle according to according to the second aspect of the present invention, or of an agricultural implement according to the third aspect of the present invention during performance of an agricultural work operation in an agricultural field.

In one embodiment of the use of the fourth aspect of the present invention said use is for reducing uneven crop growth between crops being or to be sown in and outside a wheel track, respectively; for reducing erosion and/or for reducing dilution of pesticides.

Hereby improved crop yield may be obtained.

Referring now to the drawings for further illustration of the invention in its various aspects, Fig. 1 is a side view which diagrammatically illustrates the working mode of a prior art soil loosening system for an agricultural vehicle.

Fig. 1 shows an agricultural vehicle 200 in the form of a tractor which comprises the rear wheel 4. The tractor is moving in the direction of the movement as indicated by the arrow V.

Behind the tractor a soil loosening system is mounted on mounting bracket 450. The mounting bracket comprises a soil loosening element 422 which is pivotally suspended in on the bracket 450. A spring 402 having a predetermined spring load is connected between the bracket 450 and the soil loosening element 422.

The soil loosening element is arranged in a lateral position which corresponds to the lateral position of the rear wheel 4 of the tractor. For the sake of simplicity only one soil loosening element is depicted in Fig. 1. In a real agricultural operation, more soil loosening elements 422 arranged next to each other will be applied so as to cover essentially the full width of each rear wheel 4.

As the tractor moves over the soil 2 the rear wheel 4 carrying a huge weight will effect a compaction of the soil 18 thus resulting in compacted soil 13 in the wheel track 12. This is illustrated in Fig. 1 by the lower level of soil at location 13 compared to soil at location 18.

In the soil loosening system of the prior art the soil loosening element 422 will via the spring load be pressed into the soil at position 13 of the wheel track 12, thereby loosening the soil of
the wheel track. This is illustrated in fig. 1 by the higher level of soil at location 16 compared to soil of the wheel track 12 at location 13 before its soil loosening.

However, in the prior art soil loosening system there is no possibility for dynamically adjusting the degree of soil loosening in the wheel track while driving over the soil.

Thereby the soil loosening will be determined inter alia by the fixed height of mounting of the bracket 450 carrying the soil loosening element 422, the predetermined spring load of the spring 402 actuating the soil loosening element 422, by the nature of the soil and by the driving speed of the vehicle.

The lack of any dynamic control of the degree of soil loosening in the wheel track 12 ultimately leads to different degree of compaction and thus differences in growth conditions of crops to be grown in soil being present in a wheel track and soil being present outside a wheel track.

Also, a non-optimum choice of tires or tire pressure also result in different degree of soil compaction as does varying weight load of the agricultural vehicle or implement as encountered e.g. during sowing and fertilizing.

These problems are solved by the present invention in its various aspects.

Fig. 2 is a side view diagrammatically illustrating the working mode of a soil loosening system for an agricultural vehicle according to the present invention.

Fig. 2 shows an agricultural vehicle 200 in the form of a tractor which comprises the rear wheel 4. The tractor is moving in the direction of the movement as indicated by the arrow V.

Behind the tractor a soil loosening system 100 comprising a single soil loosening device 10 is mounted on mounting bracket 50. The mounting bracket comprises a soil loosening element 22 which is pivotally suspended on the bracket 50. An adjustment mean 24 configured to be able to extend and contract is connected to an upper end of the soil loosening element thereby allowing the adjustment the working depth of the soil loosening element 22; as the adjustment mean 24 is extended, the working depth of the soil loosening element 22 is reduced and vice versa. In a real situation the adjustment mean 24 may be supplied with a spring arranged in parallel.

The soil loosening system 100 in Fig. 2 furthermore comprises a sensing system 14. The sensing system comprises a first sensor 30 arranged behind, in relation to the direction of movement, the soil working element 22. The first sensor 30 is configured for sensing a height of soil in the wheel track 12 at a location 16 after that wheel track 12 has been subjected to soil loosening by said soil loosening element 22.

A second sensor 30' is arranged on a bracket 50' mounted on the vehicle 200 in front of the wheel 4. At this position that sensor 30' is capable at sensing a soil height at a position 18 corresponding to soil which has not been be compacted by the wheel 4.
The sensing system 14 is configured to receive information corresponding to the heights sensed by the sensor 30 and the sensor 30', respectively and on the basis of this information to determine a height difference between the soil and the first sensor 30 at location 16 on the one hand and the soil and the second sensor 30' at location 18 on the other hand.

This information is being sent to a control unit 20 which according to a predetermined algorithm is configured to send a control signal 28 to the adjustment means 24. The control signal 28 adjusts the degree of soil loosening performed by said soil loosening element 22 by adjusting the working depth thereof.

This is further illustrated in fig. 3.

Fig. 3 shows a diagram illustrating part of the soil loosening system according to the present invention. In Fig. 3 it is seen that the three sensors 30, 30' and 30'' are connected to the sensing system 14, which based on the signals received form the sensors 30, 30' and 30'' sends a sensing signal 26 to a control unit 20.

Based on the sensing signal 26 received by the control unit 20, the control unit generates a control signal 28 which is being sent to the adjustment means 24 which in turn controls the degree of soil loosening by adjustment of the working depth of the soil loosening element 22 as explained above.

The soil loosening system may also comprise a monitor 52 for monitoring the settings and operations of the system. Furthermore, the control system 100 may comprise input means 54, such as a keyboard for programming and/or calibrating the working mode of the system.

The control unit 20 is usually configured in such a way the control unit 20 provides a control signal 28 to the adjustment means 24 so as to increase the degree of soil loosening of the soil loosening element 22 in case the sensing system by means of e.g. the first sensor 30 and the second sensor 30' is sensing a higher soil height at a location 18 outside a wheel track compared to the soil height at a location 16 of said wheel track after having been subjected to soil loosening.

Furthermore, the control unit 20 is usually configured in such a way the control unit 20 provides a control signal 28 to the adjustment means 24 so as to reduce the degree of soil loosening of the soil loosening element 22 in case the sensing system by means of e.g. the first sensor 30 and the second sensor 30' is sensing a lower soil height at a location 18 outside a wheel track compared to the soil height at a location 16 of said wheel track after having been subjected to soil loosening.

Returning to fig. 2 again, the soil loosening element 22 is arranged in a lateral position which corresponds to the lateral position of the rear wheel 4 of the tractor. For the sake of simplicity only one soil loosening element is depicted in fig. 2. In a real agricultural operation, more soil loosening elements 22 arranged next to each other will be applied so as to cover essentially the full width of the rear wheels.
In use with an agricultural vehicle or an agricultural implement the soil loosening system 100 will comprise two or more soil loosening devices 10, wherein each soil loosening device is responsible of soil loosening in respect of a specific wheel track of said agricultural vehicle and/or implement.

In a case where more than one soil loosening device 10 is used in respect of more than one wheel of an agricultural vehicle or implement, these more than one soil loosening devices 10 may share a common control unit 20, and a common sensing system 14. Alternatively, each soil loosening device may comprise its own dedicated control unit 20, and sensing system 14.

Fig. 4 is a top view illustrating possible positions of sensors, for use with the system of the invention, in relation to an agricultural implement.

Fig. 4 shows a field of soil 2 onto which an agricultural implement 300 is arranged and moving forward in the direction illustrates by the arrow V.

The implement 300 comprises a transverse frame 302 onto which soil working tines 304 are arranged. The frame 302 of the implement 300 is carried by two wheels 4 or gliding shoes. These wheels result in wheel tracks 12, comprising soil 13 and 16.

On the left side of the implement is arranged on a bracket 306 a soil loosening device 10 of the system of the first aspect of the present invention. The soil loosening device comprises a number of soil loosening elements 22 (not visible in Fig. 4).

The soil loosening device 10 causes the soil 13 located in the wheel track 12 located immediately behind the wheel 4 to be soil loosened so that the soil loosened soil 16 remains after being subjected to the soil loosening device 10.

In Fig. 4 possible positions P1, P2, P3, Q1, Q2 and Q3 of sensors 30, 30', 30'' in relation to the agricultural implement 300 are illustrated.

In case a sensor 30, 30', 30'' is positioned so as to sense the height of soil in position P1, the height of soil in the wheel track 12, 13 before the soil is being subjected to any soil loosening can be sensed.

In case a sensor 30, 30', 30'' is positioned so as to sense the height of soil in position P2, the height of soil in the wheel track 12, 16 after the soil has been subjected to soil loosening can be sensed.

In case a sensor 30, 30', 30'' is positioned so as to sense the height of soil in position Q1, Q2 or Q3, the height of soil 18 located outside a wheel track 12 can be sensed.

In addition to the positions Q1, Q2 and Q3 many other possible positions for sensing the height of soil outside a wheel track 12 possible.

Fig. 4 only illustrates possible positions P1, P2, Q1, Q2 and Q3 in respect of a single soil loosening device which loses soil compacted by a single wheel 4. However, a similar soil
loosening device 10 may be applied as well in respect of the right wheel 4 of the implement 300.

Likewise, the same positions P1, P2, Q1, Q2 and Q3 in relation to wheels of an agricultural vehicle, as illustrated in respect of an agricultural implement, may be used.

It should be understood that all features and achievements discussed above and in the appended claims in relation to one aspect of the present invention and embodiments thereof apply equally well to the other aspects of the present invention and embodiments thereof.
### List of reference numerals

<table>
<thead>
<tr>
<th>Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Soil</td>
</tr>
<tr>
<td>4</td>
<td>Wheels of an agricultural vehicle or an agricultural implement</td>
</tr>
<tr>
<td>10</td>
<td>Soil loosening device</td>
</tr>
<tr>
<td>5</td>
<td>Wheel track</td>
</tr>
<tr>
<td>12</td>
<td>Soil located in a wheel track before soil loosening</td>
</tr>
<tr>
<td>14</td>
<td>Sensing system</td>
</tr>
<tr>
<td>16</td>
<td>Soil which has been compacted by a wheel and subsequently loosened by a soil loosening element</td>
</tr>
<tr>
<td>10</td>
<td>Soil located outside a wheel track</td>
</tr>
<tr>
<td>20</td>
<td>Control unit</td>
</tr>
<tr>
<td>22</td>
<td>Soil loosening element</td>
</tr>
<tr>
<td>24</td>
<td>Adjustment means</td>
</tr>
<tr>
<td>26</td>
<td>Sensing signal</td>
</tr>
<tr>
<td>15</td>
<td>Control signal</td>
</tr>
<tr>
<td>28</td>
<td>Sensor of sensing system</td>
</tr>
<tr>
<td>30,30°, 30°&quot;</td>
<td>Mounting bracket</td>
</tr>
<tr>
<td>52</td>
<td>Monitor</td>
</tr>
<tr>
<td>54</td>
<td>Input means of control system</td>
</tr>
<tr>
<td>20</td>
<td>Soil loosening system</td>
</tr>
<tr>
<td>200</td>
<td>Agricultural vehicle</td>
</tr>
<tr>
<td>300</td>
<td>Agricultural implement</td>
</tr>
<tr>
<td>302</td>
<td>Transverse frame of agricultural implement</td>
</tr>
<tr>
<td>304</td>
<td>Soil working tine of agricultural implement</td>
</tr>
<tr>
<td>25</td>
<td>Bracket of agricultural implement</td>
</tr>
<tr>
<td>306</td>
<td>Prior art soil loosening system</td>
</tr>
<tr>
<td>400</td>
<td>Spring</td>
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</tbody>
</table>
422 Soil loosening element of prior art soil loosening system
450 Mounting bracket of prior art soil loosening system
V Direction of movement of vehicle or implement
P₁,P₂, Possible position of sensor
5 Q₁,Q₂,Q₃ Possible position of sensor
Claims

1. A system (100) for soil loosening of soil (2) which has become compacted by wheels (4) of an agricultural vehicle (200) or an agricultural implement (300), said system comprises:
   - one or more soil loosening devices (10) for loosening soil in a wheel track (12);
   - in respect of each soil loosening device, a sensing system (14) which is configured for sensing a height difference between soil located in said wheel track (12) and soil (18) located outside said wheel track (12);
   - a control unit (20);

wherein each of said one or more soil loosening devices (10) comprises one or more soil loosening elements (22) for loosening soil is said wheel track (12), and wherein each of said one or more soil loosening elements (22) is/are mechanically connected to adjustment means (24) for adjusting the degree of soil loosening provided by said one or more soil loosening elements (22);

wherein said sensing system (14) being configured to provide one or more sensing signals (26) representative of said sensed height difference of soil; and

wherein said control unit (20) is configured to receive said one or more sensing signals (26) provided by said sensing system (14) and to provide a control signal (28) on the basis thereof;

wherein said adjustment means (24) is configured to receive said control signal (28), and on the basis thereof to adjust the degree of soil loosening of said one or more soil loosening elements (22) of said one or more soil loosening devices (10).

2. A system (100) according to claim 1, wherein said sensing system (14) comprises one and only one sensor (30, 30°, 30°) configured for sensing a height difference between soil (13, 16) located in said wheel track (12) and soil (18) located outside said wheel track (12); or wherein said sensing system (14) comprises two or more sensors (30, 30°, 30°), wherein one sensor (30) is configured for sensing a height of soil (13, 16) located in said wheel track (12), and wherein an additional and optionally more sensors (30°, 30°) are configured for sensing a height of soil (18) located outside said wheel track (12).

3. A system (100) according to any of the claims 1 or 2, wherein said sensing system (14) comprises a sensor (30, 30°, 30°) which is configured for sensing a height of soil (13) located in said wheel track (12) before that soil (13) is being subjected to soil loosening.

4. A system (100) according to any of the claims 1 – 3, wherein said sensing system (14) comprises a sensor (30, 30°, 30°) which is configured for sensing a height of soil (16) located in said wheel track (12) after that soil (16) is being subjected to soil loosening.

5. A system (100) according to any of the claims 1 – 4, wherein said sensing system (14) comprises a sensor (30, 30°, 30°) which is configured for sensing a height of soil (13) located in said wheel track (12) before that soil (13) is being subjected to soil loosening, and wherein
said sensing system (14) furthermore comprises a sensor (30, 30°, 30°) which is configured for sensing a height of soil (16) located in said wheel track (12) after that soil (16) is being subjected to soil loosening.

6. A system (100) according to any of the preceding claims wherein the number of soil loosening devices (10) is 1 – 10, and being configured for soil loosening in a single or more wheel tracks (12), such as in the wheel tracks of one or both of the two rear wheels (4) of an agricultural vehicle (200), or for soil loosening in the wheel tracks (12) of four wheels (4) of an agricultural vehicle (200), and/or for soil loosening in one or more wheel tracks (12) of an agricultural implement (300) being towed by an agricultural vehicle (200).

7. A system (100) according to any of the preceding claims wherein said soil loosening elements (22) independently being tines or couter blades.

8. A system (100) according to any of the preceding claims, wherein in respect of one or more of said soil loosening devices (10), the working width of said corresponding soil loosening elements (22) independently being 20 – 200 cm, such as 30 – 180 cm, for example 40 – 170 cm, e.g. 50 – 160 cm, such as 60 – 150 cm, for example 70 – 140 cm, e.g. 80 – 130 cm, such as 90 – 120 cm or 100 – 110 cm.

9. A system (100) according to any of the preceding claims, wherein in respect of one or more soil loosening devices (10), said adjustment means (24) independently are configured to adjust the degree of soil loosening by altering the working depth of said one or more soil loosening elements (22), and/or by altering the angle of attack of said one or more soil loosening elements (22), and/or by altering a speed of movement of said one or more soil loosening elements (22), in a case said soil loosening provided by said one or more soil loosening elements is provided by mechanically driven soil loosening elements; and/or by movement of said one or more soil loosening elements (22) by means of parallelogrammic suspension means.

10. A system (100) according to any of the preceding claims, wherein said control unit (20) is configured for providing said control signal (28) to said adjustment means (24) of said one or more soil loosening devices (10) on the basis on said one or more sensing signals (26) in accordance with a predetermined algorithm.

11. A system (100) according to claim 10, wherein said predetermined algorithm is configured in such a way that said control unit (20) is configured to provide a control signal (28) to said adjustment means (24) so as to increase the degree of soil loosening of said one or more soil loosening devices (10) in case said sensing system is sensing a higher soil height at a location (18) outside a wheel track compared to the soil height of soil loosened soil at a location (16) in said wheel track (12), and/or wherein said predetermined algorithm is configured in such a way that said control unit (20) is configured to provide a control signal (28) to said adjustment means (24) so as to decrease the degree of soil loosening of said one or more soil loosening devices (10) in case said sensing system (14) is sensing a higher soil height of soil loosened soil at a location (16) in said wheel track (12), compared to the soil height at a location (18) outside said wheel track (12), and/or wherein said predetermined
algorithm is configured in such a way that said control unit (20) is configured to provide a control signal (28) to said adjustment means (24) on the basis of a sensed height of soil plus/minus a predetermined offset value.

12. A system (100) according to any of the preceding claims, wherein said adjustment means (24) of said one or more soil loosening devices (10) independently comprises one or more hydraulic actuators, one or more pneumatic actuators, or one or more electric actuators for adjustment of said degree of soil loosening.

13. A system (100) according to any of the preceding claims, wherein in respect of one or more of said soil loosening devices (10), said soil loosening device (10) comprises two or more soil loosening elements (22) which are configured to move in concert.

14. A system (100) according to any of the preceding claims, wherein in respect of one or more of said soil loosening devices (10), said one or more soil loosening elements (22) independently are configured for being moved by said adjustment means (24) by rotation around a rotational axis (A), such as an essentially horizontal rotational axis, or wherein in respect of one or more of said soil loosening devices (10), said one or more soil loosening elements (22) independently are configured for being moved by said adjustment means (24) by movement in an essential vertical direction.

15. A system (100) according to any of the preceding claims, wherein in respect of one or more of said soil loosening devices (10), said one or more soil loosening elements (22) are suspended in a parallelogrammic suspension, thereby allowing said soil loosening elements (22) to be moved by said adjustment means (24) by movement in a direction having a vertical component and a horizontal component.

16. A system (100) according to any of the preceding claims, wherein in respect of one or more of said soil loosening devices (10) said sensing system (14) is configured for providing said one or more sensing signals (26) via mechanical sensing means; or wherein in respect of one or more of said soil loosening devices (10) said sensing system (14) is configured for providing said one or more sensing signals (26) via non-mechanical sensing means; or wherein in respect of one or more of said soil loosening devices (10) said sensing system (14) is configured for providing said one or more sensing signals (26) via sonic sensing means.

17. A system (100) according to claim 16, wherein said sensing system is configured for providing said one or more sensing signals (26) via mechanical sensing means comprising a sensing wheel which is pivotally suspended and configured to follow the surface of soil (13,16) in said wheel track (12), and also comprising one or more additionally sensing wheels (40) which is/are pivotally suspended and configured to follow the surface of soil (18) located outside said wheel track (12); wherein the height difference between soil loosened soil (16) located in said wheel track (12) and soil (18) located outside said wheel track (12) is determined on the basis of the respective sensed heights of said two or more sensing wheels.

18. A system (100) according to claim 16, wherein said sensing system (14) is configured for providing said one or more sensing signals (26) via non-mechanical sensing means.
comprising one or more transmitters configured to transmit an electromagnetic radiation; and
comprising one or more receivers which is/are configured to receive a reflected signal of said
transmitted electromagnetic radiation; and wherein the height difference between soil (13,16)
located in said wheel track (12) and soil (18) located outside said wheel track is determined
on the basis of detection of time-of-flight, frequency, wavelength, intensity/amplitude of the
electromagnetic radiation involved, or a combination thereof.

19. A system (100) according to claim 18, wherein said sensing system (14) comprises a laser
sensing system, an infrared sensing system or a laser range scanning sensing system.

20. A system (100) according to claim 16, wherein said sensing system (14) is configured for
providing said one or more sensing signals (26) via sonic sensing means comprising one or
more transmitters configured to transmit a sonic radiation; and comprising one or more
receivers which is/are configured to receive a reflected sonic signal of said transmitted sonic
radiation; and wherein the height difference between soil (13,16) located in said wheel track
(12) and soil (18) located outside said wheel track (12) is determined on the basis of detection
of time-of-flight, frequency, wavelength, intensity/amplitude of the sonic radiation involved,
or a combination thereof.

21. A system (100) according to any of the preceding claims, wherein said control unit (20) is
configured in such a way that both in respect of soil (13,16) in said wheel track (12) and in
respect of soil (18) outside said wheel track (12), a number of measurement samples of soil
heights are made; and wherein said control unit (20) is configured for subsequently averaging
these samples of soil heights in said wheel track (12) on the one hand and also for averaging
these samples of soil heights outside said wheel track (12) on the other hand, and wherein said
control signal (28) is based on the difference of said averaged samples of soil heights.

22. A system (100) according to claim 21 wherein said control unit (20) is configured in such
a way that the measurement samples of soil heights independently is performed at a sampling
rate of 1 – 200 Hz, such as 5 – 150 Hz, for example 10 – 100 Hz, such as 25 – 80 Hz, e.g. 30
– 60 Hz; and/or wherein said control unit (20) is configured in such a way that said control
signal (28) independently is provided at a rate of 0.1 – 10 Hz, such as 0.5 – 9 Hz, e.g. 1 – 8
Hz, such as 2 – 7 Hz, e.g. 3 – 6 Hz or 4 – 5 Hz.

23. A system (100) according to any of the preceding claims, wherein said control unit (20) is
configured to perform a filtering, such as a low-pass filtering, of the sensed heights or height
differences prior to providing said control signal (28).

24. A system (100) according to claim 23, wherein said control unit (20) is configured to
provide said control signal (28) by means of, a P (Proportional) control, PID (Proportional
Integration Differentiation) control, three position control, or a step control.

25. A system (100) according to any of the preceding claims, wherein one or more of said
sensors (30,30',30") is/are configured for sensing a height of soil (18) located outside a wheel track
(12) independent is/are configured for being arranged, in relation to the direction of
movement, in front of said wheel, and/or in a lateral position in relation to said wheel and/or behind said wheel; or a combination thereof.

26. A system (100) according to any of the preceding claims, further comprising one or more mounting brackets (50) configured for carrying one or more of said soil loosening devices (10), or parts thereof, and for being mounted on an agricultural vehicle (200) or implement (300); and/or further comprising one or more mounting brackets (50') configured for carrying said sensing system (14), or parts thereof, and for being mounted on an agricultural vehicle (200) or implement (300); wherein said mounting bracket (50,50') configured for carrying one or more of said soil loosening devices (10) and said mounting bracket (50') configured for carrying said sensing system optionally are the same bracket or are different brackets.

27. A system (100) according to any of the preceding claims further comprising a monitor (52) and/or input means (54); wherein said monitor (52) is configured for being coupled to said control unit (20) so as to display to a user the settings and/or information relating to the operation of said system; and wherein said input means (54), e.g. in a form of a keyboard, is configured for being coupled to said control unit (20) so as to enable setting up and/or calibration of said system; said monitor (52) and/or said input means (54) optionally being in the form of an HMI (Human-Machine Interface) or a GUI (Graphical User Interface).

28. A system (100) according to any of the preceding claims further comprising a GNSS (Global Navigation Satellite System) receiver for providing information of the location on the field of said agricultural vehicle (200) or said agricultural implement (300); wherein said control unit (20) optionally is configured to receive information from said GNSS receiver and wherein said control unit (20) is configured to have stored therein, data relating to characteristics of the soil at different locations of a field.

29. A system (100) according to any of the preceding claims, wherein said sensing system (14) comprises one or more force transducers which are configured for sensing a horizontally oriented force of one or more of said soil loosening elements (22), such as a strain gauge; or in the form of one or more sensors for sensing a hydraulic pressure in a hydraulic actuator which is configured for suspending one or more of said one or more soil loosening elements.

30. A system (100) according to any of the preceding claims, wherein said system comprises one or more axle or wheel load sensors for sensing the load on one or more axles or wheels of said agricultural vehicle (200) or agricultural implement (300); wherein said control unit (20) is configured for receiving a load sensing signal from said one or more axle or wheel load sensors; and

35 wherein said control unit (20) is configured for providing said control signal (28) to said adjustment means (24) in a way wherein said control signal is depending on the load as sensed by said one or more load sensors, thereby allowing the severity of the soil loosening provided by said one or more soil loosening devices (10) to be dependent of the axle or wheel load of said agricultural vehicle or said agricultural implement.
31. An agricultural vehicle (200) comprising a system (100) according to any of the claims 1 - 30.

32. An agricultural implement (300) comprising a system (100) according to any of the claims 1 - 30.

33. An agricultural implement (300) according to claim 32, wherein said implement is a tilling implement, such as a harrowing implement or a sowing implement for sowing crop seeds.

34. An agricultural implement (300) according to claim 33, wherein said implement is a sowing implement, and wherein said sensing system comprises two or more sensors (30, 30°, 30°⁺) wherein one or more of said two or more sensors are configured to sense the depth of one or more seed drills on said sowing implement submerged in soil (13, 16) located in said wheel track (12), and wherein one or more of said two or more sensors are configured to sense the working depth of one or more seed drills on said sowing implement submerged in soil (18) located outside said wheel track (12).

35. Use of a soil loosening system (100) according to any of the claims 1 - 30 or of an agricultural vehicle (200) according to claim 31 or of an agricultural implement (300) according to any of the claims 32 - 34 during performance of an agricultural work operation in an agricultural field.

36. Use according to claim 35, wherein said use is for reducing uneven crop growth between crops being or to be sown in and outside a wheel track (12), respectively, for reducing erosion and/or for reducing dilution of pesticides.
Abstract

The invention relates to a system (100) for soil loosening of soil (2) which has become compacted by wheels (4) of an agricultural vehicle (200) or an agricultural implement (300), said system comprises:

- one or more soil loosening devices (10) for loosening soil in a wheel track (12);
- in respect of each soil loosening device, a sensing system (14) which is configured for sensing a height difference between soil located in said wheel track (12) and soil (18) located outside said wheel track (12);
- a control unit (20);

wherein each of said one or more soil loosening devices (10) comprises one or more soil loosening elements (22) for loosening soil is said wheel track (12), and wherein each of said one or more soil loosening elements (22) is/are mechanically connected to adjustment means (24) for adjusting the degree of soil loosening provided by said one or more soil loosening elements (22), wherein said sensing system (14) being configured to provide one or more sensing signals (26) representative of said sensed height difference of soil; and wherein said control unit (20) is configured to receive said one or more sensing signals (26) provided by said sensing system (14) and to provide a control signal (28) on the basis thereof; wherein said adjustment means (24) is configured to receive said control signal (28), and on the basis thereof to adjust the degree of soil loosening of said one or more soil loosening elements (22) of said one or more soil loosening devices (10).

(fig. 2)
Fig. 1

Fig. 2
9. Appendix / Paper VI – Seed drill depth control system for precision seeding
Original papers

Seed drill depth control system for precision seeding

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\textbf{ARTICLE INFO}

\textbf{Keywords:}
Seed drill
Coulter depth control system
Spring barley
Precision seeding

\textbf{ABSTRACT}

An adequate and uniform seeding depth is crucial for the homogeneous development of a crop, as it affects time of germination and emergence rate. The considerable depth variations observed during seeding operations even for modern seed drills are mainly caused by variability in soil resistance acting on the drill coulters, which generates unwanted vibrations and, consequently, a non-uniform seed placement. Therefore, a novel concept dynamic coulter depth control system for a low-cost seed drill was developed and studied in a field experiment. The performance of the active control system was evaluated for the working speeds of 4, 8 and 12 km h\textsuperscript{-1}, by testing uniformity and accuracy of the coulter depth in relation to the target depth of \(50\) mm. The evaluation was based on coulter depth measurements, obtained by coulter position sensors combined with ultrasonic soil surface sensors. Mean coulter depth offset of 3.5, 5.3 and 6.3 mm to the target were registered for the depth control system, compared to 6.0, 9.1 and 11.0 mm without the control system for 4, 8 and 12 km h\textsuperscript{-1}, respectively. However, speed did not affect the coulter depth significantly. The control system optimised coulter depth accuracy by 16.2\% and at a 95\% confidence interval it corresponded to an absolute reduction in the coulter depth confidence limits of 19.4 mm. The spatial variability, due to variation in soil mechanical properties was found to be \(\pm 8\) mm, across the block for the standard drill and when activating the coulter depth control system this variability was reduced to \(\pm 2\) mm. The system with the active control system operated more accurately at an operational speed of 12 km h\textsuperscript{-1} than at 4 km h\textsuperscript{-1} without the activated control system.

\textbf{1. Introduction}

A uniform seeding depth is of vital importance to achieve the desired consistent crop emergence. Consistent crop emergence increases final crop yields, as the seedling growth process affects the availability of crop biomass. Seeding operations can be conducted with or without previous tillage, and the conventional preferred seed placement is at a consistent depth, at the bottom of a shallow loose soil layer and above a more compacted soil layer (Chang et al., 2004; Gud-Simonsen et al., 2002; Hillerøde et al., 2002). However, a study has shown that such a compact layer may restrict root development (Flayley et al., 1994). If seedbed preparation is practised, the desired homogeneous structure will support an adequate combination of moisture and heat, which is crucial for the desired germination and emergence (Hillerøde et al., 2002). In addition, the risk of evaporation, erosion and pestle leaching is likely to be reduced, by creating a homogeneous seedbed (Peterson et al., 2016). The aggregates size and spatial distribution of soil aggregates in the seedbed are important, but the risk of poor emergence is also highly influenced by seedling density (Binkin and Bashin, 1998; Hillerøde et al., 2011, 2002). A delay in the development of the seedling can be crucial in the competition with weeds or neighbouring crop plants and can consequently impact yield (Dorr et al., 1992a, 1992b). Hillerøde et al. (2011) found that there was an almost linear increase in the time delay for the emergence of 50\% of the barley with increasing seeding depth, within the range of 10 to \(90\) mm at \(20^\circ\)C, with a final emergence percentage of approximately 85, 75 and 50\% at 10, 30 and \(50\) mm seeding depth, respectively. Another study showed an 80\% wheat emergence at \(55\) mm depth, decreasing to 70\% when the depth was changed to \(35\) or \(80\) mm (Klitten et al., 1993). A seed placement that is too shallow increases the risk of predation by birds and insects. A placement that is too deep may reduce the oxygen concentration, which increases the risk of seed rotants and exhaustion of the stored seed energy before the plant reaches the soil surface (Rivera et al., 2012).
It is challenging task for seed drills to achieve an uniform seed placement at the optimal depth, due to variations in soil resistance affecting coulter depth, which consequently results in coulter depth variations (Schmoeckel and Cuntz, 2014; Guerra et al., 2015; Kienen et al., 1993). Traditionally, the coulter down pressure is manually set at operation start by adjusting the tension of the static springs. This setting is based on the seed drill manufacturer’s recommendations and the operator’s experience (Kienen et al., 1993). Ideally, the operator checks the seedling density according to random check samples, in initial test drives in the field. However, this does not prevent undesired depth variation caused by spatial field variation in soil resistance, acting on the coulters. There is, therefore, a need for an applicable automated coulter depth control system to reduce undesired coulter depth deviations.

In the last few decades, a number of active seeding depth control systems have been proposed (Klien, 2012; Soomi and Oksaenen, 2015; Westphaber and Flowers, 1997). Klien (2012) found that ultrasonic sensors were to some degree able to recognize soil surface irregularities due to tillage, plant residues and stubble. Westphaber and Flowers, 1997 developed a model and a system that controlled coulter depth based on soil moisture content, as moisture is one of the important factors for determining seedling depth. Their system included a front-drying moisture sensor and used proportional hydraulic control. This approach might be sensitive to rapid changes in soil moisture content due to rainfall or drying, which may not reflect the average moisture content experienced by the germinating seeds. Soomi and Oksaenen (2015) developed an advanced depth control system for a heavy seed drill, designed for direct drilling. The seed drill levellised and compacted the soil by the lateral supporting wheels acting as a common roller. They used proportional integral-derivative control algorithms in a cascade control system to adjust the hydraulic cylinder pressure. To measure the soil surface, a gauge wheel with an angle sensor combined with remote ultrasonic rangefinder was utilized, sensing the surface in the longitudinal direction. Three out of 32 coulters were measured to determine the coulter depth. In addition, the frame of supporting wheels (colter) was measured by angle, to determine the actuating settings. Soomi and Oksaenen (2015) were able to maintain the desired working depth within a tolerance of ± 10 mm. Nielsen et al. (2015) developed a novel coulter depth sensing and control system for one coulter which was tested in a soil bin experiment. Nielsen et al. (2016) found that three-position hydraulic control system reacted fast and was the most cost-efficient solution, when compared to proportional and proportional-integral-derivative control. The sensing method was further developed by Nielsen et al. (2017) into a novel, full-scale coulter depth measurement system and the functionality was tested in a practical real field operation. In the present study, this coulter height measurement system by Nielsen et al. (2017) was further developed and combined with an automatic, real-time coulter pressure control system to adjust and maintain the desired operational depth of the coulters.

The aim of the study was to evaluate the performance of the developed automatic coulter depth control system installed on a simple, lightweight seed drill in a real field application. Our hypothesis was that the automated coulter pressure control system would limit the undesired deviations from the target depth and stabilise the coulter depths.

2. Materials and methods

2.1. Experimental setup and calibration

The experimental setup consisted of a Kongskilde Ecoline 300 (DK) drill with a single-disc, Rowmark 2000 seed drill, which had been equipped with the coulter depth measurement system developed as by Nielsen et al. (2017). The measurement system was additionally developed equipped with a control system consisting of an electro-hydraulic actuating system for dynamic coulter pressure control and a control unit.
granulometric analysis on loose soil taken from the top layer at the time of seeding, to the mean value of 14.6 kg 100 kg\(^{-1}\). A target depth of ~30 mm was chosen based on crop species, soil type, and moisture, according to the operator’s experience.

The tractor used for the experiment was a Fermas 710 that had an individual wheel load of 1550 kg on the front and 2050 kg on the rear. The tyres were Michelin Xerobal 760/60R38 at the front and 710/60R38 at the rear with an inflation pressure adjusted to 80 kPa according to the tyre manufacturer’s recommendations. The individual wheel load of the seed drill was 450 kg (± 150 kg), depending on the seed quantity, and the inflation pressure of the small 7.00-12 tyres was set high at the manufacturer’s recommended 120 kPa to ensure a constant seed dosage independent of machine weight from variations in seed quantity.

The seeding dose rate was set to 155 kg ha\(^{-1}\), verified by a test with three repetitions, corresponding to 290 seeds per m\(^2\) at 95% emergence. A targeted seeding depth of ~30 mm was used in all cases. For the trials without the control system, the coulter down-pressure was set manually by the experienced operator at the beginning of the seeding operation. The operator used multiple check samples in the initial track of the actual seeding depth observations, to adjust the coulter pressure.

To ensure the accuracy of the measurement system, additional control samples were used to calibrate the actual seeding depth to the measured coulter depth, of the system. This ensured that the measurement system took account of the specific soil-couler interaction when placing the seeds in the soil.

2.3. Statistics

Coulter depth measurements higher than 150 mm above the soil surface were regarded as measurement out of range and thus discarded from the dataset. The discarded data contributed to less than 0.2% of the coulter depth measurements. Heat-maps were generated and probability density functions were fitted to the data from the different treatments to compare distribution of the coulter depth around the target depth. Two linear mixed models were created for modelling coulter depths in order to analyse the performance of activating the coulter depth control system and test the different treatment impact on the coulter depth. Coulter, Speed, and their interactions were treated as fixed factors in the mixed linear models. Block, as well as the interaction effects between BlockSpeed, BlockCoulter and BlockCoulter/Speed, were treated as random factors in the models. The three-sigma rule was used to examine the normality of the mixed linear model residuals distribution. Likelihood ratio tests were used to evaluate the significance of the fitted and random factors of the models. The block effect caused by the soil mechanical variance was studied to compare system performance.

Finally, to compare the seeding operations in the statistical evaluation, the resultant deviations (calculated from the random effects of the models) were compared to determine the performance of the coulter depth control system. The confidence intervals (CI) of the standard deviations (SD) were found to indicate the significance. In addition, Monte Carlo simulations were applied based on the linear mixed models to test for improvement of the unintended coulter depth deviations when activating the control system. The simulations were done by calculating 1000 datasets for each of the two models. The datasets were the same size and structure as the measured datasets for the models and from these models, 1000 deviations were estimated. The difference of the two systems resultant deviations was found, with a confidence interval to compare the system performance. The data analysis and statistical calculations were carried out in R-studio (Rstudio, USA) and MatLab (Mathworks, USA).

3. Results and discussion

3.1. Descriptive evaluation of the coulter depth control system

The 11 coulter depth measurements for the three operational speeds and the different treatments "No Control" and “Control” are depicted in the form of heat-maps (Fig. 2).

The heat-maps show all the measurements registered for the four blocks and the six trials, where green colour represents target depth, blue means deeper than target depth, yellow is closer to the surface than target and red is therefore on top of the soil surface. As the soil surface was estimated from two ultrasonic sensors using linear interpolation, some of the measurements might not represent the actual coulter depth relative to the soil surface for the individual coulter. Stones, soil lumps, or curvatures generating micro-topography between the surface sensors will not be registered due to the linear interpolation. On the other hand, micro-topography in the measured row of the sensors will influence the frame height measurement. This explains the lateral lines (Fig. 2), with unanticipated rapid colour changes. This can potentially lead to small inaccuracies for the coulter depth measurement system. However, due to the brevity of the changes, the coulter pressure settings were not affected by the control system and the same measurement system was used between the treatments (control and no control). Therefore, this was not considered to impact the evaluations of the system. In the longitudinal direction there were, however, some unanticipated coulter depth variations, e.g. in Fig. 2B, block 1, where one coulter was seeding on top of the seedbed. This was most likely due to a soil with residues accumulated on the coulter. The data affected represented 1.9% of the treatment data and removing it did not impact the evaluation of the control system for the treatment.

When visually assessing the heat-maps, the seed drill with the active coulter depth control system had, overall, a more consistent dominating green colour (i.e. closer to the target depth) than without the system active, as the coulters operated more consistent (Fig. 2).

A graph displaying the cumulative displacement percentages vs. confidence interval of coulter depth measurements for the three operational speeds for the depth control and no depth control trials is shown in Fig. 3. The graph illustrates the distribution of confidence levels (percentage of the depth measurements) against confidence intervals around the ~30 mm target (presented as 0 mm) coulter depth. For example, at a confidence level of 90%, the confidence intervals were 24, 26 and 28 mm for the control system and 30, 32 and 34 mm for the standard seed drill, for 4, 8 and 12 km h\(^{-1}\), respectively.

The graph clearly demonstrates the improvement achieved by the depth control system active, compared to the standard seed drill for all working speeds. The graph also illustrates an almost non-visible difference between 8 (red) and 12 km h\(^{-1}\) (blue) with the depth control system active, which means that the system brought about a considerable improvement, allowing the operator to work at 12 km h\(^{-1}\) almost without compromising performance (Fig. 3).
Fig. 2. The coulter depth measurements shown for all four blocks and the three different operational speeds of 4 km h⁻¹ (A), 8 km h⁻¹ (B) and 12 km h⁻¹ (C). Target depth is in green, blue is deeper than target depth, yellow is closer to the surface than the target and red is on top of the soil surface. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 3. The cumulative measurement percentage against confidence intervals of depth measurements with and without the depth control system, for the three different operational speeds, the 12 km h⁻¹ line (red), and the 8 km h⁻¹ line (blue), and is hidden behind it. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Probability density functions, illustrating the mean coulter depth distributions for the three operational speeds with and without the depth control system, are shown in the histograms (Fig. 3). All six plots have approximately symmetric and unimodal forms. Nevertheless, the histograms for the depth control system show a higher relative frequency at the targeted depth and a narrower distribution around the mean depths than for the standard seed drill (Fig. 4). Even though some of the depths observed differ substantially from the target depth, including depth measurement above the soil surface, the depth control system gave more accurate and consistent results, maintaining the target coulter depths. The seeds placed on the top of the soil surface could still be partly covered by soil, due to the light post-germination harrowing carried out by the seeder.

Coulter mean depths and standard deviations for the different speeds and systems registered the following values at respectively 4, 8 and 12 km h⁻¹: with the coulter depth control system, 26.5 (SD = 14.3), 24.7 (SD = 13.5) and 21.3 mm (SD = 15.2 mm), and without the coulter depth control system, 22.0 (SD = 16.4), 21.9 (SD = 17.6) and 19.0 mm (SD = 18.0 mm). The mean depths were shallower than the targeted depth for both systems. This was caused by the hydraulic actuating system design, operating with a non-directional cylinder and therefore, the actuator's release speed depended on the soil characteristics acting on the coulters. However, the mean coulter depths for the different speeds were consistently closer to the targeted depth with the control system activated. The mean coulter depth offset from the targeted depth was 5.5, 5.3 and 6.3 mm for the depth control system for 4, 8 and 12 km h⁻¹, respectively, compared to 8.0, 9.1 and 11.0 mm without the depth control system. The offsets were calculated as the depth difference relative to the targeted depth of −50 mm, defined from the theoretical surface. Therefore, the presented coulter depth measurement might show more variation than the actual seedling depth in the specific rows, as the individual coulters were spring-loaded. This allowed the coulters to vary individually depending on
mico-topography. However, this did not influence the evaluation of the system performance as identical measurement systems determined coulter depth variations.

Sweert and Olofsson (2015) obtained a more accurate seedling depth at ±10 mm. Their machine was a heavy seed drill design for direct seeding with wedge-shaped coulters and a common roller by lateral compaction supporting wheels levelling the surface after seeding. Thus, their machine cannot be directly compared to the low-cost, lightweight seed drill, used in this study. Their study used three coulters sensors and ISOBUS control, whereas this study included additional lateral variations of the seed drill, as 11 coulters depth measurements were used as input for the control system.

3.2 Statistical evaluation of the treatment effects

The residuals from the mixed linear models followed approximately a normal distribution as shown by the values of 0.695, 0.954 and 0.995 for the conventional system, and 0.706, 0.954 and 0.994 for the control system, for one, two and three standard deviations, respectively. The statistical analysis using the mixed linear models and the likelihood ratio tests found that only Coulter was significant for the fixed terms when testing Coulter, Speed and their interaction for both models (conventional system and with the active control system), as found by Nielsen et al. (2017). It was not possible to reduce any of the random effects from the initial models, similar to Nielsen et al. (2017). Therefore, both models included the same factors of fixed terms and random effects.

In the final mixed linear models of the conventional system and the control system, different standard deviations of the random effects were found. The standard deviations express the coulter depths variation, relative to the estimated mean depths from the models.

For the system without the active control, a resultant standard deviation of 17.1 mm was found for the linear mixed model residuals. When activating the coulter depth control system, the resultant standard deviation was significantly reduced to 14.5 mm. These resultant standard deviations describe the residual for the modelled coulter depth and were probably mainly caused by the spatial variation in the mechanical properties of the soil. To evaluate the variation and the performance of the active control system, the internal block effect of the field was calculated based on the coulter depth with the static and active systems. The block effect was calculated as the longitudinal mean coulter depth for each coulter across the experimental field for “No control” and with “Control” (Fig. 5). This block effect illustrated in Fig. 5 was found by smoothing the individual coulter depths by a laterally moving average filter using ±10 data points. Nielsen et al. (2017) found a similar block effect with a bias variation of up to ±5 mm from the mean coulter depth. A similar block effect was found in this study, although it was up to ±8 mm without the depth control system activated. When activating the coulter depth control system, it was significantly reduced to ±2 mm (Fig. 5).

The improvement in the standard deviations when activating the control system was 15.2%, found by the resultant coulter depth deviation reduction, when comparing the linear mixed models of the standard seed drill to the developed seed drill with the active control system. When calculating at the 90% confidence interval, a considerable reduction in the coulter depth confidence span of 10.4 mm was achieved when activating the control system. When analysing the coulter depth deviations using Monte Carlo simulations, the difference was found to be significantly reduced (p < 0.05). At the 95% confidence interval, the span reduction ranged from 7.2 mm to 13.3 mm when the mixed models’ confidence span was calculated with the simulated deviations. In conclusion, the developed coulter drill significantly reduced the undesired coulter depth variations, when activating the control system.

3.3 Perspective and discussion of the system

The sampling rate of the coulter depth measurement was 100 Hz, which was sufficient for measuring the variation in coulter depth and statistically test the functionality of the control system. The 11 position sensors provided a high-resolution input signal for the depth control system, which significantly reduced the influence of coulter depth variations by 15.2%, caused by changes in soil resistance. To minimise hardware costs, a reduction in the number of coulter sensors can be considered. With fewer coulter sensors installed, the measurement accuracy will decrease. However, it will still provide a representative picture of the consistent coulter depth variations as shown by Nielsen et al. (2017). The two ultrasonic sensors used for sensing the traverse frame height of the seed drill were regarded as giving an acceptable interpretation of the seeded surface. However, additional sensors will
improve the estimation of the seedbed surface and thereby reduce system sensitivity to soil clumps, stones or soil micro-topography. Alternatively, soil surface heterogeneity may be assessed more precisely using multiple 2D laser range surface scanners (Janes et al., 2012). However, the drawbacks regarding the latter might be higher material cost and data computation load, as well as system sensitivity to dust in the light beam. Seed depth control samples in the field were used to calibrate the coulter depth measurement system for the soil-coulter interaction when placing the seeds in the soil. Additional studies are needed to determine the relationship between coulter depth and the actual seeding depth for a range of coulter designs against a number of variable soil conditions. If this relationship is found predictable, the initial calibration for the specific soil-coulter interaction would not be needed. However, the coulter depth measurement and control system presented in the study was found functional with great accuracy when the initial calibration was conducted.

A comparison with other active seeding depth control systems (Kiani, 2012; Suoni and Olsanen, 2015; Weatherly and Bowers, 1997) shows that this study was considerably different. Similar to Kiani (2012), this study found that the ultrasonic sensors could detect the soil surface in spite of irregular tillage ground. Weatherly and Bowers (1997) used a front-drying sensor to adjust seeding depth dynamically. This approach was not chosen in this study, as it was carried out in a cool and humid climate. However, soil moisture is an important factor of the physical soil properties and therefore important to be considered when determination of seeding depth, especially in drier climates. The depth control system presented in this paper was based on multiple sensors as was the study by Suoni and Olsanen (2015). The studies are, however, not directly comparable. In this study a lightweight and low-cost, single-disc seed drill was used. Only upperparts in intensively tilled soils, whereas Suoni and Olsanen (2015) used a direct seed drill with compaction and levelling wheels, seeding with wedge-disc coulters. Suoni and Olsanen (2015) measured on three coulters and focused on ISCRUS, whereas this study included 11 coulters sensors and did not include interaction with the tractor system. Suoni and Olsanen (2015) used a following wheel to detect the surface, whereas this study solely used remote ultrasonic distance sensors to detect the surface. In addition, Suoni and Olsanen (2015) used a proportional-integral-derivative cascade control and Weatherly and Bowers (1997) used a proportional control, where this study used the low-cost, three-position, hydraulic control system as Nielsen et al. (2016), found to be the best cost-efficient solution.

The presented system can be additionally developed for site-specific adjustment of coulter depth, i.e. based on the GNSI i.e. combined on-the-go sensors installed on the seed drill. This would need a decision support system to determine the desired seeding depth, on-the-go. Soil moisture content would be an important input parameter to include, as found by Weatherly and Bowers (1997). Information from soil maps of soil texture, etc., would also be useful when predicting the site-specific seeding depth. Another spin-off approach could be to apply deeper secondary tillage, as the moderately compacted layer below seeding depth would not be needed to mitigate too deep seeding, i.e. the coulters tend to run on top of the compacted layer in a conventional operation. A deeper primary tilled (loose) layer can be beneficial for some soils, as shown by Finlay et al. (1994).

The presented site-specific control system improves the conditions for crop establishment, which especially is targeting heterogeneous field. The system is expected to be functional for a range of seedbed conditions, i.e. loose sand or heavy clay, whenever the seed drill has been design to adjust the coulter pressure within the range, needed to achieve the desired coulter depth.

In general, the automatic coulter depth control system was found capable of maintaining the desired coulter depth, reducing the undesired block effect from ±8 mm to ±2 mm and improving the performance with 15.2%. The improved performance can either be implemented as an improvement in operational quality (depth accuracy) or in increased work efficiency (i.e. larger area covered per time unit due to increased operational speed). Greater operational speed can in general be achieved, i.e. the system maintained a more consistent coulter depth at the high speed of 12 km h⁻¹ with the depth control system active, than at the low speed of 4 km h⁻¹ without the control system, as shown in Fig. 3.

4. Conclusion

The functionality of a light-weight, single-disc seed drill with a novel coulter depth control system was tested in a real field application. The system improved the accuracy and uniformity of the coulter depth compared to the standard seed drill for all the tested speeds. The system improved the coulter depth accuracy by 15.2%, corresponding to an absolute reduction in the coulter depth confidence span of 10.4 mm (CI = 95%). Mean coulter depth target offset of 3.8, 5.3 and 6.3 mm were measured for 4, 8 and 12 km h⁻¹, respectively. This was a considerable improvement compared to the standard seed drill where offsets of 8.0, 9.1 and 11.0 mm were measured at 4, 8 and 12 km h⁻¹, respectively. Thus a more accurate coulter depth was measured at 12 km h⁻¹ when the control system was active than at 4 km h⁻¹ without the automatic depth control system. In addition, the variances of the coulter depths were significantly reduced for all the tested speeds when activating the control system, even when comparing across speeds. The spatial variation across the field manifested itself in a significant block effect both with and without the coulter depth control system. However, the coulter depth deviation from the mean depth was only ±2 mm with the activated coulter depth control system as
compared to ≥ 8 mm without the depth control system. Therefore, the system was found to be capable of maintaining a more accurate and stable couler depth across the field.

More uniform crop emergence and crop germination can be expected when using the novel couler depth control system as it maintains a more consistent couler depth independent of variations in working speeds, machine load, couler design, soil mechanical properties, which all affect the couler depth.

Acknowledgements

We thank Svend Poulsen and Robert Poulsen from Spectrometry for their help in carrying out the experiment. Peter Nielsen, Aarhus University and Thomas Schmidt, Simco are thanked for their assistance in the development of the seed drill. A special acknowledgement should go to my colleagues from Agro Intelligence for their support throughout the entire study. The work was financially supported by Innovation Fund Denmark through the research project “Future Coupling”.

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