Development of a real-time measurement method for analyzing the influence of tire-soil contact on agricultural tractor mobility

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Tiivistelmä/Referat – Abstract

Tämän tutkielman tavoitteena oli suunnitella, rakentaa ja testata helposti asennettava ja käytettävä mittauslaitteisto, joka pystyisi mittaamaan reaaliajassa yksinkertaisia suureita, joiden avulla olisi mahdollista arvioida renkaiden ja maaperän välisen kontaktin vaikutusta maataloustraktorien liikkuvuuteen. Kehitetty mittauslaitteisto perustuu Arduino Uno mikrokontrolleriin kytkettyihin kiihtyvyys- ja etäisyys antureihin sekä traktorin väylätietojen lukemiseen. CAN-väylän lukeminen ja tietojen tallentaminen tapahtui RaspberryPi pienoistietokoneeseen liitetyn CAN-väylä kortin avulla.

Anturit kalibroitiin ja niiden herkkyys tarkistettiin ennen kokeiden suorittamista peltoajossa. Kiihtyvyysanturit sijoitettiin traktorin taka-akselin päälle molempiin päihin koteloihin ja etäisyysanturit kiinnitettiin akselin takapuolelle. Kaikkia antureita luettiin RaspberryPi:n sarjaporttiin liitetyn Arduinon välityksellä ja tiedot tallennettiin tehdyllä python ohjelmalla. Raspberry Pi valittiin tietokoneeksi sen vähäisen tilavuusvaatimuksen, alhaisen hinnan sekä liitäntöjen monipuolisuuden vuoksi.
Pellon ominaisuuksia seurattiin kuukausittain suoritetuilla penetrometri mittauksilla sekä maahan upotetuilla SoilScout antureilla, jotka kertoivat maan kosteuden sekä lämpötilan kyseisessä syvyydessä reaaliajassa. Tämän tarkoituksena oli saada selville pellossa kasvukauden aikana tapahtuvat muutokset, jotka vaikuttaisivat myös traktorin liikkumiskykyyn.

Mittaukset onnistuivat hyvin ja tulokset arvioitiin olevan laadultaan luotettavia, joten ne tarjoavat monia muita mahdollisuuksia tulevaisuudessa. Tulokset osoittivat selvästi traktorin liikkuvuuteen vaikuttavat tekijät ja maanmuokkauksen eri vaiheet pystyttiin havainnoimaan. Tulevaisuuden haasteina säilyvät edelleen suuren tietomäärän suodattaminen sekä mittauslaitteiden soveltaminen jatkotutkimuksissa. Työssä kehitetty mittauslaitteisto soveltuu tarkoitukseensa mittaustarkkuuden sekä kustannustehokkuutensa puolesta hyvin. Tulevaisuudessa parempaan tarkkuuteen voitaisiin päästä tarkemmilla mittalaitteilla sekä tämän työn pohjalta saaduilla tiedoilla.

Avainsanat – Nyckelord – Keywords
Rengas, maaperä, kontakti, Arduino

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Tiivistelmä/Referat – Abstract

The purpose of this thesis was to design, build and test a system, which is capable of measuring in real time simple quantities influencing on tire-soil contact of agricultural tractors mobility. The measuring equipment is based on acceleration and distance sensors connected to the Arduino Uno microcontroller. The tractor's CAN bus was logged and the data was saved using a CAN bus card connected to a Raspberry Pi minicomputer.

The sensors were calibrated, and their sensitivity checked before performing the experiments while driving in the field. Accelerometers were placed on top of the rear axle of the tractor at both ends in housings printed for them and distance sensors were mounted behind the rear axle. All sensors were logged by using Raspberry's Raspbian operating system with a python program. The Raspberry was chosen as a computer because of its demanding low space, low cost, and versatility of interfaces.
The properties of the field were monitored by monthly penetrometer measurements as well as SoilScout sensors embedded in the ground, which indicated the moisture and temperature of the ground at that depth in real time. The purpose of this was to find out the changes in the field during the growing season, which would also affect the tractor's mobility.

The measurement were carried out successfully and the result were considered to be reliable and provide many other opportunities for the future. The results clearly indicated the factors influencing the tractor's mobility and the different stages of the tillage could be recognized. Future challenges remain the filtering of large amounts of data and the application of measuring equipment in further research. The measurement equipment developed in the work is well suited for its purpose in terms of measurement accuracy and economical affordability. In the future, better accuracy could be achieved with more accurate measuring devices as well as data obtained from this work.

Avainsanat – Nyckelord – Keywords

Tire, soil, contact, inflation, Arduino

Säilytyspaikka – Förvaringställe – Where deposited

Department of Agricultural Sciences and Viikki Campus Library

Muita tietoja – Övriga uppgifter – Additional information

The work was supervised by Antti Lajunen

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Terms and abbreviations

AD converter	Is a device that converts the analogical signal into digital numerical values
CAN	Controller area network which is used in vehicles, machinery and industrial equipment
CBR value	Californian Bearing Ratio is a test performed with penetrometer used to evaluate the subgrade strength of soil
ISO	International Organization for Standardization
PGN	Parameter Group Number defined in the J1939 standard
SAE	Society of Automotive Engineers. It is a standard developing organization.
RCI	Rating Cone Index is a soil index to describe soil shear-strength that includes the consideration of the sensitivity of soil to strength losses under vehicular traffic.

1 Introduction

Global tractor markets are showing an increasing demand for greenhouse gas emission reduction and due to the rising fuel costs also energy efficiency is getting more attention. Over the last decades, engine power has been increasing at an annual rate of 1.8kW and reaching today about 500kW for the most powerful class machines (Osinenko, Geissler & Herlitzius 2015). In field operations, the traction efficiency reaches barely 50%, which is problematic for effective use of energy. Transmission, axles, tires and tire slip consist of a significant amount of energy losses for agricultural tractors. There are several ways to affect the slip such as inflation pressure, tire size and weight distribution. It has been shown that wheelslip is causing more compaction than additional wheel loading (Davies, Finney & Richardson 1973). Real time estimation on varying terrain has been of interest in research. For example, Dallas et al., 2020 developed a nonlinear terramechanics Soil Contact Model(SCM) which can estimate the terrain parameters with high accuracy and high computational efficiency.

The vertical position of the rear axle can indicate the sinkage of the rear wheels and it can be observed with ultrasonic distance sensors. The descending of the rear axle can also be due to increased axle or rear hitch load. The intensity of the up and down movement can tell about the roughness of the surface and tire inflation pressure. The force resisting the forward movement of the wheel is caused by the wheel sinkage and resulting rolling resistance. Rolling resistance can be lowered on hard surfaces by increasing the inflation pressure and lowering it on softer soil decreases rolling resistance by reason of smaller sinkage (Saarilahti 2002). According to Arvidsson et al. the stress increases with increasing tire inflation pressure and increasing wheel load (Arvidsson and Keller 2007).

In the latest agricultural vehicles, more and more quantities is controlled and observed via external sensors either attached to the vehicle itself or previously located like Soil Scouts and weather stations. With the help of sensors measuring weather and soil conditions, maybe in the near future unmanned field robots can adjust their properties according to the current conditions.

2 Strength properties of soil

Soil has four strength properties. The shear strength, which can be tested with a shear vane, the soil compression strength which can be tested with the penetrologger, the soil tensile strength which can be tested with uniaxial tensile test and soil compressive strength which can be tested with a compression device.

In the field of agricultural machinery, understanding the soil shear behavior is important. When the mechanical implements such as plows and chisels interact in the field operations the soil mechanical properties need to be clear. In soil-tool interactions the soil internal friction and cohesion also play an important role since they affect the draft force and soil disturbance of the tool (McKyes 1985). The major factors affecting the cohesion are soil density and moisture content (Sadek, Chen & Liu 2011) but in a 2002 survey by Mouazen it was shown that also the organic content and shearing apparatus affect the shear rate. Study by McKyes (1985) showed that as the soil shear strength increases in soil water content decreases. Many studies report that strength properties reach peak at particular water content ranges (Mouazen 2002)

The force resisting penetrometer is often used as an estimate of the resistance of soil to root elongation. However in the case of field traffic it is possible for the operator to control the application of loading speed unlike the nature of the soils. Hence it is important to understand the soil behavior during the compression. The tyre slippage is often defined as a loss of the linear velocity of the wheel center due to the integrated tyre longitudinal compression and soil compaction (Andreev & Vantsevich 2017).

Since most soils have poor tension strength the roots of surface vegetation work as a fiber network to provide tensile strength to the soils. Soil reinforcement also has a stabilizing effect on slopes to minimize landslips and on saturated soils that are even more likely to have poor strength in tension (Wieder & Shoop 2018). A year 2010 study conducted by Ali investigated the mechanical properties of roots in slope stabilization and found out that root tensile strength decreases with increasing root diameter. Vegetation is also widely used to prevent surface erosion without intention to provide any additional surface strength but Gyssel et al. (2005) found out that vegetation cover is more important than plant roots on resistance of soil to water erosion.

3 Tire-soil contact

Slip means velocity difference between the tire and the chassis and it has been proven to be a more significant factor of causing compaction than additional wheel loading (Davies, Finney and Richardson 1973). Slip indicates as percentage how much shorter distance is transported during the drag compared to a distance without slip. For example if a tractor travels a distance of 80 meters without a slip, with a slip of 20% it progresses 64 meters. The slip should not exceed over 10% if it is desirable to avoid compaction of clay soils and in grass cultivation slip over 10% damages the plants (Elonen, Alakukku & Koskinen 1995). Compaction is also proven to be a major factor affecting root growth and crop yields (Gerard, Sexton & Shaw 1982). Another factor causing reduced yields is erosion due reduction in water-holding capacity and nutrient availability (Colacicco, Osborn & Alt 1989). Figure 1 presents the traffic factors and soil properties affecting the soil compaction. Although the optimal slip control has aroused interest for some researchers, Pichlmaier (2012) suggests calculating the rolling resistance coefficient and actual net traction ratio from drive torque in transmissions together with draft force and wheel load measurements. The main affecting factors related to traction efficiency of farm tractor are tire pressure, tire and track properties, vertical load and the slip.

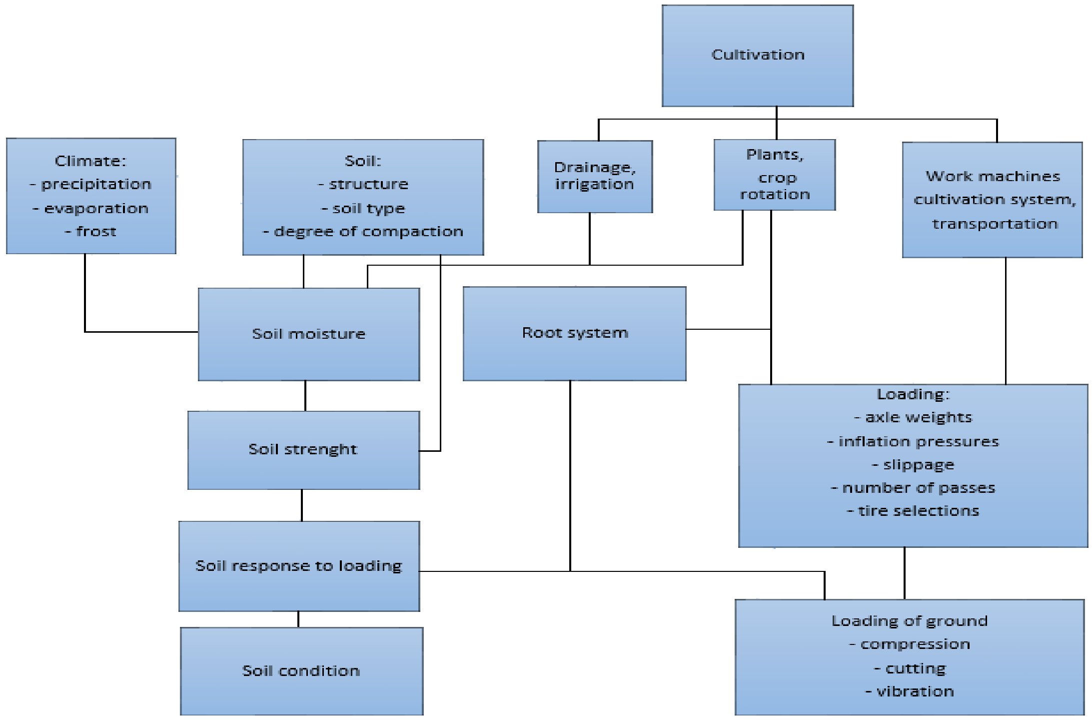

Figure 1. Soil properties and field traffic factors affecting the soil compaction process. Image edited from (Canarache 1991, Soane and Ouwerkerk 1994b).

3.1 Ground pressure

Tyre travelling over soil causes non-uniform ground pressures across the width of the tyre as well along the entire length of the tire contact area. When the recommended inflation pressure is being used, the mean ground pressure can be approximated by the tyre inflation pressure (Arvidsson & Keller 2007). According to Sandomirsky et al. wheel sinkage and the RCI (Rating Cone Index) are closely related to each other when the tractor is traveling on a specific soil (Sandomirsky et al., 2007). There are computer-based simulation models for predicting the ground pressure distribution for tracked (Gigler & Ward 1993) and wheeled tractors. Also, Hetherington and White (2002) mention the ongoing argument of the linkage between ground pressure of a vehicle and its ability to travel terrain. There is a formula (Equation 1.) at design state to predict tracked vehicles' potential to traverse soft ground but Rowland (1972) elected to use actual ground pressure measurements, deduced from draw-bar-pull data when developing the equivalent formula for wheeled vehicles.

$$MMP = \frac{kW}{2b^{0.85}d^{1.15}\left(\frac{\delta}{h}\right)^{0.5}}$$

Equation 1. Rowland method for predicting the ground pressure for wheeled vehicles

Where:

δ = tyre deflection related to the load

k = coefficient varying between 3.65 to 4.6 depending on the number of traction axes

h = height of the carcass of the tyre

The problem that is encountered often in experiments where the transducers are buried to different depths is converting the measured pressure at given depth to an inferred pressure at the surface. Common secondary problems are that soil type affects the inferred pressure values at the ground surface (Hetgerington and White 2002). Hence, it is difficult to utilize formulas on different soil types but in general it can be said that higher weight and higher inflation pressure leads to higher ground pressures.

3.2 Vibration

Vibration is induced by the terrain roughness in the chassis of vehicles moving cross-country. If the conditions are exceeded over certain point, these vibrations affect the comfort of the driver detrimentally and the vehicle can no longer be controlled by the driver (Laib 1995). Vibrations resulting from the vehicle interacting with rough terrain and from the vehicle's power source are frequently in excess of internationally accepted levels. There are primarily two types of vibrations: sinusoidal and random. Sinusoidal vibration occurs in nature and is predictable whereas random vibration is unpredictable and random in nature (Prasad, Tewari & Yadav 1995). Vibration of a certain frequency may come from a running engine or transmission and its intensity is usually expressed in acceleration (m/s^2) and frequency in Hertz (Hz) (Suomen standardisoimisliitto 2002). But originating the source of the vibration can be difficult because it is influenced by many different factors. Especially tractors equipped with belt tires (tracks), tire elasticity and air space help reduce vibration and allow the tire deformation under, smoothing the stress peaks (Jones 1999). Vibration also has potential negative effects to the occupants such as fatigue, comfort degradation, cabin noise and wayside noise (Hildebrand, Keskinen & Navarrete 2008).

3.3 Soil damage

Total cultivation area globally is 1.6 million hectares of which 25% are degraded (FAO, 2011). One form of soil degradation is soil compaction that changes soil structure, restricts water and air infiltration and reduces root penetration into the soil (Nawaz et al., 2013). Compaction can also lead to reduced water permeability, which then can cause runoff path for water and soil erosion (Hildebrand, Keskinen & Navarrete 2008). In cropping systems soil compaction is caused by machinery traffic applying larger stress than the soil bearing capacity is (Hamza and Andersson 2005). During the operations of high axle loads like tillage, harvesting and slurry spreading soils are often moist (Håkansson and Petelkau 1994) and it has been shown by numerous studies that loaded wheel compact moist soil. Especially wheeled tractors have been related to over compaction (Davies, Finney & Richardson 1973).

Whether the soil damage is erosion, compaction or salinity it eventually leads to economic damage. In many cases, the on-farm damages are caused by increased costs on inputs such as fertilizer and reduced yields (Colacicco, Osborn & Alt 1989)

4 Tractor mobility

Tractor's mobility means its capability to move easily from point to point. Demand for evaluating especially the mobility of unmanned ground vehicles is growing as the penetration levels increase (Gorsich ym. 2018). One of the key features of off-road mobility is soil moisture but predicting it is complex because it varies in both direction and magnitude along the season and location. Evaluating soil strength may not be possible by visual inspections and it is among the top causes of terrain inaccessibility. Terrain features such as slopes, can cause restrictions to vehicles and are more easily assessed on site unlike surface roughness that may slow down vehicle traffic but will not cause terrain inaccessibility (Stevens, McKinley & Vahedifard 2016).

In the evaluation of the mobility of off-road vehicles, tire-terrain interaction plays a major role. The handling and traction are influenced by soft soil affecting the mobility evaluation. The number of passes has an exert influence on evaluation of off-road vehicles' traction (Senatore & Sandu 2011). A study by Holm (1969) shows that after each pass the soil properties are converted and the variations are a function of slip.

However, most of the studies considering soil impacts on vehicles mobility are performed on bare soil and the type and amount of vegetation are not documented. This is important since many of the crucial work steps are performed on plant coated soils like mowing and threshing. It is important to understand the dynamic nature of the interaction between soil and vegetation to predict vehicle trafficability which is related to sustainable land management. Shoop et al. (2015) conducted a survey related to biomass impacts on vehicle mobility concluding that biomass had a positive benefit on increasing net traction on sandy and clay soils.

Saarilahti (1991) described the vehicle's terrain mobility with two elements, terrain and vehicle. There are also numerous physical properties that affect the tractors mobility like weight of the machinery, number of wheels, weight or volume of the load, measure and inflation pressure of the wheels. In some rare occasions the mobility limiting factors can be tractors measures like narrow underpasses (Suvinen 2002). Such cases can be forwarding in deep snow where the tractor cannot develop necessary grip from the ground. Some sources suggest that net traction ratio is the best indicator of wheel mobility and with its help precise mobility models can be created but defining the net traction can be difficult.

5 Controller Area Network

CAN bus (Controller Area Network) is an automation bus designed for data transfer which is being used especially in vehicles. Bus baud rate is between 125 kbit/s – 1 Mbit/s depending on the application. The CAN bus was originally developed in the 1980s by Robert Bosch. Its purpose was to simplify the cabling of the Anti-lock Braking System. Typical communication on the bus is between the control devices connected to it and all the messages are usually forwarded to all control devices in the bus. With current speed rate the maximum number of messages is approximately 1800 per second which can results in saturating near 100% usage of the CAN-based ISOBUS. Nowadays vehicles can utilize multiple CAN buses. The corresponding SAE standard used in agricultural vehicles is J1939. The J1939 standard series defines that implements can be semi-mounted, mounted, tow-behind or self-propelled and its purpose is to standardize the data transmission method and form (Tuunanen 2014).

5.1 Bus topology

The most common structure is a bus where from point A to point B control devices are connected to a twisted pair cable (Figure 2). The wiring is a 2-pole pair cable with 40 turns per meter as standard. It should be as straight as possible to avoid complex network structures and its maximum bus length depends on the used baud rate. In addition to the controller devices there are usually two 120Ω terminating resistors and they should be located at both ends of the bus. Their purpose is to prevent possible electrical reflections that might interfere with the operation of the bus (Voss 2008). The nodes are connected to CAN_H and CAN_L whose waveform switches from 1.5V up to 3.5V by two wires. When messages are not moving in the bus it is in recessive state and both channels have voltage of 2.5V and in data transfer mode CAN_H voltage varies from 3.5V-4.3V and in CAN_L between 0.7V-1.5V (Leminen 2015).

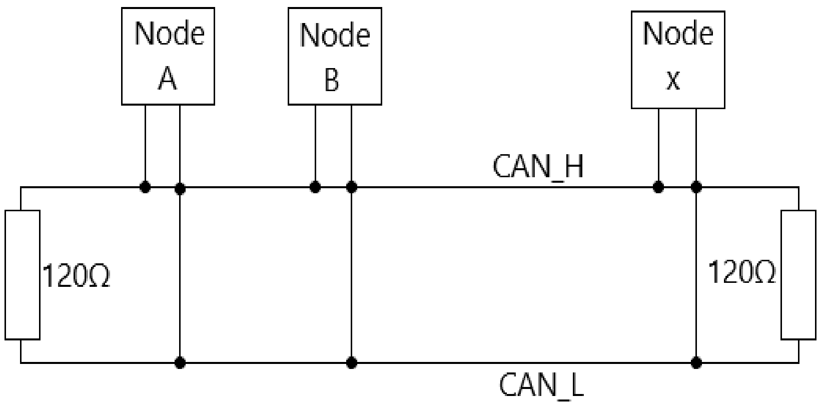

Figure 2. Controller Area Network bus topology.

5.2 ISO 11783

ISOBUS is a specification based on ISO 11783 standard that describes how to interpret the standard. ISOBUS defines a communication network suitable for control and data transmission between the virtual terminal, sensors, actuators, controls, the tractor ECU and the implement ECU. This ensures a different mechanical and digital compatibility between devices and with one ISOBUS terminal that the user can control all ISO bus-compatible implements. The ISOBUS compatibility of tractors and implements has been a problem (Oksanen et al. 2005). In commercial context the term ISOBUS refers to the brand owned by AEF (Agricultural Industry Foundation).

One benefit of the ISO 11783 is allowing the development of automatic guidance systems for agricultural machinery which demand has grown. The development is stable and new functions are integrated into newer versions like supporting the headland turning. If better accuracy is beneficial, there are standalone implement steering and guidance systems in the market e.g. Trimble (Oksanen & Backman 2016) but marketing machines equipped with the ISOBUS brand are only allowed for those who passed the conformance test by AEF (Linkolehto 2018). Furthermore, in the future versions of ISOBUS, there will be better possibilities for transferring even larger amounts of data from implements to tractors.

The AEF (The Agricultural Industry Electronics Foundation) formed a team to work on the High speed ISOBUS. From the main use-cases they found out that the greatest need is for more precise command and data logging as well for higher featured and more responsive display of information. They came into a conclusion that these could not be solved with the present level of CAN precision. From methods already developed to meet the increased requirements, the better would be CAN-FD. It is capable of 8 Mb/s data transfer but is incompatible with the present CAN-based ISOBUS and would require additional ECU’s (Engine Control Unit), e.g. FlexRay with 2 channels at 10 Mb/s, which already is being used in automotive systems or Ethernet ranging below 10 Mb/s to over 1Gb/s. In some of the use-cases, wireless connection was not seen fulfilling the requirements due the lower level of tolerable latency and safety manners even if it would otherwise meet the demands (https://www.aef-online.org/home.html).

5.3 PGN

When looking at the activity of J1939 the parameter group numbers play a significant role. The PGN tells the receiving control device what kind of data it contains. The wanted

PGN can be asked by sending the message frame with a parameter group number 59904. The PGN itself has been divided into four smaller parts. Data page tells the data page to be used. To add pages to the protocol R page exists. Fields PU-PS defines the possible destination address and message function or broadcasting to everyone. Data fields contain the data to be transmitted in the message and the content has parameters such as engine temperature. These parameters are numbered as they are called SPN or Suspect Parameter Number (Hyvämäki 2015).

6. Research objectives

The goal of this research was to build an affordable measuring equipment to estimate agricultural tractors mobility in real time and test it under practical conditions. The study was conducted in Viikki Research Farm. Test drives were performed on the Research Farm's fields during the growing season and the data were analyzed afterwards with MATLAB.

7. Materials and methods

7.1 Tractor and implement

The tractor on which the tests were carried out was a 2008 Valtra N141 with a front loader. During the measurements, it had typically used tire pressure. The dry weight declared by the manufacturer was 48.5 kN but due to the front loader and liquids such as fuel and oil, higher reading of 63.3 kN was measured. Specific features are introduced in Figure 3.

Items	Specifications
Model	N141
Manufacturer	Valtra
Rated power/speed	111,8kW/2200 rpm
Weight, kN	63,3kN
Front tire	14.9R28
Rear tire	18.4R38

Figure 3. Specifications of the tractor used in this study (https://www.tractordata.com/).

Weight measurements were performed one axis at a time with DG DINA 3 weighbridge. The scale is more accurate than +/- 0.015%, which was declared by the manufacturer in the manual. Specifications for the scale are shown in Figure 4. The total mass of the rear axle was 31 kN and the front 32.2 kN, which makes the weight distribution of the front and rear axle 49/51 without implement. The weight split is often dependent on the type of tractor and the way the implements are hitched, or mounted to the tractor (Staton, Harrigan & Turner 2005). Since the implement (Figure 13) is no longer in production and the manufacturer did not provide any specifications according to its physical characteristics its mass was calculated by weighing the tractor with and without the cultivator, thus the difference in the mass was the weight of it. The working width of the cultivator implement is 3 m and it consists of 13 spring-tooth harrows in two rows followed by straw mixers. One of the spring-tooth were missing the whole time of the measurements, which may have had an effect on the vibrations as indicated in the Figure 18.

Items	Specifications
Measuring accuracy	1 - 2 - 5 - 10 - 20 - 50
Systems weight limit	19.6kN
Minimum weight to be weighed	980N
Computer accuracy	Less than ±0.0015%

Figure 4. Weighbridge technical information.

7.2 Field observations

For the observations of the reference field conditions we used four wireless soil moisture sensors which were placed at different depths 0.25 m and 0.5 m (Figure 5). SoilScouts send data of the soil's temperature, moisture and electrical conductivity via telephone network every 20 minutes. They operate at 869 MHz and using higher frequency would cause high dielectric losses and could deteriorate further by vegetation (Tiusanen 2009). The depth was measured from the ground with the help of vertically planted plank and measuring tape like in Figure 5. We also had to make sure that the round antenna head was facing the echo repeater, which was placed on the edge of the field between the sensors and homebase antenna. The bottom of the pit was loose ground and the soil was placed on top of the sensors carefully to avoid rocks and maximize the contact area. It was also of great importance to fully fill the pit with the soil to prevent accumulation of excess water that might distort the measurement results.

Figure 5. Measuring the depth of the pit in which the sensors were placed.

To evaluate the CBR value (Californian Bearing Ratio) Eijkelkamp Penetrologger was used. CBR is an index of soil resistance to shearing under a standard load compared to the shearing resistance of a standard material subjected to the same load. Penetrologger test is performed by measuring the pressure required to penetrate the soil with a cone of suitable area. The cone is chosen according to the density characteristics of the soil and, in this study, a cone size of 2 cm^2 with head angle of 60 was used. In total, 18 measurements were taken at once from six different locations close to the locations of SoilScouts. The locations were determined with the in-built GPS of a pentrologger. A typical penetration result is presented in Figure 6. The soil type of the test area was defined earlier by Eurofins Viljavuuspalvely Oy as Clay loam which is typical in that area. Also during the field tests, there was little to nothing vegetation on the field which could have affected the slip and traction performance.

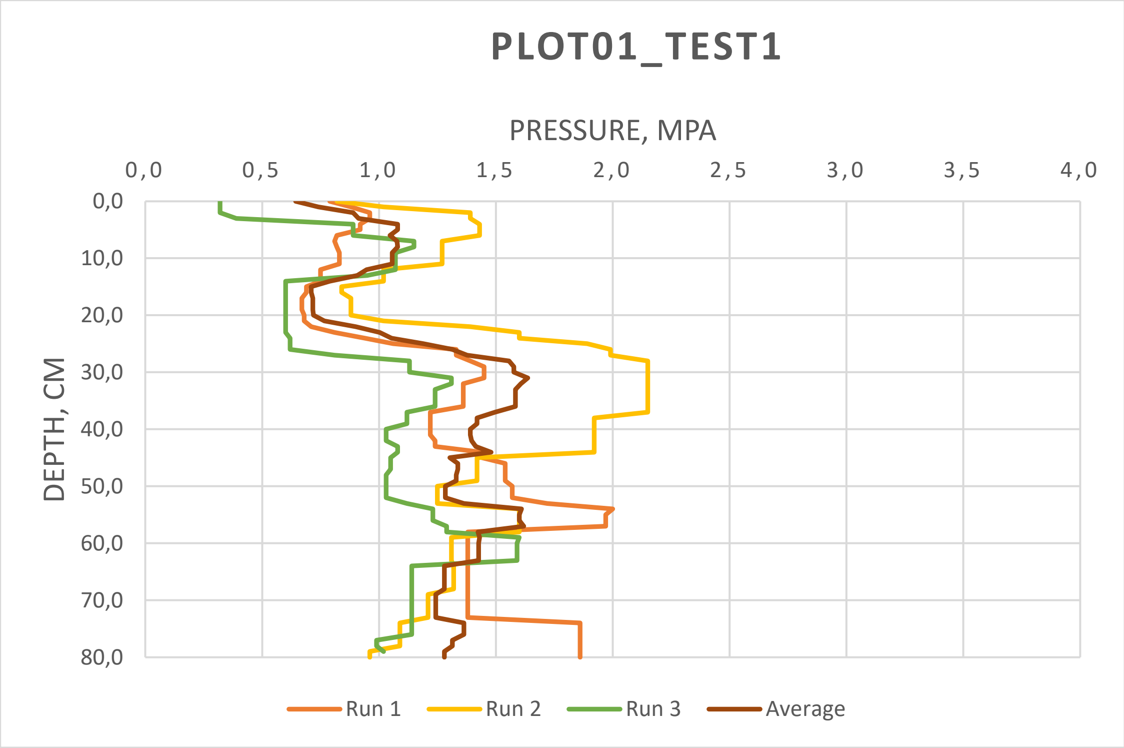

Figure 6. Penetrologger results from the test area presented as depth and pressure function

The second instrument that was used to examine the soil properties was a shear vane test. It is primarily used to determine the shear strength of fine-grained soil types. In the shear vane, four wings formed of mutually perpendicular plates are pressed into undisturbed ground and the wing is rotated by hand at a constant speed. The value of the shear strength is obtained by means of the torque required to rotate the wing and the geometry of the cutting surface. The results obtained cannot be directly applied in the capacity calculations but the values make it possible to get an idea of the local variations in shear strength.

The height of the wing is usually two times its width and the correct wing size can be determined for example based on weight drilling resistance. The drilling depth is the depth of the center of the wing at the time of measurement of the shear strength which in this case was 0.2 m. Three samples were taken from six different locations with a vane size of 16x32 mm, which has to be taken into account when multiplying the results.

Possible sources of errors in the readings are if the drilling is done too close to old drilling points or the ground has gripped to wings and rod (Kairausopas 1999).

7.3 Measurement system

Before testing the measuring equipment in practical conditions, it was built and tested with the help of a solderless breadboard to which the test connections were made. Since the device was built from start to finish by ourselves, there was no absolute guarantee if the system would work as desired. In Figure 7 the connections are presented visually to help outline the connections. In the following figure, on the left from top to bottom are the plugins for the two accelerometers, ultrasonic distance sensors and 12V power intake from the tractor.

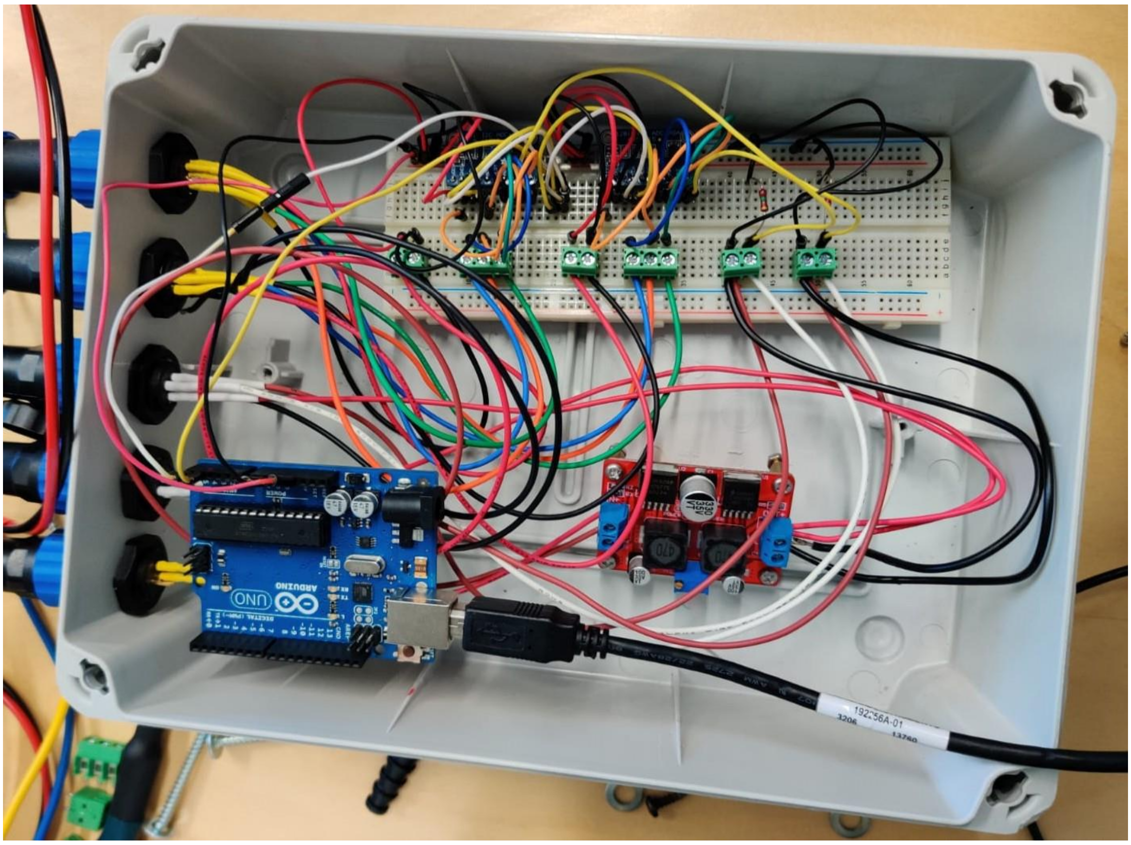

Figure 7. Connections presented visually.

The communication between the "master" or Arduino Uno and "slaves" or the sensors happens with I2C protocol (Mankar et al. 2014). In this case, the slaves were the two ADC boards that collected the measurement data from the sensors. The I2C is a simple two-way control and communication bus, which enables connecting multiple slaves to one master or multiple masters connecting single slave. The number of devices is dependent on how many bits is used in the addressing. I2C uses only two wires to communicate the SDA (Serial Data) which is for the master and slave to send and receive data and the SCL (Serial Clock) that carries the clock signal. The speed grade of I2C varies between 100 Kbit/s to 3.2 Mbit/s. In this study a baud rate of 115200 was used and it determines the speed of communication. Figure 8 visualizes the symbiosis better. In the bus, the data is transferred as messages, which are then broken into frames of data. The message begins with the binary address of the slave and then one or more data frames and stop conditions. It is also always 8 bits long and the most significant bit is being first.

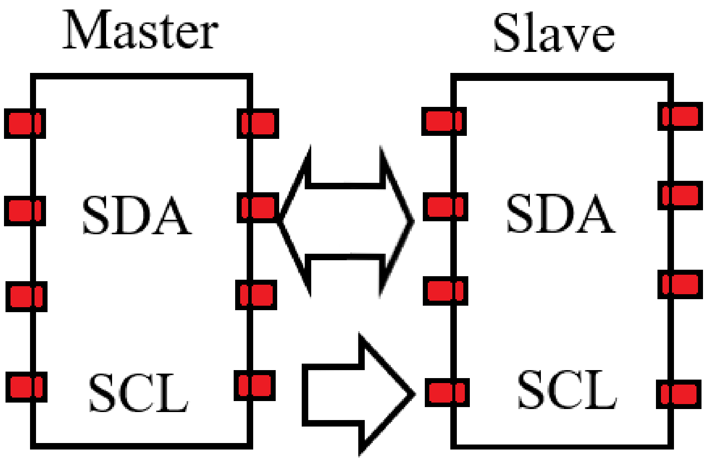

Figure 8. Communication between the master and slave.

7.4 Ultrasonic distance sensor

The microcontroller used in this survey was the Arduino Uno and the accelerometers attached to it was the SparkFun Triple Axis ADXL335. The ultrasonic distance sensor was Sick UM18-2 Pro, which more detailed information is presented in Figure 9. The operating system to collect the measured data in real time was provided by Raspberry Pi. Since the output signals from the sensors were analog, they had to be converted to digital format because of the technical limitations of the Arduino Uno board (number of analog inputs and 10-bit AD converter), separate AD converters (Adafruit ADS1015) were used also for higher measurement resolution.

Items	Specifications
Model	UM18
Manufacturer	SICK
Max./min sensing distance	1300mm/120mm
Resolution	≥0,2mm
Response time	80ms
Minimum operating voltage	DC 9V
Accuracy	±1%
Power	4mA...20mA, ≤500Ω

Figure 9. More detailed information of the ultrasonic sensor.

To get a better sense of the measuring range beam, it is presented in Figure 10. It is important to recognize how differently shaped beam will affect the measuring. For example, how wide measuring angle reduces the accuracy of the sensors in the width direction and might distribute the beam over a wider area, so that the echo reflected back is weaker than with a narrow measuring angle. But compared the echo intensity to the narrow beam which varies more when measuring uneven surfaces (Airmar 2016). As can be observed from the following figure, the soundwave is divided into near field and far field zones presented in different colors. This is due the unevenness of the wave. In addition, at the beginning of the wave is the so-called dead zone, the length of which depends on the duration of the waves (Cartz 1995)

Other key points regarding the operation of the ultrasonic sensors are the sensing range, beam angle, echo confidence and attenuation. The maximum sensing range is marked with 2 in the Figure 10. Voltage used affects the length of the sensing range and the remaining voltage from its formation forms side lobes. Low-frequency ultrasonic sensors maximum operating range extends further that of high-frequency sensors since they suffer less from environmental conditions. High-frequency sensors are being used in more accurate measurements with shorter range and better resolution. Sensors have also minimum sensing distance and this because the waves transmitted by the sensor must be received before echo can be received from the target (Massa 1999 and Milligan 2006).

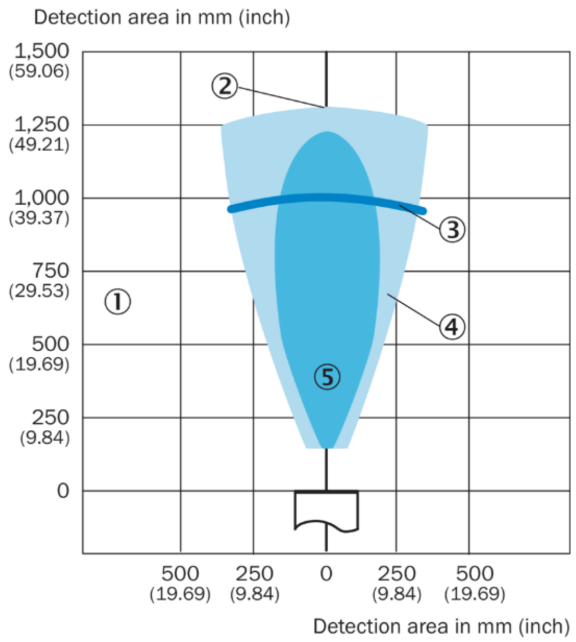

Figure 10. The detection area of the ultrasonic distance sensors.

Ultrasonic distance sensors are used to detect movement or distance and they can be roughly divided into three groups: receivers, transmitters and transceivers. The last one being the type used in this study. To calculate the distance of an object or in this case the soil surface the time between sending a signal and receiving an echo is calculated. Measuring the distance can be continuous or discrete bursts if wanted and the power of the transducer depends on the intended use. The Frequency which affects the range of the ultrasonic sensors was in this case 200 kHz which is considerably high. At this frequency, the resolution can be as high as one millimeter. The output voltage was measured as voltage drop over 150 Ω resistor, which produces a measurement range from 0.6 V to 3.0 V corresponding to 4 mA and 20 mA of current signals, respectively.

The reference measures were performed in the classroom in such a way that the ultrasonic sensors were facing up the roof. We could utilize its full range and regulate the distance with a flat plate moving up and down along the measuring range. This resulted in the maximum voltage outputs of 2.95 V and 2.98 V and minimum outputs 0.63 V and 0.64 V.

Based on the calibration measurement of the ultrasonic distance sensors, the absolute distance was defined with equation (2)

$$Distance = \left(\frac{880}{2400}\right) * Raw\ data - offset$$

Equation 2. A formula that can be used to calculate the distance

Where:

Raw data = Output of the ultrasonic sensor (measurement)

880 mm = Length of the measuring range (1000mm – 120mm)

2400 mV = Voltage distribution over 150 Ω resistor (3 V – 0.6 V)

Offset = 80 mm (based on calibration measurements)

7.5 AD converter

The AD converter operates so that the S/H (sample and hold) circuit in it stores the current voltage level from the analog voltage signal in the capacitor of the circuit. After that the connection to the voltage source is disconnected by the sampling switch. After this process the sample can be converted or quantized to binary form. The 12-bit AD converter is able to differentiate $2^{12} = 4096$ voltage levels. Depending on the voltage range used in the measurements, the voltage resolution changes. Because the acceleration sensors were measured with the same AD converters, the input voltage was limited to 3.3 V and the measurement voltage range was set to ±4.096 V from the Arduino program hence having gain of one. Hence, there was no need to increase the gain of the signal. Therefore, the measurement resolution was 2 mV. Figure 11 shows how the input range of the AD converter is divided into increments.

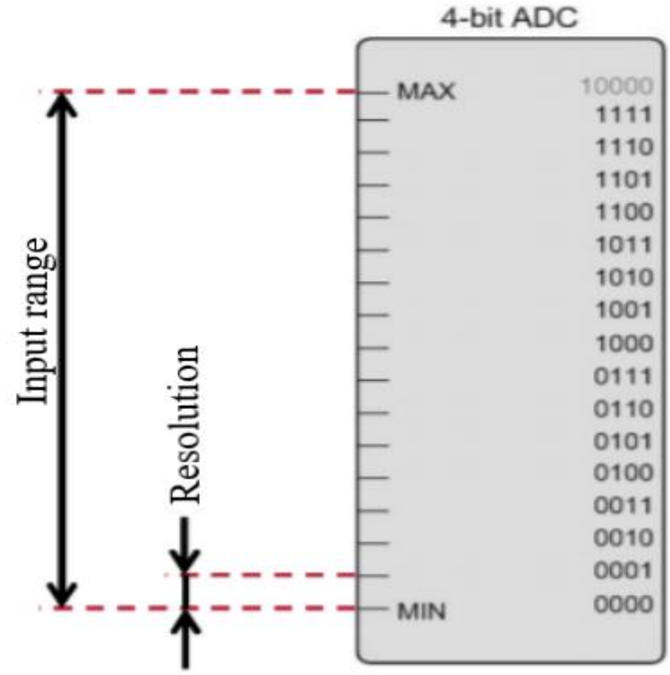

Figure 11. The input range of a 4-bit AD converter.

7.6 Accelerometer

An accelerometer is a sensor that measures self-acceleration or physical acceleration experienced by an object. Self-acceleration is not the same as acceleration compared to a fixed coordinate system but the rate of change of velocity in its own momentary resting frame. Accelerometers are often used to detect and monitor vibrations of rotating machines but are rare in agricultural machinery. They can also measure the condition of devices with rotational motion or repetitive movement, which is the most common condition-based condition monitoring measurement technique (Mills 2010).

Accelerometers are available as single and multi-axis versions depending on the purpose. The resolution of the accelerometer is determined by the used bandwidth. Inside the sensor are polysilicon springs which are used to suspend a beam over the surface of a silicon wafer and provide a resistance against applied force. According to Hooke's law when acceleration is applied to the sensor the beam deflects and a differential capacitor is used to measure the distance of the beam deflected. The output voltage increases linearly with the acceleration over the range. These outputs are then sampled by the AD converter. More specific details of the accelerometer are provided in Figure 12.

Items	Specifications
Model	ADXL335
Manufacturer	SparkFun
Sensing range	±3g
Sensitivity	270 - 330mV/g
Operating voltage range	1.8 -3.6V

Figure 12. Specific information about the accelerometer.

The relative acceleration was calculated with the equation (3)

$$Aout = \frac{\left(\frac{ADC\ value * Vref}{3300}\right) - Voltage\ Level\ at\ 0g}{Sensitivity\ Scale\ Factor}$$

Equation 3. The formula that gives the acceleration values in g unit for X, Y, and Z axis

Where:

ADC value = depends on the acceleration of the axis (measurement)

Vref = 3.3 V

Voltage Level at 0 g = 1.65 V

Sensitivity Scale factor = 0.33 V/g

7.7 Step-up/down DC/DC Converter

To regulate the tractor’s 12 V voltage and ensure the controlled direct current, a step-up DC/DC converter was used for the distance sensors (Figure 13). The DC converter works by taking the current and passing it through a switching element and turning it into a square wave or alternative current. Then it passes through another filter which turns it back to a DC signal of the appropriate voltage. In this case, the wanted voltage output was regulated by turning a knob, which then linearly changes the output voltage. The location of the converter in the measuring system can be perceived better by looking at the Figure 7.

Figure 13. Step-up/down DC/DC Converter 1.3-26V 1A (Photo: www.partco.com)

8 Results

8.1 Field measurements

The measurements were carried out with the machinery and on the field that can be seen in the Figure 15. SoilScout sensors (Figure 5) were buried in this particular field before the first measurements. The cultivation performed during the time of the picture was taken was second measurement run on that test area which had affected on the soil structure, vegetation, moisture and traction resistance. The field and climate conditions are constantly changing and we had no possibility of knowing beforehand how the chosen field would react to those. In addition to these the high groundwater level and clay layer the moisture and temperature variation was little at the depth of 25cm (Figure 16).

As can be seen from the Figure 14, the average length and location of each test drive are presented in different colored lines. Driving with 6.6 km/h set by the cruise control, each draft lasted about 200 seconds. These tests were conducted on uncultivated soil the only exception being the yellow trace located perpendicular to the others. Its purpose was to get data driving on cultivated soil, on transverse to the cultivation direction and lateral glide. The soil turned out to be too soft which attenuated the vibration and lateral glide was so small that it cannot be reliably separated from the data. As it is driving on vegetated soil is more realistic considering the intended use of the implement since its purpose is to cultivate stubble.

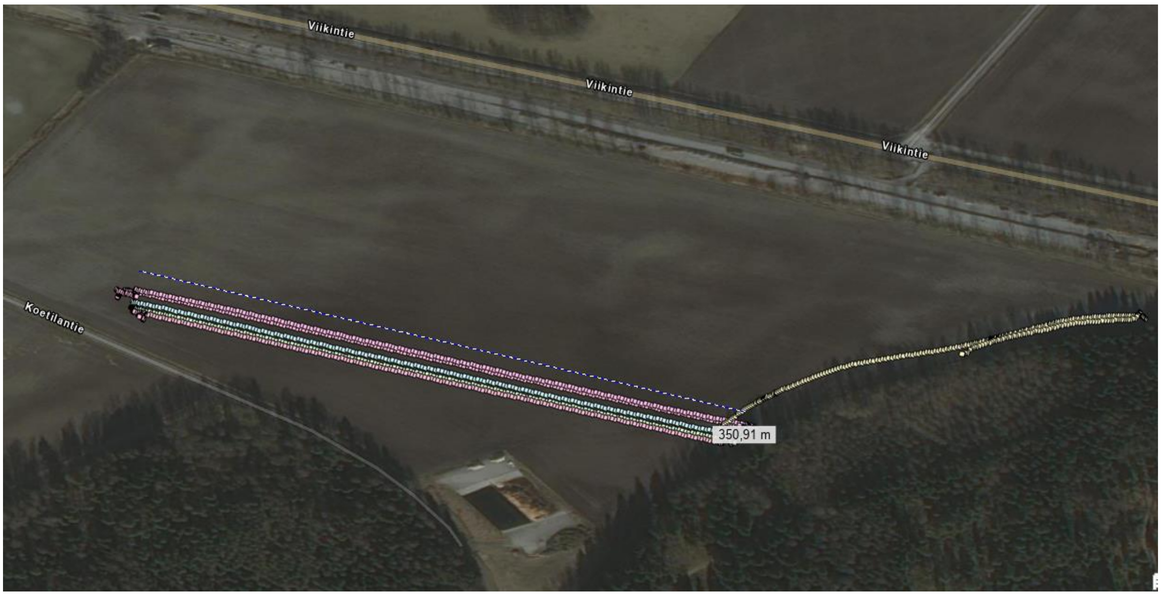

Figure 14. Map of the follow-up trace recorded with GNSS connected to Raspberry Pi.

Tire pressures in front and rear were set to 1.2 bar to increase traction and reduce soil compaction as would normally be done. The implement height adjustable tires tended to sink into the ground due to wet conditions and narrow tires but on uncultivated soil, they worked as supposed to.

Figure 15. The tractor and the implement used in this study cultivating the test field.

The variation of moisture between the two depths (25 cm and 50 cm) was not remarkable taking into account the period of time and uniformity of the soil. The maximum humidity percent observed during this period was 51% and minimum 42.3% and both of these was achieved at the depth of 50cm, but the difference between maximum moistures was only one to two percentage points. At both depths, the moisture remained at high level for considerably long time before starting to change in August even it was less rainy than the 30-year average (https://www.ilmatieteenlaitos.fi/).

The moisture starts to descend towards the October in the 25 cm figure when the air gets colder. Equal change can be observed also from the beginning of June until the late August. It is normal for the changes in condition to be higher in lower depths where weather conditions have a greater impact.

In further future, this would be valuable data especially for the unmanned field robots to be aware of the field conditions. At least still, it is hard even for the human eye to tell if the soil is moist just from the surface or deeper without digging the soil. To avoid getting stuck and damaging the structure of the soil, it would be convenient for the working machine to know beforehand the conditions. The right placing of the SoilScouts is important to get comprehensive picture of the state of the field. If it is possible for the unmanned vehicles to work night and day, it would save the time, if they were able to always work on the dry area of the field e.g. when cultivating. However, some work steps must be completed as continuously as possible such as sowing so that inflammation would happen simultaneously.

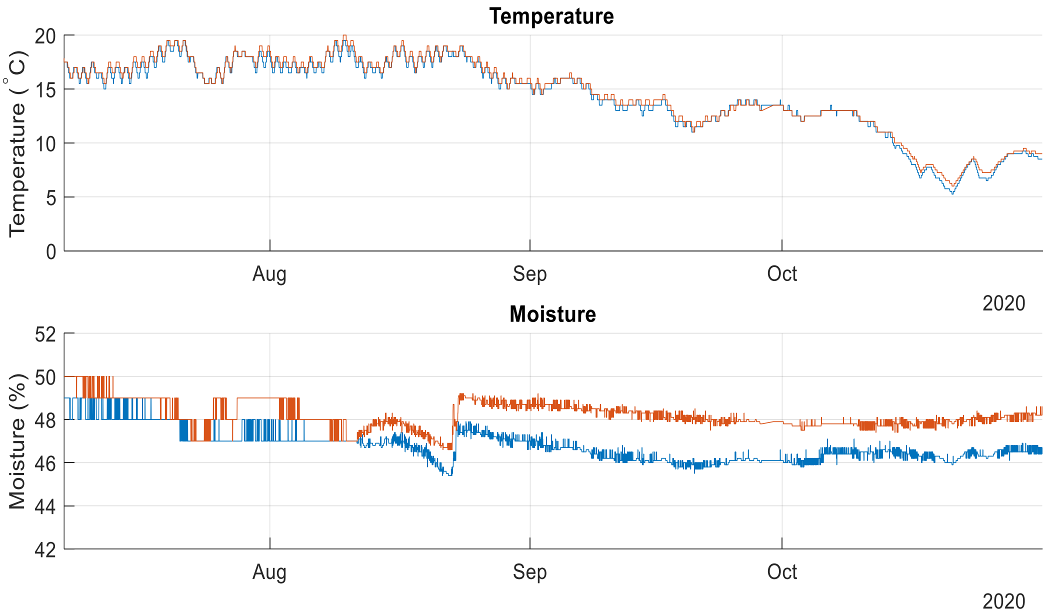

Figure 16. SoilScout temperature and moisture graph at 25cm depth.

The penetrations performed monthly on the test field can be seen in timely order in Figure 16 presented as function of pressure (MPa) and depth (cm). From the six figures, a rising trend can be seen towards the end or going deeper. It begins roughly going past the depth of 20 cm, which is common tillage layer.

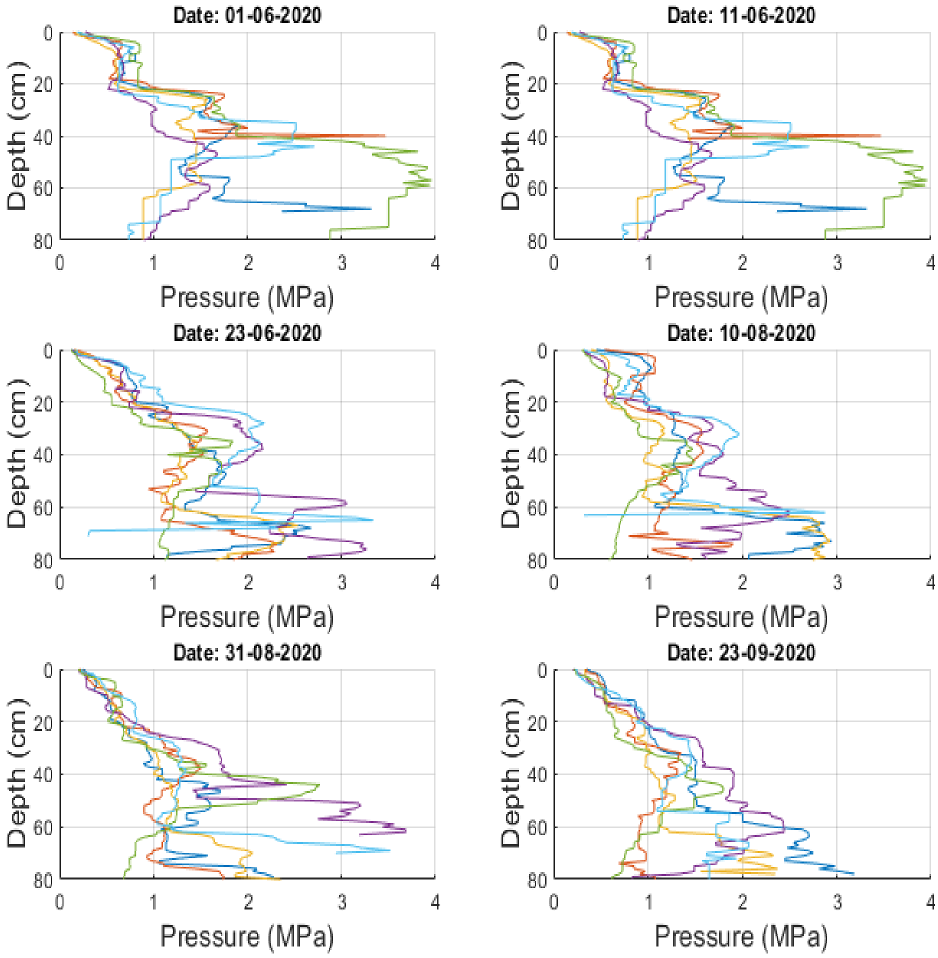

Figure 17. Compilation of the penetrometer results.

8.2 Measurement results

All the measurement data were imported into MATLAB in raw format and then analyzed to produce meaningful results. Figure 17 represents a typical set of four signals received as a result including all three axes from the tractor's left side accelerometer and ultrasonic distance sensor. Similar results were acquired from the right side of the tractor. The measured values have been calculated into relative acceleration (m/s^2) and absolute distance (mm) as described in Chapter 6. An example of the raw measurement data is presented in the Annex 1. The accelerometers were placed on the rear axle the way that the acceleration of the X-axis corresponds to the direction of travel of the tractor and Y-axis corresponds to lateral movement of the tractor.

The acceleration variation along the X-axis (longitudinal) can be due the vibration caused by the harrow spikes and the variation in the traction resistance moving on different soil types. At the end of each acceleration measurement, there is clearly lower acceleration, which is caused by slowdown of the speed at the end of the test drive. The acceleration in lateral direction is much lower, which can be considered normal behavior, as there are practically no forces influencing in this direction. Driving transversely across the forage harvesting direction may cause some acceleration peaks.

Z-axis reflects the vertical acceleration of the rear axle. As can be seen, the acceleration amplitude is highest due to the larger up and down movement of the rear axle. The axle distance results corresponds to the distance from the bottom of the rear axle to the ground surface. Lower distance is due to minor sinking, increased weight on the rear axle, increased tire slip, or increased resistance.

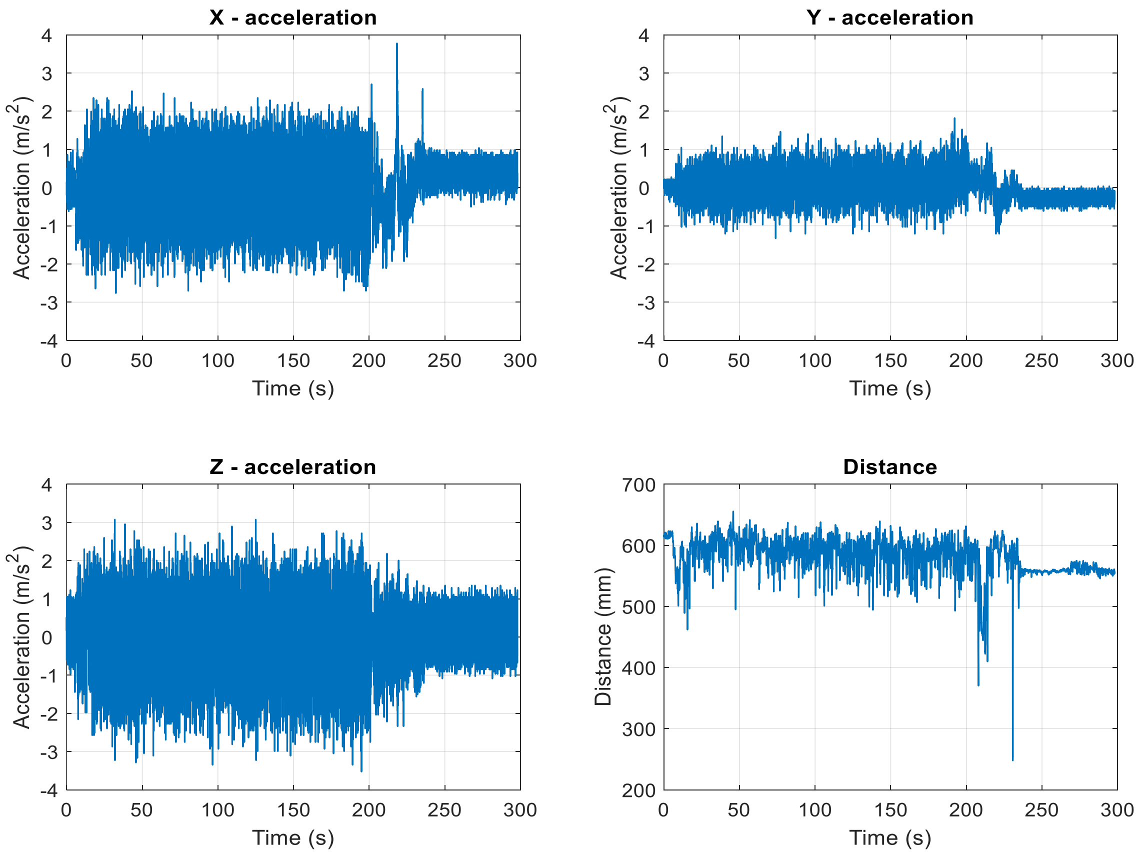

Figure 17. The relative acceleration and rear axle vertical position.

Figure 18 presents the standard deviation of the measured accleration for the nine similar measurements. The results clearly indicate that the test conditions have been very similar and barely any measurement disturbances can be recognized. The quite significant difference between the X-axis acceleration (longitudinal acceleration) indicate a major difference either in the tractor tires, traction force or in the implement. There was one spike missing on the left side of the harrow that could cause some vibration to the longitudinal axis.

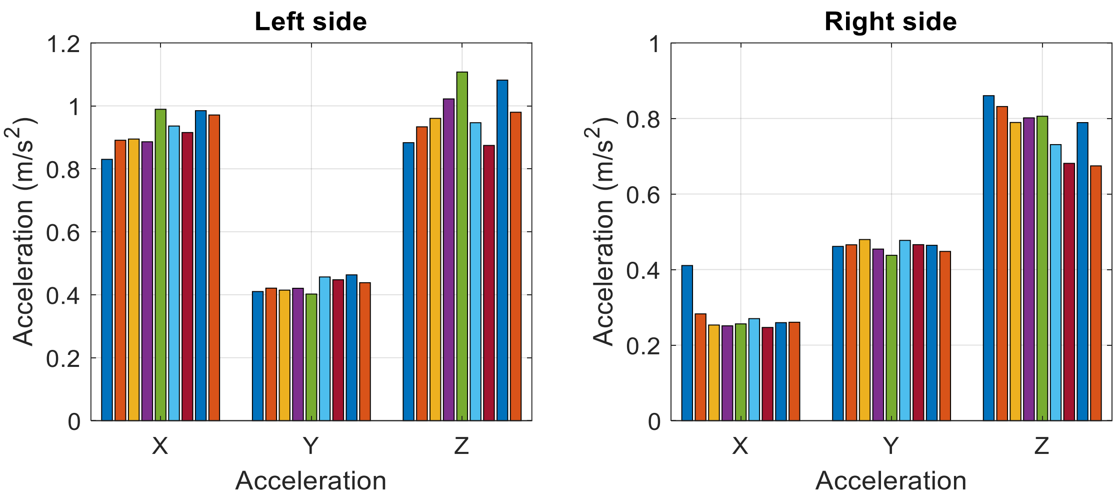

Figure 18. Standard deviation of the acceleration.

Draft force means any force that pull pieces away each other and this case how much the towed implement resist advancing (Figure 19). As can be seen, the draft force does not change radically during the first 200 seconds of measuring the only exception being the spike when the implement is lowered to the ground. Then the draft force decreases to under 10% when the position of the implement is raised as the header approaches. The general belief could be that the draft force varies a lot driving across the field as the soil type changes. Few things that might have an effect on such flat curve is that the tillage depth and driving speed were kept the same during the measurement.

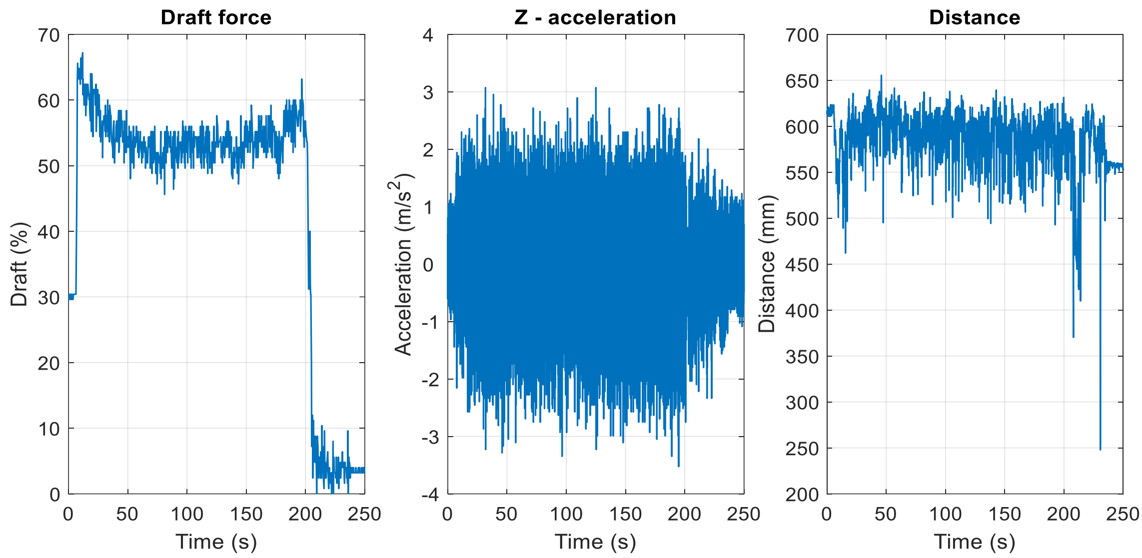

Figure 19. Draft force and change in the vertical distance and acceleration.

9 Discussion

In the interpretation of the results it became noticeable that the vibration changes in resistance and driving speed should be able to differentiate in order to focus on the mobility. There are ready-made filters to filter out the excess data but choosing the right or right ones is the hard part. We could not benefit from the agricultural studies concerning ultrasonic sensors and accelerometers since they are not used very often in agricultural technology researches.

Although the accelerometers have been used so far mainly for monitoring the movements or immobility of livestock, it has countless opportunities when it comes to agricultural automation.

Ultrasonic distance sensor are still in limited use in agriculture particularly in the field of cultivating. Mostly they are being used to monitor the height of the grain surface in the silo and the distance of the spraying boom from the ground to keep it horizontal. In the future, they would also be convenient for keeping the implement straight for achieving a flat seedbed, for recognizing higher weed among other crops or other obstacles. Accelerometers would be well suitable for monitoring the driver's well-being,

With the help of draft force and the distance between the rear axle and ground level may potentially draw conclusions that I think would require further research. Increased draft force may be a sign of harder soil type, which thus requires more power to get cultivated. At the same time, the distance should remain relatively the same as harder soil type carries better. While increased draft force, lowered speed and decreased distance may indicate of getting stuck, hence softer soil type or wetter conditions. Usually increased draft force is a sign of higher fuel consumption.

After doing the reference measurements, it became known that the accelerometers were very sensitive to angular changes. Even a slight change of one degree in the position of the accelerometer could multiply in the end such that results would not be reliable.

Some discussion occurred during the early planning concerning measuring the flattering or deformation of the tires. This plan was then rejected because of the uncertainty of conducting the measurements and its relevance. Although there are available reasonably easily installable sensors for monitoring the tire air volume, measuring the outer dimensions precisely would have been challenging.

The options where the field measurements could be performed were limited since the fields are in the use of Viikki research farm. This led to that test field located on the area where the water table was considerably close to the ground and thus kept the pit wet where the SoilScouts were placed. The whole square is pretty open so there can be no certainty if the weather conditions were better elsewhere. Another influential factor was the current weather when the sensors were put into the ground that could have affected the moisture in the pit.

After performing the first measurements which in themselves would have been sufficient for the amount of data offered an opportunity to run the test on an uncultivated field. This corresponded more realistically to the real cultivation conditions. But still repeating the exact measurements are nearly impossible due constantly changing weather conditions and the operations must be conducted in a timely manner. Reproducibility is from a scientific and reliability point of view appropriate but must be taken into account that the measurement conditions are never exactly the same in such experiments.

10 Conclusions

For a measuring device this price the results were accurate and precise. Even lower precision would have been enough to estimate the mobility. Higher resolution brings unwanted white noise to the data which must be in any case filtered out and detects so small surface changes(such as grass and stubble) that will not have any effect on the mobility. All though, mobility as a concept is wide and keeps inside several different areas which cannot be measured directly by these methods, this measuring equipment is suitable for what it was designed for.

For the future development could be interesting to study more the tire flattening and wheel sinkage to get a better understanding of the weight and traction distribution under load. Also, to study how the movement and vibration of the implement affects the tractor by placing appropriate sensors to it. This would be interesting even from the point of view of understanding in the future how unmanned tractors respond to irregular changes on the field.

11 Thanks

First and foremost, I would like to thank my supervisor and immediate superior Antti Lajunen for his exquisite professional skills related to this line of work and providing me the opportunity to conduct my thesis. I would also like to thank all the other University personnel and my colleagues Mikael Änäkkälä and Niila-Sakari Keijälä who have provided me their expertise and help.

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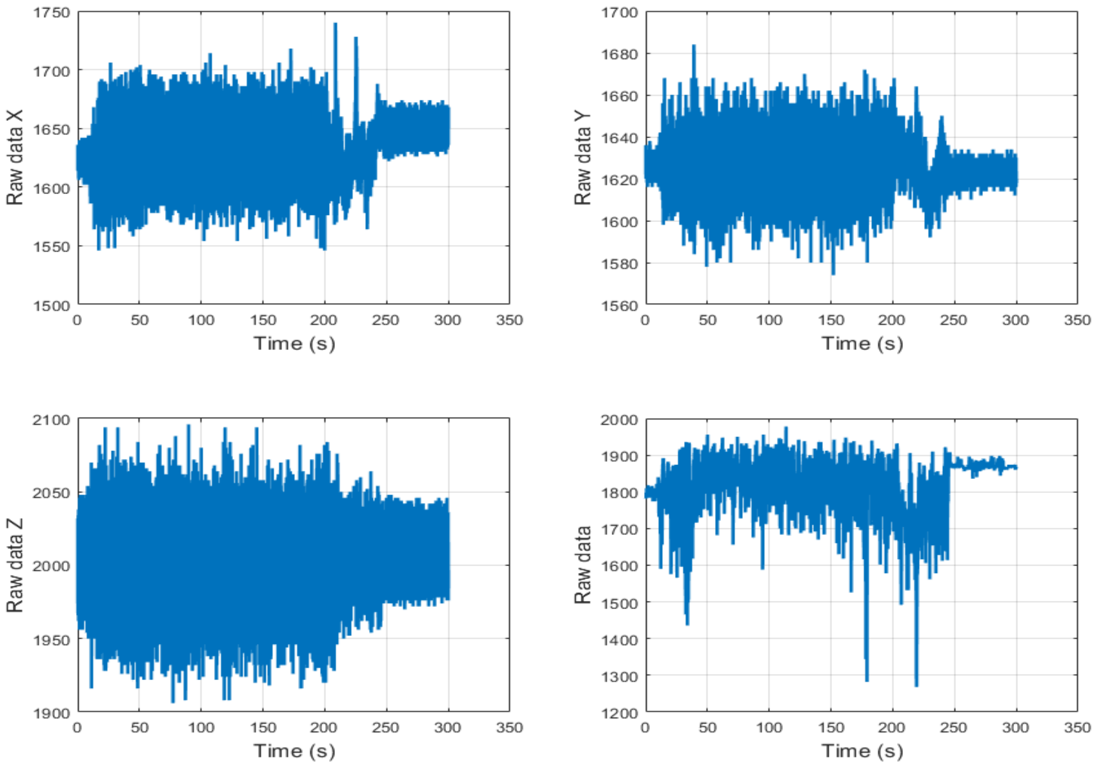
Annex 1. Figures of axis and ultrasonic sensor as raw data before transformation



Annex 2. MATLAB code that allows to transform the raw data into function of acceleration and distance

```
%% Acceleration (g)

X1_ms2 = ((X1_raw*3.3)/3300 - 1.65)/0.33;
X2_ms2 = ((X2_raw*3.3)/3300 - 1.65)/0.33;

Y1_ms2 = ((Y1_raw*3.3)/3300 - 1.65)/0.33;
Y2_ms2 = ((Y2_raw*3.3)/3300 - 1.65)/0.33;

Z1_ms2 = ((Z1_raw*3.3)/3300 - 1.65)/0.33;
Z2_ms2 = ((Z2_raw*3.3)/3300 - 1.65)/0.33;

% acceleration (m/s2)
a1 = (Z1_ms2-mean(Z1_ms2(1:2500)))*9.81;
a2 = (Z2_ms2-mean(Z2_ms2(1:2500)))*9.81;

v1 = ([0; diff(time)].*(Z1_ms2-mean(Z1_ms2(1:2500)))*9.81);
v2 = ([0; diff(time)].*(Z2_ms2-mean(Z2_ms2(1:2500)))*9.81);

s1 = cumsum((v1.*[0; diff(time)]));
s2 = cumsum((v2.*[0; diff(time)]));

% distance
e1s = (880/2400)*E1_raw-80;
e2s = (880/2400)*E2_raw-80;
```