UNIVERSIDAD DE CÓRDOBA

STUDY, DEVELOPMENT AND APPLICATION OF PRECISION AGRICULTURE TECHNIQUES IN AGRICULTURAL MACHINERY

Estudio, Desarrollo y Aplicación de técnicas de agricultura de precisión en maquinaria agrícola.

D. Jacob Carballido del Rey

Doctoral Thesis

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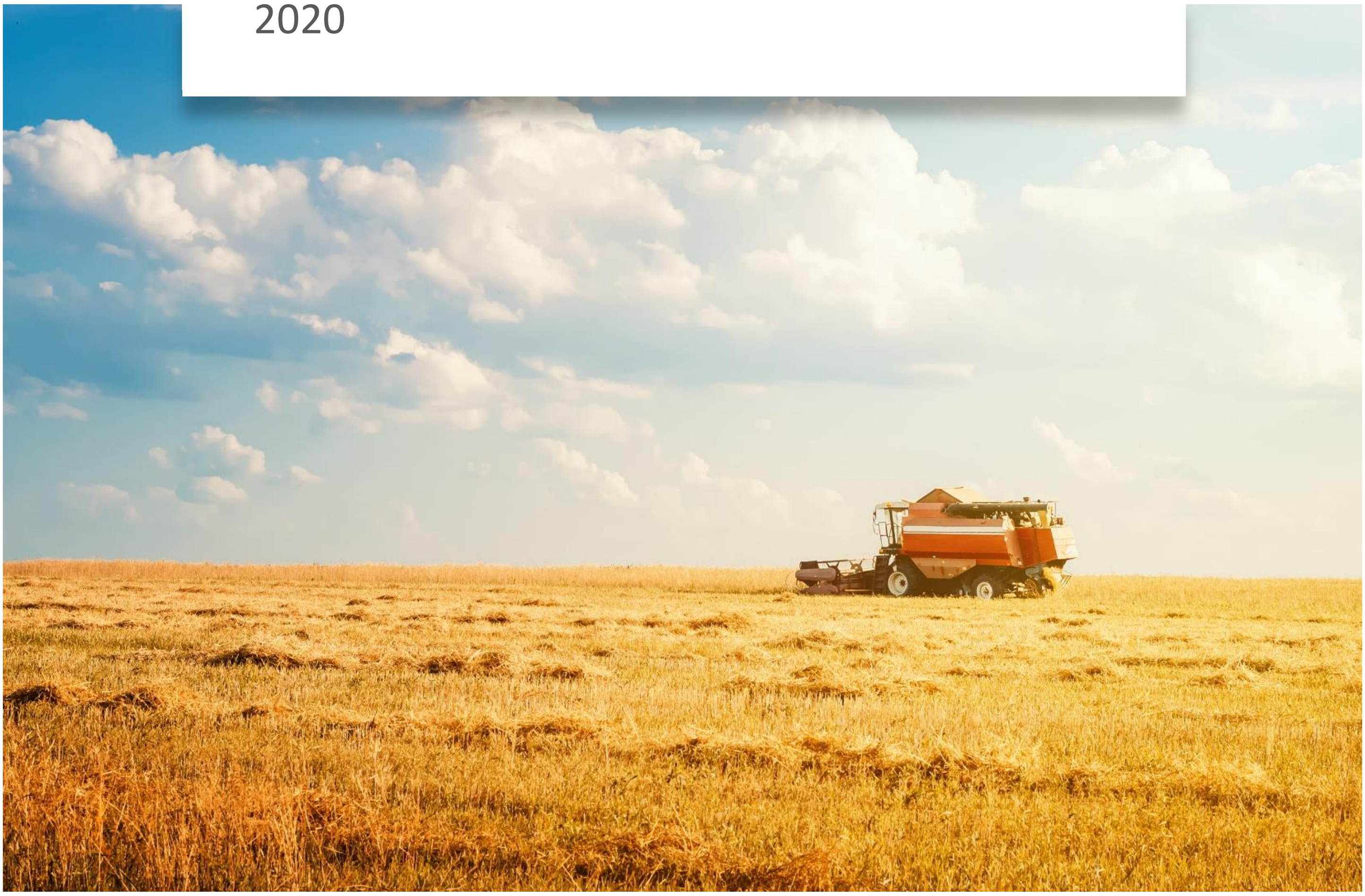

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Universidad de Córdoba

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STUDY, DEVELOPMENT AND APPLICATION OF PRECISION AGRICULTURE TECHNIQUES IN AGRICULTURAL MACHINERY

Presented by Mr. Jacob Carballido del Rey with the aim to receive the “Título de Doctor con Mención Internacional” by the Universidad of Córdoba.

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Abbreviation Index

GPS	Global Positioning System
RTK	Real-time Kinematic
GNSS	Global Navigation Satellite Systems
DGPS	Differential Global Positioning System
CI	Cone Index
EMI	Electromagnetic Induction
DEM	Digital Elevation Model
FR	Resultant force
FC	Cutting force
FF	Frictional force
FM	Reaction force
FBD	Vertical upwards force
FBT	Vertical downward force
SD	Standard deviation
SSPS	Soil Strength Profile Sensor
XTE	Cross Track Error
CA	Conventional application
EA	Experimental application
BS	Base Station
CMR	Compact Measurement Record
EGNOS	European Geostationary Navigation Overlay Service
ESA	European Space Agency
EUREF-IP	European Reference Frame over Internet Protocol
FM	Frequency Modulation

GLONASS	Global Orbiting Navigation Satellite System
IAG	International Association of Geodesy
MSAS	Multi-Functional Satellite Augmentation System-Japan
NASA	National Aeronautics and Space Administration
PDOP	Position Dilution of Precision
RASANT	Radio Navigation Satellite Aided Technique
RDS	Radio Data System
RNE	Spanish National Radio
RTCM	Radio Technical Commission for Maritime Services
SBAS	Space-Based Augmentation System
VBS	Virtual Base Station
WAAS	Wide Area Augmentation System
UTC	Co-ordinated Universal Time
UTM	Universal Transverse Mercator
AIMCRA	Research Association for the Improvement of Sugar Beet Crop of Spain
NSH	Non-selective herbicide
PPS	Pulse per second
NMEA	National Marine Electronics Association
SH	Selective herbicide
BBCH	Biologische Bundesanstalt Bundessortenamt and Chemical industry
GIS	Geographical Information System
CISC	Spanish National Research Council
PDOP	Position Dilution Of Precision
RMS	Root Mean Squared

Abstract

Precision agriculture applied to machinery is today one of the most important working fields regarding agriculture innovations. These tools are meant to be a propeller of the future of farming, well needed in order to face the challenges of modern society, a global increasing food demand while providing a sustainable management of natural resources.

Available technology on this field covers a wide range of possibilities. During the last 10 years, together with the expansion of electronics and digitalization, the offer of products and technics have become quite rich and it generates, in some cases, difficulties to farmers in order to choose the more adequate solution to their production scenarios.

For this reason, this doctoral thesis will focus on the study, develop and validation of two of the most important disciplines in precision agriculture: GNSS guidance and site-specific application.

Today's most important and extended technology in precision agriculture is the use of GNSS guidance systems. Those systems allow the vehicle to be driven automatically, by taken control of guidance interface, resulting in important reductions of the overlap between parallel passes. This reduction impacts directly the time invested on the task, but also all the inputs used. However, the maximum precision reached will depend on the GNSS technology used, as a combination of the receiver installed on the vehicle and the external signals used to enhance the calculations. How to evaluate and classify the technology used to improve GNSS positioning and recommendations on the specific use of them in determinate agriculture applications will be the scope of this thesis.

A second field of work is focussed in one of the most promising technologies within precision farming, site specific application.

This doctoral thesis has developed a procedure to achieve the characterization of soil properties along and across the profile, allowing a variable tillage. This results not only on important saves during the task but also on better and sustainable soil management.

Site specific application of herbicide has been as well part of studies, where significant saves on chemicals were achieved thanks to the assessment and development of a combined, chemical and mechanical, weed control implement commanded by a RTK-GNSS system.

I. Introduction

1.1. Precision Agriculture. General background.

Since 1995 when the American Global Positioning System (GPS) became available and fully operational for the use of civilian applications, the number of products and techniques developed using as based such technology seems to be endless. Agriculture has been clearly one of the early adaptors integrating and tanking advantage from this technology. In part, due to the existing lack that the sector was experiencing in technology and innovation in the field of mechanization, the favourable conditions to deploy such technology, large and simple pattern fields in addition to repetitive tasks, and the continuous pressure to increase production while reducing cost and environmental impact. All these factors have driven a fruitful discipline, which is practically impacting all different crop production systems in arable lands around the world. (Bauer and Schefcik, 1994; Petersen, 1991; Wilson, 2000; Pérez et al., 2004).

Regarding the sector, the adoption of new technologies in agriculture is rarely immediate. Even though much effort is placed into in persuading users to adopt new ICT tools, adoption is a complex activity and many factors influence these decision-making processes. In order to be widespread among farmers, PA tools should be based on a low-cost and a low-performance technology. However, they must be useful enough to provide a benefit to the farmer, either through an improvement, by doing something easier or cheaper than before, or an innovation, something that was not previously done because of financial constraints or an incongruence between the technology and farmer's skills. (Emanuele Pierpaoli et al. 2013)

1.2 PA disciplines: Guidance and implement control -> Sensors & Site-Specific technics -> IOT, Big Data & Robotics.

One of the firsts and today´s most extended GNSS applications in agriculture are the guidance assistance and auto guidance systems. Those systems, commercially available since the end of the 90's, were rapidly introduced in the market, probably due to their easy adoption and numerous advantages in terms of driver stress reduction, increase on task productivity and overall job quality. Buick and Lang (1998) and Buick and White (1999) compared already the efficiencies of GNSS assistance guidance against the existing technology, establishing a base methodology to evaluate different guidance systems while following straight and parallel swaths. The best results and user´s advantages are achieved when using higher accuracy, for that reason, it will be object of this study, to compare and evaluate different types of correction signal. RTK-DGNSS (Real Time Kinematic-Differential GNSS system) provides centimetric accuracy and unlocks the possibility for using this technology on any agronomic task (Griepentrog et al., 2004; Blackmore et al., 2005; Fennimore et al., 2010). Although the use of two GNSS receivers requires a significant financial investment, RTK-GNSS systems are becoming increasingly common among commercial farming operations for automatic steering of tractors and other types of field equipment.

GNSS guidance hasn´t change significantly in the last 20 years, the kinematic and dynamic vehicle models (bicycle model steering) are still used widely for 3 and 4 wheel based vehicles, however a growing number of applications have been developed for autonomous driving in other kind of platforms (B. Thuilot, 2001). Tracked and articulated vehicles or implement steering are some of these advances. Implement steering, as demonstrated later on this compendium, allows the possibility to use weeding mechanical systems up to a few centimeters close to the plants, while driving at a reasonable high speed, which results on maximizing the effects of the treatment, reducing the use of chemicals or manual weeding and improving the crop yields. More recently, Systems which utilize implement-mounted cameras for machinery feedback, such as row crop cultivators and sectional sprayers, can be upgraded to provide high-accuracy ground speed and tracking data using visual tracking algorithms (P. Stanhope 2016).

A part of guidance systems, other significant applications have been developed, especially in the field of implement control. Automatic sections and rate control is a technology that allows chemical sprayers and fertilizer spreaders to enhance their operation performance by reducing drastically the overlapped/skipped surface and adjusting accurately the applied rate. The spray boom is divided in several sections, which are controlled with the use of electro-hydraulic actuators, able to open or close the flow to a certain number of nozzles connected in series. Different boom configurations can be found, from a single section, to 3, 5, 9 or up to individual nozzle control (HAWKEYE® NOZZLE CONTROL SYSTEM Raven, ExactApply JD). In this case manufacturers provide a special nozzle cartridge with a built-in electro-vale, in many cases controlled via CAN bus (Controlled Area Network). The main controller stores the boom geometry and it´s relative position regarding the GNSS. By using its current position and a log from the applied areas, the controller can determine if part of the boom is approaching a worked area, and eventually, send a command to close/open certain sections. Precise rate control is achieved with the use of electro-actuators that regulates the main flow, pressure transductors, flowmeters and the actual boom status calculated by the GNSS, working width and vehicle current speed.

But the most advance technology in the field of implement control and vehicle-implement communication is currently being implemented by most of the agricultural machine manufacturers around the world. ISOBUS or ISO-11873 is a standard communication protocol based on SAE J1939, managed by the AEF (Agricultural Electronic Foundation) that provides the necessary hardware and software specifications to handle any bidirectional communication between different vehicle, implement or electronics providers. The protocol includes all the necessary elements to support GNSS guidance, section and rate control, sensor data logging or actuating available implement movements and most recently, taking the control of the vehicle speed, PTO or hydraulic services (www.aef-online.org, AEF).

Another application in the field of implement control are the GNSS controlled drainage and ground levelling systems. Widely used thanks to its known advantages and benefits on soil management and crop production, water management technics became extremely powered when upgrading from Laser to GNSS technology. This technology added new possibilities to shape the ground surface and increased field operativity, as this kind of equipment is not affected by dust, fog or windy conditions, can reach longer coverage areas, is easier and faster to install and set up and guides the tool across the true earth altitude. (Field Level, Trimble)

A second group of technologies on PA is that conformed by Site-Specific management technics, and in general, they can be based on maps or on real-time sensing and application. Site-specific management technics share the maxima of measuring variables, like crop vegetation indexes, soil properties (as the methodology proposed and evaluated on this compendium) or weather conditions at a very high resolution, usually in the range of one sample per square meter, analyze and compare those samples with a reference scenario and make decisions, by applying, the necessary corrections within the same spatial resolution.

Map based technics basically use historical series of datasets linked to a production field, such as data from soil analysis, proximal and remote soil and crop sensing, crop yield or weather information. By the use of statistical tools, data fusion can be performed with remarkable results (Durrant-Whyte 2001) and, as well, the use of multi-collocated co-kringing technics will help to obtain Management Zones (MZs). Some results pointed an association of 40 % between the calculated MZs (using soil proximal sensing data) and the final crop yield harvested, which means that more than the 50% of the yield variation could be attributed to other dynamic factors, like weather conditions, diseases and nutrition stresses (S. M. Shaddad 2015).

Use of real-time sensing to develop variable rate application reduces the management time constraint to site-specific crop management. Decisions that must be made by a human in map-based systems are embodied in software rules that use the sensor data to control input application.

In precision farming, the use of optical spectrometry sensors able to indirectly assess the crop nutritional status in a non-destructive way represents a technological innovation in N fertilization. (Raun et al., 2001, 2002, 2005; Argenta et al., 2003; Berntsen et al., 2006; Jørgensen & Jørgensen, 2007; Portz et al., 2012).

One of the most important nutrients impacting crop yield is Nitrogen. Generally, soil nitrogen is not enough to ensure high grain yields and due to the difficulties managing a right fertilization: N volatilization, N leaching, lack of synchrony between demand and N availability, inter-annual variability in the crop response to N fertilization and spatial variability of soil properties, such as: SOM content, horizon thickness, water content, etc. have effects on the N nutrition status of plants in the field. This has led into a variable-rate nitrogen fertilization (VRF) based on crop sensors, as a technic that could increase N fertilization efficiency (Singh 2006).

Some commercial sensors, like the Yara N-Sensor, has shown to increase 3-13% yield and up to 14% reduction in N fertilization. It is used mainly for wheat and other small grain crops. (Singh 2006)

The last group of technics is related to the IoT and BigData. These technologies appear to be more and more a common tendency across all sectors, and in agriculture have experienced a rapid growth. This is in part due to the amount of data that is generated on a farm, where tractors, combines, implements or monitoring stations are equipped, at least since the last decade, with a large number of sensors that produce tons of data. Until now there has not been an easy way to process and analyze that data, in many cases data was scattered over USB sticks or private computers, with different formats and time scales. Today, thanks to the proliferation of standards in communication (like ISOBUS), a new generation of connected devices (IoT) and the use of centralized webcloud-repositories, farm data is getting gathered on a structure way, unlocking the possibilities to perform high level computing technics and uncover important insights (Paraforos et al., 2017).

1.3 GNSS localization. State of the art.

The most relevant satellite constellations that provide 24h, all weather conditions and anywhere on the earth positioning today are the North American Positioning System known as Navigation by Satellite Timing and Ranging Global Position System (NAVSTAR GPS or simply GPS) and the Russian Positioning System known as Globalnaya Navigatsionnaya Sputnikovaya Sistema or Global Navigation Satellite System (GLONASS) both qualify as GNSS. Two other satellite localization systems, Galileo (European Union) and Compass (Chinese), are expected to achieve full global coverage capability by 2020.

By means of a triangulation, this is, estimating the distances from at least three satellites orbiting the Earth, along different and sufficiently separated trajectories, a GNSS receiver can calculate its position. The unit measures the time it takes for the signals to travel from the satellites and use that time to calculate the distance (or range) between them. A GNSS receiver must lock onto the signals from at least three satellites to calculate a two-dimensional (2D) position (latitude and longitude). If four or more satellites are in view, the receiver can determine three-dimensional (3D) position (latitude, longitude, and altitude) of the user. Detailed information on GNSS technology is plentiful, and there are many books that provide a complete description of these navigation systems.

1.3.1 GPS system

GPS consists of 24 operational satellites in six different orbits. Normally 4 to 10 satellites can be seen anywhere in the world with an elevation mask of 10 degrees (field of signal interception created by a cone which has its apex at the antenna receiver and creates a certain angle from the horizon). These orbits are nearly circular with an elevation of 20,200 km and an eccentricity of less than 1%. The orbital period is 11 hours and 58 minutes. This means that these satellites go around the Earth two times a day. The orbits are inclined at 55 degrees to the equatorial plane. The satellites have orbital speeds of about 3.9 km/s in an Earth centered non-rotating coordinate frame of reference. This system was completed in 1993 and became fully operational in 1995.

The current GPS consists of three major segments- space, control and user. The space segment consists of 24 operational satellites plus additional spares (- 8 at present). Control segment consists of worldwide network of tracking stations and a Master Control Station (MCS) to track the satellites in order to predict their exact locations, almanac and ephemeris, obtain data related to satellite integrity, satellite clocks, atmospheric data, etc., and upload the information to GPS satellites. The user segment consists of GPS receivers.

1.3.2 GLONASS system

GLONASS (Global Navigation Satellite System) was developed by former Soviet Union in 1980s almost in parallel with the United States and is now operated for the Russian government by the Russian Space Force. The original GLONASS constellation was completed in 1995, but then the unstable economic situation following the collapse of the former Soviet Union led to the deterioration of this satellite constellation. In December 2011 the GLONASS achieved full global coverage for the second time (27 satellites, 24 operational and 3 in reserve). These satellites are located in medium Earth orbits (MEO) at 19,100 km altitude with a 64.8 degrees inclination and a period of 11 hours and 15 minutes. This constellation operates in three orbital planes, with 8 evenly spaced satellites in each.

1.3.3 Galileo system

Galileo is a program for a global navigation satellite system and it is currently being built by the all European Union countries and the European Space Agency (ESA). Recognizing the importance of satellite navigation, positioning, and timing in different fields, a civilian European system was conceived and developed in the early 1990s. It started with the European contribution to the first generation of GNSS (GNSS-1), the EGNOS program, and continues with the generation of GNSS-2, the Galileo program. The goal is for it to be completely functional by 2020 and will provide coverage to the Polar Regions. When developed, the Galileo system will consist of 30 satellites (27 operational + 3 active spares), positioned in three circular medium Earth orbit (MEO) planes inclined at 56 degrees to the equatorial planes at an elevation of 23,222 km altitude above the Earth and an orbital period of 14 hours and 5 minutes.

1.3.4 BeiDou-COMPASS system

The BeiDou Satellite Navigation and Positioning System is being developed by China. This system was designed to provide positioning, fleet-management, and precision-time dissemination to Chinese military and civil users. At present, it has 10 satellites and covers the Asia-Pacific region. Unlike other GNSS, which use MEO (altitudes between 19,000-23,000 km), BeiDou located its satellites in geostationary orbit, approximately 36,000 km above sea level in the plane of equator. However, the Beidou system is being currently upgraded under the name COMPASS to achieve full GNSS capability by 2020. When completed this system is expected to have 35 satellites in 21, 150 km orbits inclined at 55.5 degrees to the equatorial plane and an orbital period of 12 hr and 36 min.

In addition to the above systems that either have or expected to have GNSS capability, two other regional systems also provide position measurement over a limited region. Indian Regional Navigational Satellite System (IRNSS) is planned to have seven geostationary (GEO) satellites and is expected to provide 20 m accuracy within India and 2000 km of its neighborhood. The Japanese Quasi-Zenith Satellite System (QZSS) is primarily a communication system with navigational capability. It consists of three highly inclined, geosynchronous satellites. At least one satellite is over Japan at all times.

1.3.5 Real-time differential GNSS corrections

When calculating its own position, a GNSS receiver will be predisposed by internal and external factors that will become into loss of accuracy. Most important are related to the precision of its internal clock, atmospheric and multipath effects and ephemeris and satellite atomic clock errors. As the GNSS receiver calculates its position by measuring the travel time of the signals and assuming a constant speed (the speed of the light, 3 x 10^8 m/s), its overall precision will be limited by the accuracy of its clock. But as well, the different atmospheric conditions affect the speed of the signals when travelling through the atmosphere. Multipath issues are related to the fact that signals can be reflected by surrounding objects, like soil, walls or roof surfaces. Specialized filtering technics, software and hardware, has been developed to ignore and minimize the effect of those reflected signals. Changes on the solar radiation pressure will have effects on the satellites ephemeris, and therefore will produce localization errors until this information gets corrected on the satellites.

The accumulation of these and other less significant errors results on a dilution of the precision, up to a few meters, at the GNSS receiver level. However, many of the GNSS applications already introduced, requires sub-metric positioning. One of the most extended solutions is the use of a second GNSS receiver placed on a stationary position and close to the rover. Assuming that they will be affected by the same disturbances, the first one will be used to calculate a correction signal, used by the second one to improve its position calculation. However, some other alternatives or corrections sources are available.

1.3.6 Radio beacons (DGPS)

This correction signal is generated using the concept explained before, but in this case, the connection between the stationary base and the rover receiver is done via standard radio modulated frequency (FM) as encoded data. This signal is free of charge and improve the GPS positioning up to sub-meter accuracy. However, precision reduces significantly when driving away from the beacons. It is relatively easy to use but it is almost not used on agriculture due to its low performance.

1.3.7 Space-Based Augmentation System (SBAS)

This type of correction signal is received directly on the rover receiver from a geostationary satellite. The signal is broadcasted via different satellites around the world, supported by a number of international organizations: WAAS (North America), EGNOS (Europe), MSAS (Japan) and GAGAN (India). These signals are served freely, but correct only the L-band (DGPS), causing its precision to vary from sub-metric to some meters depending on the number and position of the GNSS satellites, atmospheric conditions, etc. Two providers Fugro (OmniSTAR) and Deere (Starfire) provide also a geostationary, but dual frequency signal under payment, increasing its accuracy significantly on the range of 10 to 30 cm.

Many farmers use these kinds of signals for less accurate operations such as, spraying or spreading.

1.3.8

1.3.9 Dedicated-use Real Time Kinematic base station (RTK)

The use of an own base station on the range of the working area (<10km) generates the best results, typical errors of less than 2 cm. However, it is the more expensive solution due to the high initial cost, a second dual frequency stationary GNSS receiver is needed and a couple of radio-modems to transmit the signal between the base and the rover. A second issue is related to the “mobility” of the base station. This is not a problem when used on large farms, in that case the base can be installed centrally on a fix position and use long rage radio-modems and repeaters to spread the signal. An alternative for contractors or when a more flexible solution is needed, is the use of Ntrip. Ntrip stands for an application-level protocol for streaming Global Navigation Satellite System (GNSS) data over the Internet. So, in this case the standard radio modems will be replaced by GSM modems, adding to the system extra freedom and the single base station in the farm by a network of base stations placed at a region level. Ntrip is fully configurable allowing the user to setup different server (the broadcasting party or network) and a mountpoint (the signal type: format, technology, distance…). The most common services over Ntrip are the Nearest Base Station and the VRS. The first one uses the position from the rover and connects it to the closer Base Station on the Network, the second one, uses a dedicated software application that provides a unique correction signal using a Virtual Reference Station, as combination of the corrections from all the bases on the Network compensated for the position of the rover. (https://igs.bkg.bund.de/ntrip/about).

Due to the signal costs, flexibility and precision, Ntrip VRS has become the most reliable and popular correction signal during the last years.

1.4. Precision weeding. State of the art.

Site-specific weeding stands for the group of technologies that allows the detection and the consequence removal of weeds wronging in competition against the crop, taking into account a number of factors, like the economical or environmental impact limitations.

Many studies have proven the advantages of using site-specific weeding, having as a result that a 19 till a 60% of the amount of herbicide used could be saved. Savings are strongly dependent on crop and year. In the study form, C.Timmermann et all, for grass weed herbicides, the savings were about 90% in winter cereals, 78% in maize, and 36% in sugar beet. For herbicides against broadleaf weeds, 60% were saved in winter cereals, 11% in maize, and 41% in sugar beet. The monetary savings resulting from the reduction in herbicide use varied between the crops, depending on the amount of herbicide saved and the price of the herbicides. In maize, savings of 42euro/ha were achieved, in winter wheat of 32euro/ha, in winter barley of 27euro/ha and in sugar beet of 20euro/ha. (C.Timmermann et all. 2003).

Few farmers, however, have adopted site-specific weed management, although several studies have shown that weed occurrence and density varies significantly within a farm or a field (Lutman & Miller, 2007). Technologies developed so far are dedicated to specific crops and ranges of weed species. Sensing a large, unknown number of species, while simultaneously making instantaneous decisions about the level of control, choice of herbicide, etc., is still a very complex process.

There will be three main parts on any site-specific weed technology:

1. A weed sensing system, identifying, localizing and measuring crop and weed parameters.

2. A weed management model, applying knowledge and information about crop–weed competition, population dynamics, biological efficacies of control methods and decision-making algorithms, and optimizing treatments according to the density and composition of weed species, economic goals and environmental constraints.

3. A precision weed control implement, e.g. a sprayer with individual controllable boom sections or a series of controllable nozzles that enable spatially variable applications of herbicides.

1.4.1 Weed sensing

Research progress can be summarized into two categories: remote and ground sensing.

The first one exploits the use of aerial transported sensors, mainly cameras carried out by UAV's, planes or satellites and able to capture sufficient spatial and spectral resolution. Brown and Noble (2005) studied aerial-based remote sensing finding that the technology was suitable for detecting patches larger than 1x1 meters when they are dense and uniform and present a unique spectral sign.

More recent studies, Junfeng Gao et al (2018) used ultra-high resolution UAVs digital imaging (1.78 mm/pixel Visible) to identify inter-row weeds, based on features recognition and Hough transform, and OBIA and machine learning methods for intra-row weed detection, demonstrating a feasible way to obtain an accurate weed map.

Today, new sensor technology like the Imec Hyperspectral filters (2017) is changing the paradigm regarding weed recognition. This little sensor can be integrated on many commercial cameras carried out by UAV's, featuring up to 140 bands in the 470-900nm range. (https://www.imec-int.com/en/articles/imec-introduces-broad-spectrum-hyperspectral-imaging-solutions).

Higher spatial resolution (below 1 mm) can be collected with ground-based camera systems and sub-sequent image processing routines are able to segment vegetation from soil background and delineate individual weed plants from the crop (Thorp & Tian, 2004).

1.4.2 Weed management models

An important number of factors influences the occurrence of a great within-field variance of weed. The effect of soil conditions (type, water, nutrient content), crop management (crop rotation, fertilizer, etc), machinery used (tillage management, harvester) added to the infinite combination of biological variables with the range of efficacies of all possible control methods (herbicide, dosage, frequency, etc) generates a need for a decision model that optimizes economic goals and meets environmental limitations (S. Christensen et al, 2008).

Two classical decision models for weed management are the efficacy-based and population-based system (Wiles et al. 1996). The first one provides a number of tables to help the decision maker selecting the appropriate herbicide and dose, and the second one incorporates weed biology and ecology through simple, deterministic models. These models rely on the assumption of evenly distributed weeds, therefore overestimate yield loss and population growth (Brain & Cousens, 1990), especially when site specific weed control technologies operate on a higher field resolution. Brain and Cousens (1990) showed that at very low weed densities yield loss was almost the same for different degrees of aggregation, while at high densities, aggregation reduced the impact per weed plant because of intra-specific competition.

1.4.3 Precision implement control

The simplest and extended precision implement control is the one using a detection system in front of the sprayer and a controller and actuation system able to adjust herbicide rate and open/close sections on a conventional wide (20m) sprayer boom. Many studies have been carried out using such combination and the use of predefine maps for the treatment of weed patches (Felton and Mccloy 1992, Kempenaar and Leemans 2005, Gerhards and Oebel 2006). The results of the experiments showed an average of 60% herbicide savings when spraying annual broad-leaved weeds and up to 90% when spraying annual grass weeds.

A variant of this technology is to use direct injection systems. Here, the main tank is filled with clear water and the herbicide active matter (one or several) is injected directly into the pipes, preferably close to the end nozzles in order to reduce the reaction time. The system computer will regulate the rate and locate the herbicide regarding to the sensing system.

New commercial developments like Hawkeye® Nozzle Control from Raven 2017, are able to control the rate on each individual nozzle. The system can compensate the different speed between the inner and the outer nozzles when the sprayers turns, thanks to the individual electric PWM output control present on each nozzle.

In the field of experimentation, more accurate systems have been tested, like the Drop OnDemand (DOD) application system, that has been used to apply very low volume rates (c. 1lL) of glyphosate to weed plants. Potential herbicide savings using this system is >95% compared with conventional broad-cast application systems. An additional advantage of a system using the DOD technology is that herbicide exposure on the crop and the soil can be avoided (Lamm et al 2002).

But also, a number of no chemical control implements have been developed and tested during the last years. Consisting on mechanical knives that rapidly positioned in and out of the row, or rotating hoes, plates or discs that remove the weeds while avoiding damaging the crop (Wisserodt et al. 1999). We can find as well the use of high-voltage (15-60 kV) electrical discharge to kill single weeds (Blasco et al. 2002), precision flame weeding (Poulsen 2006) or the use of a laser beam to destroy the apical meristems of weeds (Mathiassen et al 2006). All of them have proved a significant potential for very accurate control of weeds, but in many cases, due to the difficulty of achieving the whole process instantaneously or the extra inconveniences of managing complex equipment, have reduced its final development into a commercial product.

Today’s more extended practices on site-specific weed management are those related to the use of Vis-NIR sensors during pre-emergency treatments, like Weedseeker ® Trimble, able to detect and spray precisely over plants at high speed (16 km/h), but not able to differentiate between crop or weeds.

1.5. Soil sensing and precision soil management. State of the art.

Structured or periodic factor variation on space and time can be found easily on natural production systems. This is usually the case for soil systems where homogeneous subareas can be found as a result of topography, base material, climate and biology factors (Khosla et al. 2010). Castrignano et al. 2009, described that using geostatistics technics over simpler spatial methods can provide valuable information to be complemented by secondary attributes, those will be collected at a higher frequency or resolution, like visible and near infrared spectroscopy, providing fine-scale information about soil properties.

Delineation of site-specific management zones (MZ), is the methodology used to separated those “potentially homogeneous subareas” and can aid in order to improve site-specific applications of farm inputs. There are many documented advantages of using MZ for site-specific applications, with the aim of increase yield (Mulla et al. 1992) and/or nitrogen-use efficiency (Khosla and Alley 1999). Over the years, delineation techniques for MZs have been developed, including the use of more complex assessments of soil fertility variation and oriented, more and more, toward a multivariate approach.

1.5.1 Geomorphology

Local geomorphology has been widely used to delineate soil variations and have a recognized influence on soil fertility. The main reason of this is that subareas having a common topography present in many cases common soil properties (E.g. OM content, pH and/or soil depth). Many studies like MacMillan et al (2000), Nolan et al. (2000) use the elevation data to delineate the field by classes of type “high”, “medium”, “low” and “very low” or of type “shoulder-slopes”, “back-slopes” “foot-slopes” and “level”. Researchers conclusions are mixed, in general, the use of this methodology may vary at different sites and from year to year. Landscape attributes alone seem unable to account for the many factors affecting fertility, however, the wide availability of data and the diffusion of accurate sensors, keep geomorphology as a potential valuable tool for completing other data and improving the definition of MZ’s.

1.5.2 Soil chemical analyses

Laboratory chemical analysis of soil samples has the advantage to provide real fertility soil potential at a certain moment. However, they are expensive and quite time consuming which make them not suitable for exploring within-field variability, which needs a large number of samples.

The selected soil properties to be measured and the number of samples will vary between location, soil type, crop or management strategies. It can be found often on literature that authors use OM, nutrient storage, available N, available P, pH, CEC or available K as the most relevant soil properties and crop yields as fertility indicator. Fu et al. (2010) and Yao et al. (2014) used Kriging interpolation and fuzzy c-means clustering in order to fusion the data from the different properties and delineate MZs. The resulting MZs were found to reflect the rotation systems already applied in the fields, confirming the suitability of the approach. However, no performance indicator was proposed, and also no economic evaluation.

1.5.3 Proximal soil sensors (PSS) and data fusion (Soil sampling, ECa, others)

As seen before, the traditional way of doing soil chemical analyses is not convenient when detail within the field variability is needed, for that reason, PSS has gained more attention in PA, due to its ability to perform huge number of samples, rapid, inexpensive but scarifying some accuracy. PSS can be used to better understand and quantify the spatial and temporal variability within a field (Kuang et al., 2012).

Samples are taken normally at fixed intervals (eg. One per second) from a vehicle or implement carrying out a sensor or a multisensor head. A GPS receiver add the exact location and time of each sample. The vehicle drives at a constant speed describing parallel lines, which creates a kind of a sampling grid. Some of the more used PSS sensors are:

- ECa Measurement

EMI sensors measure variations in ECa, which is quite related to Moisture Content (MC) and Clay Content (CC). Other soil properties have been related to ECa (Chen et al, 2004, Hossain et al, 2010, Meirvenne et al., 2013) and it has been used with satisfactory results as a primary variable to delineate MZs, however, it is very limited for measuring soil chemical and fertility parameters (eg. OM, total nitrogen, CEC).

This sensor uses a contactless noninvasive method for measuring. An electro-magnetic field is created and measured at real time or an electrical current is injected into the ground and measured at the other side of the sensor. Distance between the emitter and the receiver will determine the measuring deep.

Areas with deep topsoil (>60cm) provide low readings and when the clay pan is close to the surface (<20 cm), a higher EC will be observed. Main factors influencing the readings are MC, salinity, BD, temperature and CC.

- Vis-NIR

Vis-NIR spectrophotometers capture the soil diffuse spectral reflectance at very specific wavelengths. Visible range (400-780 nm) are related to soil color, which assist in the measurement of OM and MC. In the NIR range, above the 1000nm, data can be used to detect and quantify OM, MC, clay minerals and total nitrogen (Mouazen et al. 2010, Stenberg et al., 2010). It is also possible to quantify properties by measuring indirect spectral responses, like Ca, CEC, pH, P, K and Mg, but with much lower accuracies (Kodaira et al, 2013; Marín-González et al, 2013).

Online vis-NIR sensors mounted on vehicles have shown the potential to map a variety of yield-limiting soil properties (Kodaira and Shibusawa, 2013, Kuang and Mouazen, 2013, Kuang et al. 2015, Mouazen and Kuang, 2016) and show potential for inclusion in MZ delineation techniques. However, it is still an expensive equipment and it is required expert knowledge in order to process the survey data.

- Passive gamma ray

This technic is based on the measurement of the gamma radiation emitted from the radioactive isotopes present in all soils (Castrignano et al 2012, Viscarra Rossel et al 2007).

The main radioactive elements in soils are potassium (K), uranium (U) and thorium (Th), which can be used to predict, after an important preprocessing phase, soil properties like CC and CEC (Rodrigues et al, 2015, Taylor et al. 2010).

The sampling can be performed by a vehicle carrying a portable gamma-ray sensor. In combination with EMI an RTK elevation measurements, gamma-rays readings have been used to identify MZs (Rampant and Abuzar 2004). They concluded that using all the geophysical and terrain data, prediction of yield zones was quite well, misclassifying only 5% of the area.

- Ground Penetration Radar (GPR)

The principle of GPR is based on the transmission and reflection of Electromagnetic waves in the soil (106-109 Hz). Measures are based on the differences between the dielectric constants of water, air and minerals (Lambot et al 2004), this enables the possibility to survey subsurface properties. Soil penetration and the type of properties measured can be tuned by selecting different frequencies. A multifrequency groundwave data could be used to map three-dimensional water content distribution as demonstrated by Galagedara et al 2005 and Grote et al. 2010.

GPR has been used to identify soil vertical structures (Gish et al. 2002), water table depth (Hengari et al., 2013), soil MC (Lunt et al. 2005), soil salinity (Al Hagrey and Müller, 2000), nitrogen loss (Walthall et al., 2001), soil compaction zones (Petersen et al., 2005) and soil pollution (Van Meirvenne et al, 2014). De Benedetto et al. (2013) used multisensory datasets from EMI, GPR and soil hyperspectral reflectance to delineate MZs and use them for a site-specific management.

II. Overall Summary of the Objectives

During the process of this doctoral thesis an important research effort has been done in order **to study, develop and validate a number of different technologies related to GNSS guidance and site-specific applications**, with the aim to improve the working conditions and the profitability of the conventional agricultural machines and technics.

In this way, the studies have been separated and focused on different subjects of the Precision Agriculture.

GNSS is the main technology across all PA disciplines. For that reason, is very important for researchers and farmers to have a clear view on which are the limitations of a specific GNSS receiver and correction signals and to know in which applications can be used. Site-specific technology will be as well one of our focus, as it is the most promising PA discipline, it chases the maxima of “maximizing the benefits, by acting at the right place and at the right moment”, however too few experiences have been satisfactory introduced in the region of study.

1. In this way, is the aim of this thesis to determine the accuracy of available GNSS agricultural receivers and correction signals. By establishing a methodology to compare the dynamic position accuracy and to generate recommendations for farmers, depending upon the precision required for each of agricultural operations.
2. As well, to use the proposed methodology and to compare high-accuracy GNSS receivers and correction signals (RTK vs RTX), while used to drive autonomous vehicles developed for agricultural applications.
3. To design and construct a field-ready strength profile sensor, to generate calibration algorithms and to produce soil strength profile variability maps in combination with a GNSS receiver, used as site-specific tillage prescription maps.
4. To develop and evaluate the performance of a GNSS driven site-specific implement, able to combine inter-row cultivation and intra-row herbicide spraying for weed control.

III. Publications: Chapter 1

Design of a Soil Cutting Resistance Sensor for Application in Site-Specific Tillage

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Abstract

One objective of precision agriculture is to accurate information about soil and crop properties to optimize the management of agricultural inputs to meet site-specific need. This paper describes the development of a sensor equipped with RTK-GPS technology that continuously and efficiently measures soil cutting resistance at various depths while traversing the field. Laboratory and preliminary field tests verified the accuracy of this prototype soil strength sensor. The data obtained using a hand-operated soil cone penetrometer was used to evaluate this field soil compaction depth profile sensor. To date, this sensor has only been tested in one field under one gravimetric water content condition. This field test revealed that the relationships between the soil strength profile sensor (SSPS) cutting force and soil cone index values are assumed to be quadratic for the various depths considered: 0-10, 10-20 and 20-30 cm (r2=0.58, 0.45 and 0.54, respectively). Soil resistance contour maps illustrated its practical value. The developed sensor provides accurate, timely and affordable information on soil properties to optimize resources and improve agricultural economy.

Keywords: soil cutting resistance map; site-specific management; soil sensor; GNSS

3.1.1 Introduction

Crop yield variability within a field depends on soil properties and environmental conditions. To optimize the management of agricultural inputs according to site-specific need, geo-referenced information about the site is required [1]. Spatial yield variations provide opportunities for exploring the cause with site-specific technology [2]. An important aspect of precision agriculture has been the use of sensor data to obtain accurate information that help minimize crop yield variation. This georeferenced data is incorporated with more broadly related information such as edaphic, meteorological, biological, anthropogenic and topographic factors. Site-specific management is extremely complicated because all of these factors must be considered. Researchers and farmers must overcome several challenges, such as simplifying the complexities that delineate site-specific management zones based on a single factor (for example, edaphic properties), and determining the yield variation related to this factor [3]. Mouazen & Ramon [4] investigated the use of an on-line measurement system of soil compaction, the bulk density model, in different soil textures (i.e., loamy sand, loam, silt loam and silt).

Some soil parameters vary in space and time. Therefore, logistical and analytical costs are often limiting when addressing spatial soil variability, especially in large-scale applications [5]. The traditional method of exploring field soil variation is through grid sampling, which is time-consuming, labor-intensive and costly. Advanced technologies and developments in precision agriculture applications have allowed researchers to scrutinize an on-the-go soil strength profile sensor [6-8].

To determine the magnitude of the overall compaction or the depth location of the compacted layers, soil strength profile sensors have been developed. Hemmat et al. [9] reviewed and analyzed soil profile sensors that should be capable of accurately mapping both spatial and vertical variation in soil mechanical resistance. In this work, two different approaches, a tip-based and a tine-based sensor, were used to classify the soil profile sensors.

With tip-based sensors, soil compaction is traditionally analyzed by measuring soil strength indices such as the cone index (CI). This index is often measured using an ASABE (American Society of Agricultural and Biological Engineers) standard cone penetrometer. The force per unit area required to push the penetrometer through a specified small increment of soil depth is measured. However, a cone index (CI) is a point measurement that exhibits high variability, requires a significant amount of manpower and is time-consuming to measure because large amounts of data are needed to map a field. Current guidelines in the ASAE Standard EP542 [10] recommend that the sample size be based upon visible heterogeneity and that a sample size of at least 20 samples be used to characterize a site. Geo-statistical analysis has proved to be useful for characterizing soil spatial variation properties [6, 11, 12]. Work at the Department of Biological and Agricultural Engineering at UC Davis has indicated that variation in water infiltration rates caused by soil compaction variability within a processing tomato field was a major factor affecting tomato yield [13].

Over the last few years, interest in applying tine-based sensors for commercial purposes has risen. Their proposed applications can be classified into two types: (1) using an array of strain gauges mounted on a rigid tine [14,15] and (2) multiple active cutting edges [16]. An instrumented implement has also been developed using a load cell to determine soil resistance in real-time to enable field mapping [17]. This system produced satisfactory results but only at one depth, which is a major constraint. Hall and Raper [18] developed equipment consisting of a novel sensor mounted on the leading edge of a tine and a reciprocating drive for oscillating the tine vertically while it moved horizontally through the soil. In this work, 30 sensing tips were used and a wedge index defined as the measured force divided by the area of the tip was used to represent soil cutting strength. By increasing the base area of the tip from 6.25 to 25 cm2, the slope of the wedge index and the CI related to the base area increased from 1.52 (r2=0.65) to 2.99 (r2=0.83). These results indicate that a direct equation describing the relationship between the wedge index and the CI might not be possible. This was due to empirical measurement methods that may be affected differently by various soil factors.

Based on previous work [8], Andrade-Sanchez et al. [12] developed a soil cutting force profile sensor that consisted of five 5.1-cm long, active cutting elements directly connected to five customized octagonal ring load-sensing units that could measure the cutting resistance of soil directly ahead of the cutting element. This device was capable of measuring soil cutting resistance over the depth profile of 7.5 to 45.7 cm. These load-sensing units were custom-designed based on their relative location along the depth and expected load at that depth to maintain similar sensitivity levels among all five sensing units. A sub-meter accuracy Differential Global Positioning System (DGPS) receiver that used a coastguard beacon differential correction was employed with this system to provide position information. In addition, radar (model Radar II, Dickey-john Corporation, Illinois, USA) was employed to measure ground speed. The effect of travelling speed on the cutting force was not significant between 0.65 and 1.25 m s-1, and the sensor output could be expressed as a function of CI and operating depth with a coefficient of multiple determination of 0.985 [8].

The dynamic effects of an on-the-go sensor moving through the ground can include both inertial forces, due to soil volume acceleration, and changes in ground strength at a high rate of shear. These effects were studied in detail by McKyes [19], who also indicated that the effect of the shear rate was not significant in simply frictional soils but was significant in clay soils and outweighed the inertial forces. The soil force on a tool is known to approximately increase with the square of its speed [20, 21].

In the last decade, the integration of Global Navigation Satellite Systems (GNSS) with sensors for off-road vehicle systems and other platforms has provided real-time sub-meter to centimeter-level accuracy and significantly enhanced the spatial accuracy of data needed for precision agriculture [22]. The GNSS receivers are a key part of the precision agriculture technologies, as position information is a prerequisite for site-specific crop management. However, researchers believe that not all of the tasks that are or can be performed in precision agriculture require the same level of GNSS accuracy [22, 23]. Some precision agriculture applications, such as yield monitoring, soil samples or variable rate applications, are performed sufficiently accurately with differential GPS (DGPS) devices with submeter accuracy. Currently, Real-time Kinematic-Global Positioning System (RTK-GPS) technology offers the possibility of transitioning site-specific techniques from sub-meter-level precision to centimeter-level precision. Although differential correction signals (DGPS) have been used to successfully geo-position electromagnetic induction (EMI), elevation or compaction soil measurements, accuracies of ±10 cm should be insufficient. Given the topography, the travel direction and terrain irregularities/inclinations, sensor measurements should be corrected. Accurate measurements (±2 cm) of the terrain elevation for DEM construction and geo-referencing geophysical measurements allow for sensor error corrections.

The overall objective of this research was to develop a soil strength profile sensor equipped with RTK-GPS technology that could perform measurements continuously and efficiently at various depths while traversing the field. An articulated parallel linkage system was used to transmit the cutting resistance from the blades to the load cell situated above-ground, which permitted a reduction in the width of the blade and associated energy requirements in soil cutting compared to previously reported research and makes it possible to use this sensor in non-till farms. The specific objectives of this research were:

1. Design and construct a field-ready strength profile sensor.

2. Perform laboratory and preliminary field tests to optimize the sensor for reliable operation.

3. Obtain georeferenced soil mechanical resistance from commercial field and produce soil strength profile variability maps.

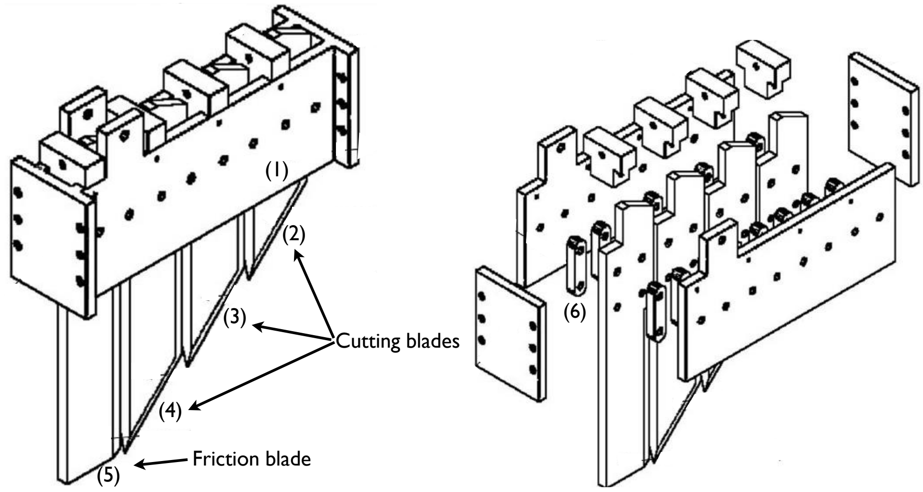
3.1.2. Materials and methods

We have designed and built a sensor that quantifies the soil cutting resistance free from the influence of the friction force exerted by the ground upon steel blades. The cutting force was simultaneously obtained at different depths. These measurements were performed by making a continuous cut through the soil with four steel blades positioned one behind the other. Each steel blade was at a different depth with narrow cutting widths. In this work, the sensing mechanism, which utilized an RTK-GPS receiver to locate the soil cutting resistance data, was pulled by a conventional tractor and was successfully operated in the laboratory and in a commercial field in Spain. This sensor was specifically designed to be economically feasible for variable-rate management compared to a cone penetrometer grid-sampling sensor [24].

Sensor description

Four blades were each equipped with load sensors [Figure 1a & 1b] similar to the prototype developed by Siefken et al. [25], except the load cells that supported the blades were situated above ground. An implement frame was designed, developed and assembled to ensure that the steel blades were orientated vertically during the operation. The cutting blades were located between two horizontal plates (1) of the frame. Vertical support bars (6) were mounted on each side of the cutting blades (2), (3), (4) and the friction blade (5) according to Adamchuk et al. [15] and allowed quadrilateral articulation. Each blade module consisted of four vertical bars, two on each side, thus providing mechanical strength. The blades were chamfered around their edges; therefore, the cutting area was oblique (45°) to the soil surface with a blade width of 100 mm. Each blade was 100 mm longer than the preceding blade, except for the last blade. We selected the width of the blade as 10 mm to provide minimum soil disturbance and energy consumption (minimum cutting width). The blades were attached to the implement frame using a shear bolt mechanism, and the implement was attached to the tractor with a three-point hitch. In the working position, the frame is horizontal, and the first blade is at a depth that positions its top most oblique front cutting edge at the soil surface.

Figure 1.1. The soil strength profile sensor



(a) (b)

Idealized Force and Moment Balance on the Cutting Blade

The portion of the steel blade below the ground surface is subjected to a resultant force (FR) that originates from two different mechanisms when the system is moved forward:

1. The cutting resistance is caused by shearing soil aggregates. This force is distributed along the cutting edge. Their resultant (FC) is a horizontal vector and is located at a depth that is intermediate between both ends. FC would be located at the midpoint just when the soil exerts a uniform shear throughout the cut edge profile.

2. Frictional force is caused by soil particles pressing on the sides of the blade. The frictional force (FF) will be a horizontal vector and is located at a depth that depends on the distribution of these elemental forces. For a uniform distribution, the force vector will be at a depth that divides the exposed surface of the blade into two equal portions.

The FR is in opposition to the advancement of the blade and will be located at a depth that results from the distribution of both components. In addition, this distribution may differ according to the location within the plot of interest.

The reaction force (FM), which counteracts the FR, was measured by a load cell (model LFH-71/0280 model, Sensotec, Columbus, OH, USA). As shown in Figure 2, the distance between both forces generates a moment that must be counteracted so that the system is in balance. The balance condition causes torque to be exerted on the hinge points of the vertical arms of the blades. The arm located at the front, according to the forward direction, exerts a force on the blade vertically upwards (FBD), while the rear arm exerts a downward vertical force (FBT). Both must be equal but in opposite directions to cause a moment equal to the product of FBD by the distance that separates them.

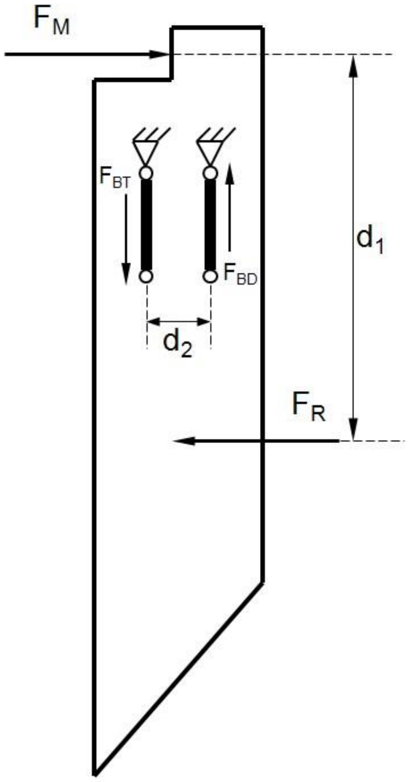
Eq. 1 illustrate the horizontal forces in balance:

$$\vec{F}_M = -\vec{F}_R \tag{1}$$

Furthermore, to maintain the moment balance, the torque generated by the horizontal forces should be equal and opposite to that generated by the vertical forces. This indicates that the force measured by the load cell FM will always equal to the sum of the cutting and friction components, regardless of the depth at which its action is located within the line. The origin is the moment generated by the equal and opposite vertical forces, FBD and FBT, the magnitude of which varies according to FR and d1:

$$\left|F_{BD}\right| = \left|F_R\right| \cdot \frac{d_1}{d_2} \tag{2}$$

Figure 1.2. Distribution of FR, FM and the distances on the cutting blade



The load cell supporting the blade was situated above ground, thereby reducing the incidence of complications compared to its placement below ground level. The novelty of this sensor is the unique load cell-mediated fastening of the steel blade to its frame support. This allows the load cell to experience horizontal thrust while supporting the blade, thus removing the need to correct the load cell readings to determine the total soil resistance.

To determine both FC and FF, a special knife-tool (friction blade) was used. This friction blade does not cut when moving through the soil. It only moves inside the space previously opened by cutting blades and therefore is only subjected to FF. The force measured by the load cell of this blade, divided by the ground contact surface, yields the FF per unit area.

The FF value can be applied to the cutting blades, considering its contact surface, revealing what part of the total force, as measured by the load cell, corresponds to the friction and which part corresponds to the soil cutting. Evaluating both forces is an important innovation of this novel strength profile sensor. For site-specific tillage application, only the cutting force is relevant. However, the friction force auxiliary measurement is essential for correcting the total force FM obtained by each load cell attached to the three cutting blades.

Laboratory Tests and Initial Field Tests

Laboratory tests were performed to compare the forces exerted on the blades and the load cell that were installed in the main frame with the force measured by a reference load cell (SM-5000 N model, Interface Inc., Scottsdale, AZ, USA). The reference load cell was connected to the blades through tension locks with hook and eyelet attachments. Both load selections were based on the size and design of the sensing element and on previous experience gained through obtaining the expected maximum soil resistance values with the soil cone penetrometer. Force data for each load cell were conditioned and recorded by a data acquisition system (DEWETRON, Graz-Grambach, Austria). This system is a portable unit compatible with plug-in signal conditioning modules with selectable ranges and an analogic filter that facilitates a suitable signal-to-noise ratio. Load cell and other sensors, such as an accelerometer and thermocouples, can be directly interfaced with the data acquisition system.

The laboratory tests were performed in four replicates. Each blade was tested individually and at different depths (first blade at 10 cm; second blade at 10 and 20 cm; third blade at 10, 20 and 30 cm). Readings for each blade and its depth were collected individually. The reference load cell was linked to the blades through tension locks with a hook and a 50-cm-long eyelet. One end of the tension lock, a steel "S" fastener was used as an adapter for the cutting and frictional blades. At the other end, a 20-cm-long tension lock was attached to a metal pole with sufficient bearing capacity. Increases of 490 N were achieved by manually tightening the tensor lock.

Simple field examinations were performed on a commercial (South of Spain) field to assess adequate sensor performance [Figure 3a]. Two types of monitors were used: a hand-operated soil cone penetrometer (CI) and the field-ready soil strength profile sensor (SSPS). Soil moisture was measured in field on the test day. SCPS data at three depths (0-10, 10-20 and 20-30 cm) were collected with a 10-m transect spacing at 40 m in length (Nov. 11, 2010). The transect spacing was set according to the shape and dimensions of the field. The soil of the field test, a loamy-textured alluvial soil (45% sand, 45% silt, 10% clay), was classified as a Typic Xerofluvent [26].

On a 10-m interval along each transect, six CI profiles were obtained with a hand-operated soil cone penetrometer equipped with a straight circular stainless steel cone at an angle of 30º fixed on a stainless steel bar according to the ASAE S313.3 standard. Operating parameters were set according to the ASAE EP542 standard, and the penetration speed was set to approximately 3 cm/s. The first reading was collected when the cone base was even with the surface of the soil. The reported CI value was the mean value of the pressure (MPa) identified by the cone as it was inserted into the soil. A load cell measured the force with which the soil opposed penetration, and a potentiometer measured the displacement rate to determine the exact depth location of the force data. The hand-operated soil cone penetrometer was retrofitted with an RTK-GPS receiver (model AgGPS 332, Trimble Navigation Ltd., Sunnyvale, CA, USA). This GPS receiver was interfaced to a field computer (model AgGPS 170, Trimble Navigation Ltd., Sunnyvale, CA, USA) to record the location of each sampling point. Thirty measurements were obtained with the hand-operated soil cone penetrometer in clusters of five along of the cutting line.

Figure 3b illustrates the recording of soil strength measurements with the implement sensor that is being pulled by a tractor. All of the passes were performed at a velocity of 5.7 km/h. To avoid readings influenced by ground breakage effects, measurements were taken approximately 0.3 m from the cutting line of the sensor. To analyze the data, the 15 strength sensor measurements that were obtained close to the measurements collected at the cone penetrometer measurement locations were used to investigate the relationship.

Figure 1.3. (a) The yellow circles represent the geospatial location of each 6 set of cone penetrometer measurements and the red track the straight strength sensor measurement transect. (b) Implement sensor at the working location with a GPS antenna

(a)

(b)

Data Analysis

The performance of the soil strength sensor was evaluated using laboratory and field tests. In laboratory tests, the mean and standard deviation (SD) of simulated soil resistance from the reference load cell for each blade and depth were determined. A regression analysis was performed to investigate the force transmission system (articulated parallel linkage system) when the cutting force changed along the blade. In a commercial field test, a non-parametric one-sided Wilcoxon-Mann-Whitney procedure was used to compare the soil resistance among independent samples. The field trial data was first corrected in order to obtain the cutting forces, free from the influence of the friction forces, using for that the data from the frictional blade. The relationship between the cone penetrometer measurements and cutting forces was determined using the least trimmed squares regression [27]. Analysis of the dataset was performed with R software [28]. A robust Elliptic Plot using the Replot function was used to detect and study outliers [29].

A geostatistical method of interpolating sparse data for random spatial processes was used to achieve the cutting resistance maps (ordinary kriging). The original formulation of kriging is the most robust method and is often used in precision agriculture [30].

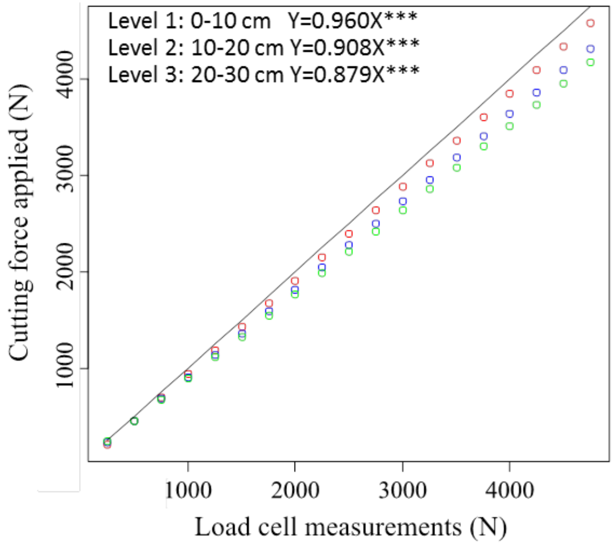
3.1.3. Results and Discussion

Laboratory test

Eighty separate static force measurements were collected for each blade and for the reference load. The means and SDs of the static force exerted on the blades by the load cell were calculated in increments of 490 N from 0 to 4413 N. The average SDs for static force for the first, second, third and fourth blades were 4%, 5.3%, 3.4% and 5.2%, respectively. These SDs displayed acceptable performance indices for this method. An SD of 5% or less indicates adequate method performance, whereas an SD of 10% or higher indicates problematic performance.

The laboratory tests demonstrated that the strength sensor design performed successfully based on an articulated parallel linkage system and separated steel blades. This indicated that the application point of the cutting force is independent of the cell load measurements. Figure 1.4 displays the regression through the origin that was employed, where Y values are the cutting force applied and X values are the load cell measurements on the third steel blade. The estimated regression functions are:

Figure 1.4. Scatter plot and fitted regression through the origin for the third steel blade. Level 1 (0-10 cm) in red circles, Level 2 (10-20 cm) in blue circles, Level 3 (20-30 cm) in green circles.



The equations and regression plots for the steel blade (1), (2) and (4) were similar. However, we observed minimal slope differences in all of the blades. The trend indicates that when the support is farther from the resultant force (i.e., at a greater depth), the response is smaller. Stated another way, the same FR applied to the blade generates less force on an upper support that is more distant from the support. This is caused by friction at quadrilateral articulation. This friction is proportional to the axial stress that supports the quadrilateral arms, which is proportional to the torque moment that must be balanced. Although the force applied on the blade is the same, the greater the distance from the reaction (upper support), the greater the friction force absorbing articulations, which withstands less force to maintain balance. Therefore, this test is not just a simple calibration but also a way to quantify the influence of friction phenomena in the initial theoretical model that were not taken into account.

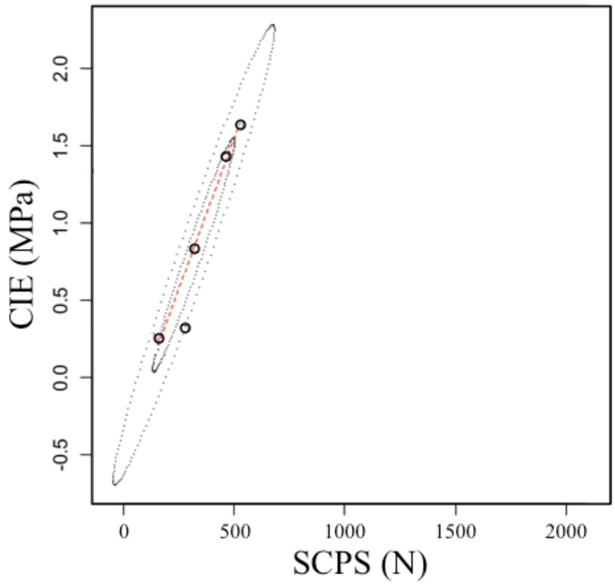
Simple field examination

A simple field test was conducted to analyze the performance of the sensor as it traversed the ground. The main objective of this brief field test was to demonstrate an adequate performance, with particular attention to problems with operating the equipment (mechanics and electronic components), integrating technology systems and collecting and managing strength force data.

The sensor measurements were compared with the hand-operated soil cone penetrometer measurements. Equation 8 provides insight into the soil cutting force requirement of this sensor. If the SCPS cutting force requirements are linearly related to the soil CI values, then this sensor can be used to measure soil strength. At present, this sensor was only tested in one field under one gravimetric water content condition (θg0-10=0.204 g g-1; θg10-20=0.184 g g-1; θg20-30=0.170 g g-1). In this field examination, the relationships between the SCPS cutting force and soil CI values were assumed to be quadratic for the various depths considered. However, it poorly correlated at each of the depths: 0-10, 10-20 and 20-30 cm (r2=0.58, 0.45 and 0.54, respectively). Data collected with large handles and a slightly stony ground could produce this type of data interference. This relationship was similar in magnitude to that observed by Chung et al. [31], although this study introduced two research fields with variations in bulk density, soil water content and soil texture.

Profile-average measurements of the cutting force are plotted versus measured profile-average soil cone index values in Figure 5. Five data points were compared by each strength sensor pass. As an example, each point in Figure 5 represents the profile-average of six measurements that were collected in clusters of five CI values along 10 m of cutting line. In this study, the average data profiles were analyzed independent of depth. These initial test results were satisfactory but revealed a more general trend, such as the mapping of spatial variability with as many data as possible. In the future, large commercial field tests are needed to verify the potential of this developed soil strength profile sensor.

Figure 1.5. One-pass relationship between the profile-average cone index and the soil cutting resistance



The relationship between the CI equipment (MPa) and the soil cutting resistance sensor (N) reveal a clear linearity in the measurements taken (, p<10-4). There were no outliers [Figure 5]. The linear regression was:

$$y = -0.4 + 0.04x \qquad (8)$$

where

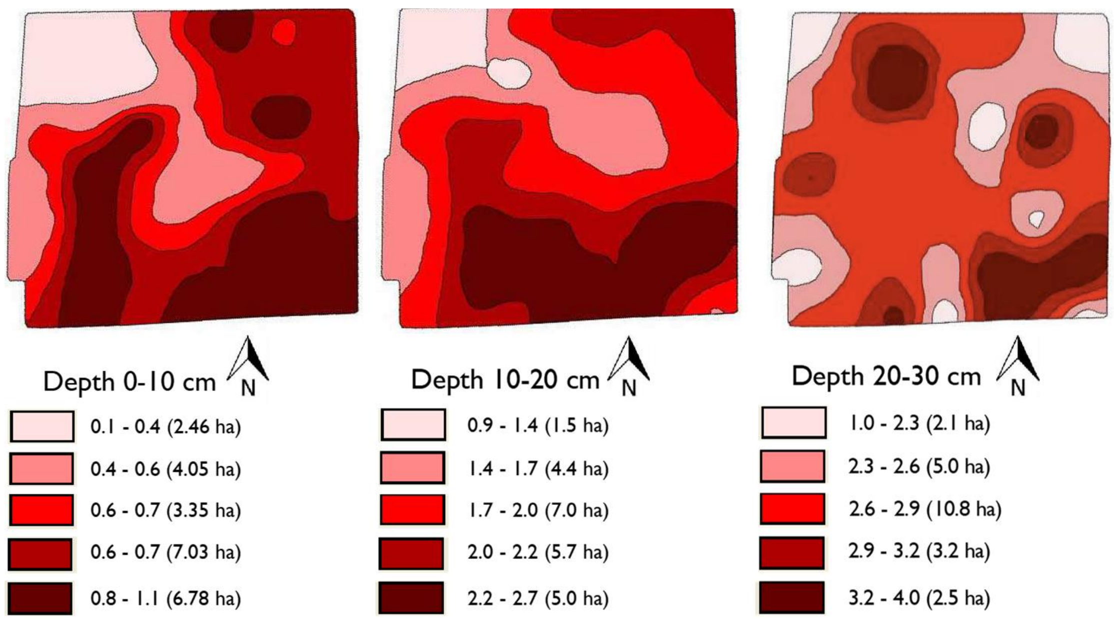
y=CI measurements (MPa)

x=strength profile sensor measurements (N)

3.1.3 Conclusions

A potential application of this strength profile sensor in site-specific tillage as shown in figure 6. The performance of this sensor resulted in soil resistance that ranged between 0.1 and 4 MPa. Contour maps were generated using a kriging. We assumed that 2.5 MPa was the agronomically limiting CI value based on prior studies [32]. This indicates that for all measured values of SSPS that exceed this value at a certain depth, the soil should be tilled to that depth. This work demonstrates the possibility of identifying localized areas for sub soiling and the capacity to subsequently till to variable depths to obtain desired soil strength conditions. This study suggests that significant amounts of energy could be saved if site-specific tillage is implemented.

Figure 1.6. Contour maps of soil resistance (Megapascal) at different soil depths using SSPS data.



3.1.4. Conclusions

We developed a prototype SSPS sensor continuous soil cutting resistance mapping at multiple depths while traversing a field and tested it under laboratory and field conditions. Our major contributions are as follows:

- Design of a sensor implement based on an articulated parallel linkage system and separated steel blades, which successfully records the FR independent of the cutting force application point. However, a redesign and redevelopment of several aspects, such as bearing capacity, are needed to avoid variations at different depths.

- Continuous and efficient data collection by a soil strength profile sensor, equipped with RTK-GPS technology, at various depths while traversing a field.

- Assessment of the relationship between the SSPS and CI measurements (r2=0.58, 0.45 and 0.54) when the data were segmented by different depths (0-10, 10-20 and 20-30 cm)

- Assessment of the relationship between the profile-average measurements of the cutting force and measured profile-average soil cone index values revealed coefficients of determination greater than 0.9 when measured with the soil strength profile sensor.

Employment of this innovative sensor for soil cutting resistance mapping may result in a new era of site-specific tillage, which we plan to pursue through future research. Further work is also needed to provide additional insight into the SSPS and CI relationship in large commercial fields so that data obtained with the strength sensor can be related to the plethora of published research that used the CI to quantify soil strength.

Acknowledgments

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References

1. Van Uffelen, C.G.R.; Verhagen, J.; Bouma, J. Comparison of simulated crop yield patterns for site-specific management. Agricultural Systems. 1997. 54, 207-222.

2. Griffin, T.W. The spatial analysis of yield data. In: M Oliver (Ed) Geostatistical Applications for Precision Agriculture. Springer, The Netherlands. 2010, pp 89-116.

3. Corwin, D.L.; Lesch, S.M. Delineating Site-Specific Management Units with Proximal Sensors. In: M Olier (Ed) Geostatistical Applications for Precision Agriculture. Springer, The Netherlands. 2010. pp. 139-166.

4. Mouazen, A.M., Ramon, H. Expanding implementation of an on-line measurement system of topsoil compaction in loamy sand, loam, silt loam and silt soils. Soil & Tillage Research. 2009. 103: 98-104.

5. Viscarra Rossel R.A.; McBratney A.B. 1998. Laboratory evaluation of a proximal sensing technique for simultaneous measurement of clay and water content. Geoderma. 1998. 85: 19-39.

6. Adamchuk, V.I.; Hummel, J.W.; Morgan, M.T.; Upadhyaya, S.K. On-the-go soil sensor for precision agriculture. Computers and Electronics in Agriculture. 2004. 44:71-91.

7. Sudduth, K.A.; Kitchen, N.R.; Wiebold, W.J.; Batchelor, W.D.; Bollero, G.A.; Bullock, D.G.; Clay, D.E.; Palm, H.L.; Pierce, F.J.; Schuler, R.T.; Thelen, K.D. Relating apparent electrical conductivity to soil properties across the North-Central USA. Computers and Electronics in Agriculture. 2005. 46, 263–283.

8. Andrade-Sanchez, P.; Upadhyaya, S.K.; Jenkins, B.M. Development, construction, and field evaluation of a soil compaction profile sensor. Transactions of the ASABE. 2008. 50, 719-725.

9. Hemmat A., Adamchuk, V.I. Sensor systems for measuring soil compaction: Review and analysis. Computers and Electronics in Agriculture. 2008. 63: 89-103.

10. ASABE Standards. EP542: Procedures for using and reporting data obtained with the soil cone penetrometer. St. Joseph, MI, USA.: ASABE. 2009

11. Corwin, D.L.; Lesch, S.M. Apparent soil electrical conductivity measurements in agriculture. Computers and Electronics in Agriculture. 2005. 46:11-43.

12. Andrade-Sanchez, P.; Upadhyaya, S.K.; Plouffe, C.; Poutre, B. Development and field evaluation of a field-ready soil compaction profile sensor for real-time applications. Applied Engineering in Agriculture. 2008. 24, 743-750.

13. Josiah, M.N.; Upadhyaya, S.K.; Rosa, U.; Andrade, P.; Mattson, M. Mapping field variability in infiltration rate and evaportransporation in a tomato production system. Paper No. 011017, ASAE, St Joseph, MI, USA. 2001. Paper No. 011017.

14. Glancey J.L., Upadhyaya, S.K., Chancellor, W.J., Rumsey, J.W. An instrumented chisel for the study of soil tillage dynamics. Soil & Tillage Research. 1989. 14: 1-24

15. Adamchuk, V.I., Sudduth, K.A., Ingram, T.J., Chung, S.O. Comparison of two alternative methods to map soil mechanical resistance on-the-go. ASABE Paper No. 061057. 2006. ASABE, St. Joseph, MI.

16. Sharifi, A., Godwin, R.J., O´Dogherty, M.J., Dresser, M.L. Evaluating the performance of a soil compaction sensor. Soil Use Manage. 2007. 23: 171-177.

17. Topakci, M.; Unal, I.; Canakci, M.; Celik, H.K; Karayel, D. Design of a horizontal penetrometer for measuring on-the-go soil resistance. Sensors, 2010. 10, 9337-9348.

18. Hall, H.E.; Raper, R.L. Development and Concept evaluation of an on-the-go soil strength measurement system. Transaction of the ASAE. 2005. 48(2) 469-477.

19. McKyes, E. Soil physical properties. In Soil Cutting and Tillage. 1985. 105-123. New York, N.Y.: Elservier Science.

20. Stafford, J.V. The performance of a rigid time in relation to soil properties and speed. J. Agrc. Eng. Res. 1979. 24 (1): 41-56.

21. Wheeler, P.N., Godwin, R.J. Soil dynamic of single and multiple tines at speeds up to 20 km/h. J. Agrc. Eng. Res. 1996. 63(3): 243-250.

22. Perez-Ruiz, M., Carballido, J., Agüera, J., Gil, J.A. Assessing GNSS correction signals for assisted guidance system in agricultural vehicles. Precision Agric. 2011. 12: 639-652.

23. Wilson, J.N. Guidance of agricultural vehicles- a historical perspective. Computers and Electronics in Agriculture. 2000. 25: 3-9.

24. Hornung, A., Khosla, R., Reich, R., Inman, E., Westfall, D.G. Comparison of site-specific management zones: soil color based and yield based. Agronomy Journal. 2006. 98: 405-417.

25. Siefken, R.J., Adamchuck, V.I., Eisenhauer, D.E., Bashford, L.L. Mapping Soil Mechanical Resistance with a Multiple Blade System. Applied Engineering in Agriculture. 2005. 21(1): 15-23.

26. Soil Survey Staff. Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys. 1999. 2nd ed. Agric. Handbk. 436. U.S. Gov. Print. Office, Washington, DC.

27. Rousseeuw, P.J. Multivariate estimation with high breakdown point. Mathematical Statistics and Applications. 1985. Vol. B (Grossmann et al., eds.), 283-297, Reidel, Dordrecht.

28. R Development Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing. 2011. Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/ Last accessed June 18, 2012.

29. Goldberg, K.M., Iglewicz, B. Bivariate extensions of the boxplot. Technometrics. 1992. 34: 307-320.

30. Journel, A.G.; Huijbregts, C.J. Mining geostatistics. London: Academic. 1978.

31. Chung, S.O., Sudduth, K.A., Motavalli, P.P., Kitchen, N.R. Relating mobile sensor soil strength to penetrometer cone index. Soil & Tillage Research. 2013. 129: 9-18

32. Groenevelt, P.H., Grant, C.D., Semesta, S. A new procedure to determine water availability. Aust. J. Soil Res. 2001. 39 (1): 577-598.

III. Publications: Chapter 2

Development and Evaluation of a Combined Cultivator and Band Sprayer with a Row-Centering RTK-GPS Guidance System

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Abstract

Typically, low-pressure sprayers are used to uniformly apply pre- and

post-emergent herbicides to control weeds in crop rows. An innovative machine for weed control in inter-row and intra-row areas, with a unique combination of inter-row cultivation tooling and intra-row band spraying for six rows and an electro-hydraulic side-shift frame controlled by a GPS system, was developed and evaluated. Two weed management strategies were tested in the field trials: broadcast spraying (the conventional method) and band spraying with mechanical weed control using RTK-GPS (the experimental method). This approach enabled the comparison between treatments from the perspective of cost savings and efficacy in weed control for a sugar beet crop. During the 2010–2011 season, the herbicide application rate (112 L ha^{-1}) of the experimental method was approximately 50% of the conventional method, and thus a significant reduction in the operating costs of weed management was achieved. A comparison of the 0.2-trimmed means of weed population post-treatment showed that the treatments achieved similar weed control rates at each weed survey date. Sugar beet yields were similar with both methods ($p = 0.92$). The use of the experimental equipment is cost-effective on ≥20 ha of crops. These initial results show good potential for reducing herbicide application in the Spanish beet industry. **Keywords**: weed control; automation; GPS; sugar beet.

3.2.1 Introduction

Weeds compete with crops for nutrients, water and light and may reduce yield significantly, especially during early growth, and impair crop quality, resulting in financial losses to the farmer [1,2]. Typically, the selection of a weed control method is determined based on crop variety and condition, weed type and size and available equipment [3]. Chemical methods are frequently used because they control a broad spectrum of weed species. However, precision and automation in weed control technology development have been motivated by increased consumer demand for organic produce as well as consumer and regulatory demands reducing the environmental degradation caused by excessive pesticide and fertilizer usage. Farmers have also experienced a decrease in the availability of workers willing to perform manual tasks such as hand weeding. Alternatives have been developed to reduce or eliminate herbicide applications, a step that is required for organic production [4–7].

The past decade has experienced significant improvements in cultivators and band sprayers that have increased agricultural efficiency. These improvements include steer-by-wire technology linked to global navigation satellite systems (GNSS) utilizing remotely received maps [8,9]. New technologies, such as automated control and robotic sprayers [10], provide opportunities to pursue a different approach for achieving higher productivity while lowering production cost.

The three areas requiring within a typical field are as follows: between rows (inter-row), between crop plants (intra-row) and close (30–40 mm) to the plants [11]. Weeds present between crop rows can be controlled effectively with conventional inter-row cultivation, such as with disc cultivators, brush weeders, rotary hoes, rolling cultivators and rolling harrows [12,13]. Hand hoeing can be eliminated with mechanical weeding in this area. Intra-row weeds are more difficult to eliminate, as they grow within the seed-line [14,15]. Hand labor for intra-row weed removal, band spraying on the seed-line [16,17] and broadcast applications over the whole field are the common practices [18] in sugar beet fields. Countries of central and southern Europe routinely use pre-emergence and several post-emergence herbicide applications with a mixture of many active ingredients. However, mechanical intra-row weeding and manual labor are used when chemical treatments are not effective in treating herbicide-resistant weeds [19].

Genetically modified herbicide-tolerant crops can reduce operational costs [18]. However, despite the use of transgenic organisms in several countries, such as the USA, Canada and Japan, they are not used in regions such as the European Union, Mexico, South Korea, Australia, New Zealand, Colombia, Russia and China [20]. For this reason, in these areas effective weed control has been achieved by the use of herbicides [18]. However, environmental concerns motivate the combined use of spraying and tillage, especially when runoff events are problematic [21].

Sugar beet inter-row cultivators hold a number of rigid or vibrating shanks mounted on half sweeps. These sweeps are distributed in gangs suspended from a toolbar. These cultivators generally cannot work close to the crop plant unless an implement-positioning control system is utilized. Manual steering by a second operator has been a common guidance method to control the toolbar position to reduce crop damage by increasing cultivation accuracy. However, three problematic issues remain: increased operation costs, low availability of trained workers and low efficiencies associated with human error, especially during conditions of poor visibility (e.g., at night or in dusty conditions). Hydraulically powered implement systems based on computer vision and GPS guidance technology have been developed to reduce the error caused by the tractor driver [22,23].

Real-time kinematic GPS (RTK-GPS) provides a row-positioning accuracy of ±25 mm, comparable to machine vision guidance systems but without the need for visual guidance landmarks in the

field [24]. Targets may not always be visible, such as when the crop has not emerged or is too small. This level of geo-positioning accuracy in row crops can enhance the precision of chemical placement in narrow bands or cultivation close to the plant line [25]. However, one disadvantage of RTK-GPS solutions is the high capital cost due to the requirement that a base station be located within 10 km at all times. GPS service providers and government institutions are working to mitigate this challenge by developing networks of base stations that provide access to RTK correction signals over a wider geographic region via cellular or radio modems or satellites [26].

The overall objective of the present work was to develop and evaluate the performance of an implement suitable for commercial production that combined a row crop cultivator with a band sprayer. This hardware consisted of a retro-fitted row-centering position implement controlled by an RTK-GPS geo-positioning system. The specific objectives were to: (i) design and build a fully automatic electro-hydraulic side-shift frame controlled by GPS location information; (ii) incorporate mechanical inter-row cultivation and intra-row band-spray weed control; and (iii) assess the field performance, weed control efficacy and cost-effectiveness of the combined weeding system compared to conventional systems.

3.2.2 Materials and Methods

Equipment Design and Manufacture

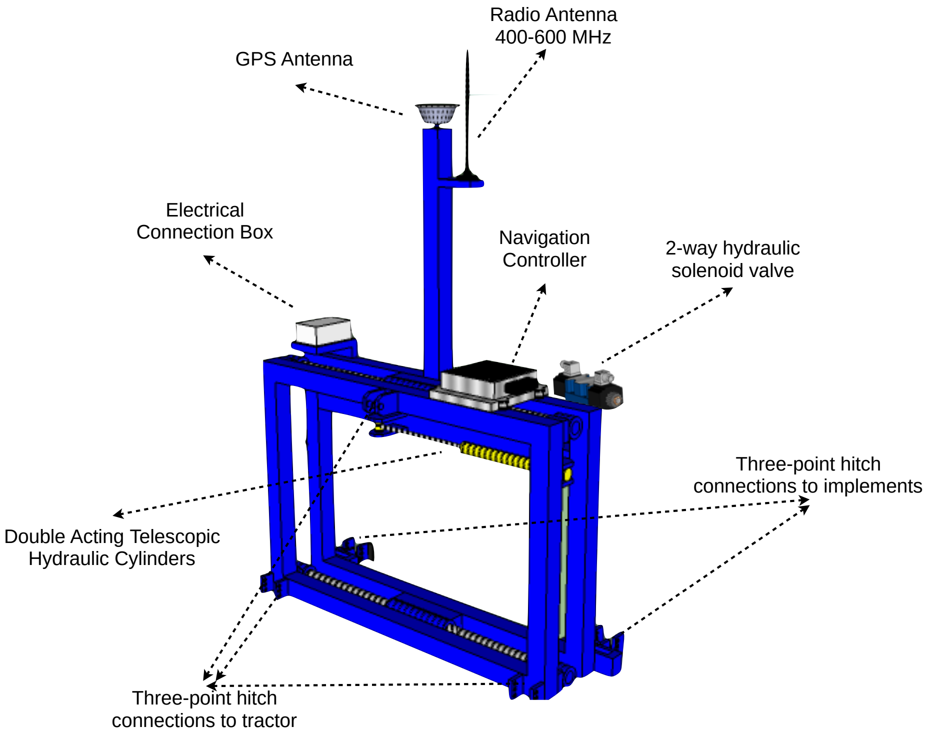
A system was developed for weed control of inter-row and intra-row areas with a unique combination of cultivation for six rows, a narrow band sprayer and an electro-hydraulic side-shift frame for row center positioning:

Side-Shift Frame System

A side-shifting frame was developed for centering the narrow band treatments of herbicide above the rows and parallel to the crop rows with a minimum of lateral drift (cross-track error). For applications with significant side-slope and/or with very wide implements, precise weed control can be best achieved if the implement is also controlled in addition to the tractor navigation.

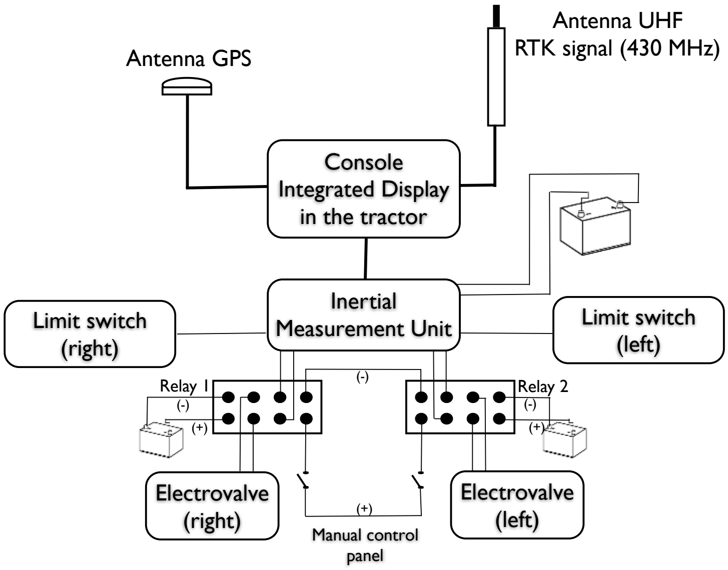
A double-acting hydraulic cylinder with a stroke length of 0.3 m was mounted on the metal frame. This cylinder consisted of a rectangular tube 0.6 m long that was strong enough to support the mechanical and chemical weeding implement (Figure 1). A 2-way hydraulic solenoid valve (model 450–500 psi, Parker Hannifin Co., Cleveland, OH, USA) allowed left/right shifting, and a manual proportional control valve regulated the oil flow rate to vary the piston velocity. A direction-specific calibration setting was used to ensure the same piston speeds for left and right movements.

Figure 2.1. Schematic diagram showing the side-shift frame system developed for row position centering controlled by an RTK-GPS geo-positioning system.



A positioning sensor was interfaced to a relay control circuit that actuated the hydraulic system on the shifting frame. The controller's function was to operate the 2-way solenoid valve responsible for shifting the frame in one direction. The controller was not connected directly to the valves but was connected to separate 12 V relays responsible for operating the valve (Figure 2). These relays allowed the use of an external control device to manually control the lateral movement of the shifting frame. Two limit switches were used to restrict the motion of the hydraulic cylinder. The side-shift frame was attached to the tractor using the rear three-point linkage.

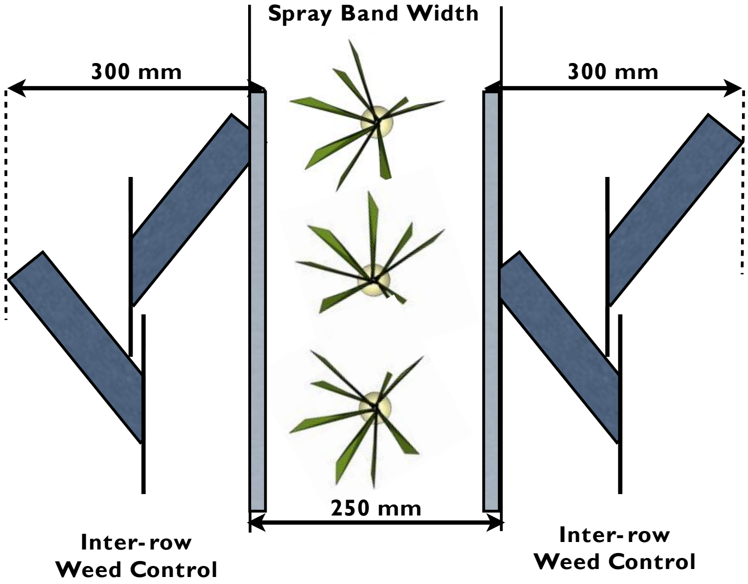
Figure 2.2. Communication and control diagram for the side-shift frame system.



Mechanical and Chemical Weed Control System

An implement that incorporated tools for mechanical and chemical weeding was attached to the side-shift frame using an anchoring plate. For the inter-row weed control system, seven units were used to cultivate six crop rows. Five central units, consisting of two beet hoes and outer two units, had only one hoe, were mounted on spring shanks and were attached to the implement chassis with an angle plate (90°). The beet hoe shape was selected to provide good cutting performance for both plant material and the high clay soil present on the farm [27]. Figure 3 shows how a set of beet hoes worked between crop rows, 100 mm from the center of the row and with a working width of 300 mm. There was a 25 mm overlap between the spray band and the beet hoes on each side to avoid untreated areas. The system had two gauge wheels for controlling the working depth and two folding bars, joined by hinges at both the left and right sides, to allow a larger implement width that was easily compacted for safer field-to-field transportation.

Figure 2.3. Mechanical inter-row weed control and herbicide spray band with the overlapped zones (gray).



The hydraulic sprayer components needed to apply herbicide to six crop rows in narrow bands and in broadcast application were mounted on the chassis along with a 500 L tank. In the banded application, the angle of the spray pattern and mounting height of the nozzle were critical in controlling band width. Before field tests, a specific band width was selected and checked with the appropriate nozzle height for a spray angle of 80° with respect to the crop (band width 250 mm and nozzle height 150 mm). In the broadcast application, the nozzles were positioned 500 mm above the crop and separated by 500 mm with a spray angle of 110°, which is the conventional practice of local sugar beet producers.

An initial test of the system was conducted to characterize the lateral implement movement, with a forward speed of 7.5 km/h. A rigid disc was attached to one beet hoe to create a small furrow to indicate the beet hoe path as it passed across the field. A hand ruler was used to characterize the lateral implement movement by measuring the ground distances between this furrow and the crop rows; a similar procedure was described and used by Griepentrog et al. [23] The side-shift RTK GPS output string was also logged.

Global Positioning System (GPS)

An RTK-GPS system was used to correct the lateral deviation of the combined row crop cultivator and band sprayer implement. The system consisted of a rover RTK GPS (model AgGPS 450, Trimble Navigation Ltd., Sunnyvale, CA, USA) with the GPS antenna mounted 2 m above the ground and located in the center of the three-point hitch support frame (Figure 1). The system received RTK-fixed quality correction signals from a dedicated RTK base station located ~0.5 km from the test site. The base station was configured to broadcast compact measurement record (CMR)-RTK correction signals when transmitting through a radio-modem to the RTK receiver mounted above the tractor. The controller (Trimble AgGPS NavController II) was mounted on the side-shift frame 0.8 m below the GPS antenna to compensate for tilt and yaw and provide precise lateral correction information to the implement by using guidance information from the console (model FMX, Trimble) with an internal RTK receiver. The horizontal position dilution of precision (HDOP) was recorded during the field test, and these values ranged between 2.7 and 2.9, indicating that the satellites were well distributed and the computed position was accurate. An RTK-GPS automatic guidance system (AgGPS Autopilot, Trimble Navigation Ltd.) was used to pilot the tractor (John Deere model 6820, John Deere, Moline, IL, USA) during the seeder operation. The AB line used for seeding was stored internally in the tractor navigation system for future use during the weed control trials.

Field Experiments

Large-scale field tests were conducted during the 2010–2011 sugar beet season in the Sevilla region located in the southern part of Spain (36.95436°N, 6.084717°W). Approximately 8 ha were planted with a 12-row pneumatic drill seeder in a commercial sugar beet field, within which a 1 ha section was selected for the weed control trials. The tractor used for the seeding operations was guided with an automatic steering system of centimeter-level precision to ensure straight seed-lines and to generate a

6 m AB line, which was converted into two 3 m AB lines for use during the trials. A 3 m offset distance was added using the user-interface of the automatic steering system; this distance is a typical implement width (here, the experimental implement width was 3 m).

In this experimental plot, two types of weed control treatment (i.e., conventional and experimental herbicide application) were compared to analyze the herbicide savings and efficiency achieved when a side-shift frame based on the RTK-GPS correction was used for weed control. Both treatments were performed at a rate of 225 L ha^{-1}, 4 bars of pressure and a nominal tractor speed of 7.5 km h^{-1}.

The tractor (Kubota model B2530, Torrance, CA, USA) used for the test was a small tractor of 18 kW rated power. This light-weight tractor has tractive characteristics that allow field entry only a few hours after rain, which is an important consideration in this area of marshy fields.

Conventional or broadcast herbicide applications were conducted on six experimental plots, applied uniformly on the ground (pre-emergence) or over the crop canopy (post-emergence), and the experimental applications were conducted on six experimental plots. Each of these experimental plots was 216 m2, and 15 untreated control plots with a total area of 18 m2 were left between these plots. The treatments were randomized between different experimental plots.

One pre-emergence and three post-emergence herbicide applications were carried out in this test. For the conventional application, the shifting frame was not activated; thus, the spraying operation resembled the common practice of local farmers. The 6 nozzles were set at 50 cm above the crop and 50 cm between nozzles, with a spray angle of 110°. For the experimental weed control treatment, the automatic shifting frame with RTK-GPS-based control was used to correct the implement position, and the banded spray was set to 6 nozzles located 150 mm above the crop and separated by 500 mm with a spray angle of 80°. The wetted surface using the conventional application was 3 m, and the surface using the banded application was 1.5 m. The mechanical cultivation tools were not required until the third post-emergence herbicide treatment because until then, the weeds between rows were not in competition with the crop.

Ten days after this 3rd treatment, the weeds that had escaped the mechanical/chemical control were removed manually. The time spent by the tractor driver and the hand-hoeing crew were recorded to calculate weed control costs. To assess the impact of the two methods on yield, the sugar beets in the experimental trials were harvested, and Wyse's method [28] was used to correct to a standard 16% sugar content.

Data Analysis

Determination of the Cross-Track Error

In many agricultural applications, such as tillage, planting, spraying and harvesting, the vehicle passes should be parallel and separated by a constant distance H. If the actual distance is greater than H, an area can be skipped, and if the actual distance is less than H, there is an overlap.

The single-point cross-track error (XTEi) was defined as the perpendicular distance from the straight line AB to each recorded RTK GPS system point. The total XTE was calculated using the RMS value of all the single-point XTEs along the full length of the line AB [29]. Cross-track error is an important variable that affects the potential skip or overlap. The real distance can be calculated from the simple analytic geometry shown in Equation (1):

$$\varepsilon \, \mathrm{RMS}_t = \sqrt{\frac{1}{N_t}\sum_{i=1}^{N_t} e_{it}^2} \qquad (1)$$

For each pass, a root mean squared (RMS) error was then calculated with the following equation:

$$e^2{}_{it} = (x_i - x_t)^2 + (y_i - y_t)^2 \qquad (2)$$

where:

RMSt = the RMS error for the tth pass

Nt = total number of measurement point for the tth pass

eit = distance from the ith point to the tth pass

Descriptive statistics and the Shapiro-Wilk contrast were calculated using R software [30].

Weed Control Efficacy Study and Crop Yield Response

In the untreated control, conventional and experimental plots, weed counts were used to evaluate the weed population (plants m−2). The weed species included knotted hedge parsley

(Torilis nodosa L.), hairy buttercup (Ranunculus sardous L.), scarlet pimpernel (Anagallis arvensis L.) and oxtongue (Picris echioides L.). Weeds were counted after each post-emergence application (one week) using a rectangular steel frame with a size of 0.5 m × 2 m, and the area under the frame was 5% of the experimental unit size. This area was selected according to the published principles of weed science [31], which recommend that the area under all the quadrats be 5 to 10% of the plot size. The rectangular frame was placed by throwing it into the experimental units where weed infestation was representative of the treatment. The weed population in the control experimental units was used as a reference for all other treatment experimental units.

Statistical analysis of the data was performed with an analysis of variance (ANOVA) model in a completely randomized design with two fixed factors to determine the effects of treatments on the

total weed population. The factors were the date of treatment (three levels: 12/02/10, 01/05/11

and 02/22/11) and the treatment type (three levels: conventional application-CA, experimental application-EA and control). The response variable was the population of emerged or surviving weeds after the treatments.

The homogeneity of variances was tested using the Levene test, and normality was tested using

the Shapiro-Wilk test. The heteroscedasticity of the surveyed populations led to the use of a robust model [32] using 0.2-trimmed means. Differences between means in the ANOVA models were compared using the Yuen-Welch test [33].

In addition, a comparison of the 0.2-trimmed means of independent populations to determine the effect of CA and EA treatments on crop yield was undertaken. The dependent variable was the average sugar beet yield (t ha^{-1}) at standard 16% sugar content. The sugar beet yield was not harvested in the control zone. Analyses were performed with IBM SPSS Statistics 19 and R software [30].

Feasibility Study

Engineering economics comparisons require at least two alternative proposals for prospective receipts and disbursements. In this study, we compared the payment required for the purchase of a conventional sprayer or an experimental machine, which are the two alternatives presented for analysis. The difference between payments on investment is 10,200 €.

Cash flow analysis is necessary and was included in this feasibility study [34]. Cash flow analysis includes separate components, such as investment payment (Ko), or the amount to pay for the implementation of the project; cash flow (Fj), calculated as the difference between receipts and annual payments; rate of interest (r), according to the expectations of the investor; and the project life (N).

To determine cash flow, we started from the fact (shown in the Results and Discussion section) that crop yield will be similar between methods using each of the two machines. Thus, to determine the increase in cash flow, we only evaluated the difference between payments. This restriction is necessary to evaluate only those differences that are exhibited between the two applications. Table 3 shows

the annual cost associated with the use of each alternative. This total included the cost of herbicide application and hand weeding, insurance, GPS-RTK signal fee, fuel, repair and maintenance for

both scenarios.

The costs for herbicide application were determined according to the current prices of the ingredients used and the cost of wages in the local area. Furthermore, the GPS signal subscription fee for 1 year and cost of fuel were based entirely on the theoretical fuel consumption [35]. Insurance was obtained by applying a percentage of the purchase price of the equipment, 0.25%, similar to that used by Srivastava et al. [36]. Finally, the costs of repairs and maintenance were determined using the following equation:

$$\frac{C_m}{P_u} = RF1\left[\frac{t}{1000}\right]^{RF2} \quad (3)$$

where:

Cm = accumulated repair and maintenance, euros

t = accumulated use, h

RF1, RF2 = repair factors from [36]

The discount rate in the presence of inflation was fixed at 6%, a conservative rate given the current rates in the country. The working lifetime of the sprayer used for economic estimation was 10 years, in accordance with other publications [37].

Frequently, in economic analysis, some parameters are based on assumptions that are difficult or impossible to verify a priori. Therefore, it is common to perform a sensitivity analysis of those parameters that are most likely to be affected by the outcome of the analysis, thus providing simultaneous scenarios that can lead to very different results. This study sensitized inflation cash flows, providing variations between −4% (unfavorable scenario) to +2% (favorable assumptions).

We also analyzed scenarios of different areas cultivated by the owner, including 5, 10, 15, 20, 50 and 100 ha. Finally, analyses were carried out with two payments of investment, the initial estimate by the authors, 10,200 €, and another, unfavorable investment of 12,750 €, an increase of 25% above the initial estimate. The life of the machine, always difficult to determine [38], was not included in the analyses because the results have made it unnecessary. This method provided a total of 84 scenarios.

The index used to determine the return on investment was the recovery period (Equation (4)), defined as the year n that φ ≥ 0 such that:

$$\left(\varphi = -K_o + \sum_{j=1}^{N} \frac{F_j}{\left(1+r\right)^j} \right) \qquad (4)$$

This criterion must be satisfied for n ≤ N to guarantee profitability. When considering the inflation rate, the cash flow used to determine the rate of recovery was:

$$r^* = r - q \qquad (5)$$

where q = annual inflation rate in cash flow.

3.2.3 Results and Discussion

In this study, an experimental implement, which combined six-row crop cultivators and six band sprayers with row-position centering using an electro-hydraulic side-shift frame, was developed and operated for weed control within inter-row and intra-row areas (Figure 4). The GPS antenna mounting location on the frame and the open nature of the sugar beet field enabled an unobstructed view of the sky during the entire trial. This condition allowed for optimal signal reception regardless of satellite geometry, and RTK GPS fixation was obtained for the recording of all passes during this experiment.

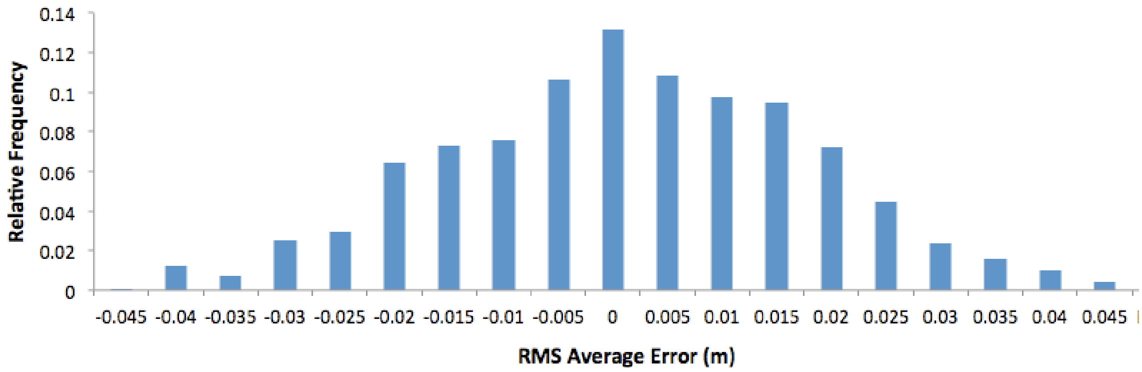
Figure 2.4. Prototype of six-row mechanical weed control cultivator for inter-row areas and band spraying for intra-row areas.

A total of 1,409 events were automatically recorded in three different passes. XTE was analyzed, which was the distance between the side-shift frame's actual position and the reference pass at each moment. The GPS receiver error was the transverse deviation from the travel direction. The frequency histogram (Figure 5) shows a good correspondence between the average and median position error, with an asymmetry coefficient of −0.02, and a normal distribution. The Shapiro-Wilk test yielded a

p-value of 0.16. The absolute deviation of the modal value was 4 mm, and the 95% transverse deviation was between 0 and ±33 mm at 7.5 km/h. The magnitude of the RMS transverse deviation errors presented a level of accuracy comparable to the results of Griepentrog et al. [23] who observed cross-track error mean values of between −16 mm and 11 mm.

All measurements of lateral implement movement, i.e., the ground distances between the mark left by a rigid disc and the crop rows, were located within the intra-row bandwidth, which for this study was defined as ±125 mm from the row center line. This result confirms that the side-shift control did not cause transverse interaction between beet hoe units and the sugar beet plants.

Figure 2.5. Relative frequency histogram of mean lateral deviations.



Weed Control Efficacy Study and Crop Yield Response

The weed control efficacies of the treatments (conventional and experimental methods) and the control (no treatment) were compared. Some descriptive statistics are shown in Table 1, including the mean, trimmed means of weed counts, weed surveying dates and sugar beet yield for each treatment. These data illustrate the variability between treatments and dates, with the variance on the earliest date (12/02/10) being consistently greater than on other sampling dates. The data also illustrate that the variability of the weed population was greatest with the conventional treatment on the final date (02/22/11), which, according to AIMCRA technicians, is a key factor in the sugar beet yield. This variability was confirmed by the fact that the conventional treatment exhibited greater yield variations, as observed in the variance estimators and normalized median absolute deviation (Table 1). The experimental treatment tended to provide a more uniform yield by providing a more uniform control of adventitious weeds. The analysis of variance yielded p-values of 0.001 (date factor), 0.003 (treatment factor) and 0.032 (interaction). Therefore, the results were significantly different for all components within the model.

The results indicate that treatments CA and EA achieved similar global weed control for each of the survey dates, with both being significantly better than the control (Table 2). Comparing trimmed means, the control zone showed between 67% and 132% more weeds than those that received conventional or experimental treatments during the crop cycle. No significant differences between treatments CA and EA were observed (Table 2). However, for the first two survey dates, treatment CA had consistently fewer emerging weeds. The difference on 01/05/11 was notable, with 23.6 weeds m^{-2} (CA) vs. 34.6 weed m^{-2} (EA). These results were expected. The experimental treatment did not use mechanical weed control between crop rows until the last post-emergence treatment. At this time, weeds between the application bands were controlled with mechanical cultivation. In general, there was a downward trend in the population of weeds in the two treatments studied. This result contrasted with the control treatment, where there was an initial increase in weed population. Thus, the interaction of the model was significant.

Table 2.1. Weed population for three survey dates and sugar beet yield statistics.

Treatment	Survey date	$\bar{x}$	σ^2	Minimum	Maximum	0.2-Trimmed mean	NMAD †
		Weed population (weed m^{-2})					
CA þ	12/02/2010	35.1	463	3	61	34.5	29.6
	01/05/2011	22.9	36	14	28	23.6	5.0
	02/22/2011	11.4	17	7	17	11.2	5.4
EA þþ	12/02/2010	47.6	540	18	77	47.8	20.0
	01/05/2011	33.4	69	19	44	34.6	4.0
	02/22/2011	10.9	5	8	15	10.6	2.2
Control	12/02/2010	48.9	1340	13	150	39.9	23.7
	01/05/2011	65.6	485	38	108	63.4	25.2
	02/22/2011	47.1	616	15	97	45.6	26.0
		Yield (t ha^{-1})					
CA þ	07/15/2011	95.4	60.0	75.7	107	95.8	8.5
EA þþ	07/15/2011	96.5	13.8	91.3	106	96.0	2.6

† Normalized median absolute deviation. þ Conventional application. þþ Experimental application.

Table 2.2. Comparison of the 0.2-trimmed means of weed population (weeds m−2) between treatments and survey dates.

	Treatments (means)			
Dates	Conventional (CA)	Experimental (EA)	Control	Date factor (mean)
12/02/2010	34.5 a	47.7 a	39.9 a	39.9 ab
01/05/2011	23.6 a	34.6 a	63.4 b	42.2 a
02/22/2011	11.2 a	10.6 a	45.6 b	23.1 b
Treatment factor (mean)	19.6 a	27.4 a	45.6 b	

Within each factor level, values followed by different letters are significantly different ($p < 0.005$ for both factors).

As shown in Table 2, on 12/02/10, there was no significant difference between treatments. In weed counts carried out on 01/05/11 and 02/22/11, the plots that received no treatment (control) had a significant increase of weed population. As expected, without weed control, the competitive weed pressure on the crop increased significantly. There were no significant differences between CA and EA in weed count on 02/22/2011.

The data highlight the fact that even though the experimental treatment (EA) only used the mechanical method on 02/22/11, which resulted in a 30% increased weed population with respect to CA (not significant) on 05/01/2011 and 46% (not significant) on 12/02/10, the sugar beet yields from the EA and CA treatments were similar, with nearly identical 0.2-trimmed means (Table 1). There was no significant difference between the two management systems ($p = 0.92$). The sugar beet yield confidence interval for the difference between the 0.2-trimmed means of the CA and EA treatments was (−4.45 t ha^{-1}, 4.08 t ha^{-1}). This result is consistent with previous indications and the visual field observations of AIMCRA technicians that the weed population at the time of the last herbicide application (with almost identical values between CA and EA) is the most important determinant of sugar beet yield [39,40].

Feasibility Study

Table 2.3 shows payments to be made with the two machines in different treatments, including through the payment of fuel required by the tractor in operation. All other payments attributable to the tractor (e.g., tires, maintenance, etc.) are independent of the machine used. Weed control costs for

both treatments were significantly different. The optimized equipment provided a band application width of 250 mm and a nozzle height of 15 cm (80° nozzle). This setting reduced the flow by half, and only half of the ground area received herbicide, but the intra-row plants received the same herbicide dosage. This result implies that the herbicide usage cost, both pre-emergence and post-emergence, could be reduced by 50% compared to conventional treatment. The reduction of the herbicide application rate observed in this study was consistent with the level of reduction observed by Wartenberg and Dammer [40] in a precision spray application using an opto-electronic sensor for weed counts within the tramlines.

Table 2.3. Payments for weed control for both applications.

Area payments	Conventional application method	Experimental application method
Herbicide cost (€/ha)		
- Pre-emergence	81.67	40.84
- 1st Post-emergence	38.64	19.32
- 2nd Post-emergence	74.95	37.47
- 3rd Post-emergence	145.83	72.92
Hand weeding (h/ha)	15.32 *	13.19 *
Worker cost (€/ha)	117.96	101.56
Cost of fuel (€/ha)	5.32	6.92
Total cost per ha (€/ha)	459.05	272.11
ANNUAL PAYMENTS		
Insurance (€/year)	147	307.50
Repair and maintenance (€/year)	Variable	Variable
GPS-RTK signal costs (€/year)	0	820
INVESTMENTS		
Electro-hydraulic side-shift frame (€)	0	900
Mechanical and chemical weed control system (€)	0	10,000
RTK-GPS (€)	0	9,100
Conventional broadcast sprayer (€)	9,800	0

* Not summed in these columns because of differences in units (*i.e.*, h/ha and €/ha)

Table 2.3 shows that the payment of hand weeding labor was reduced from 117.96 € ha−1 to 101.56 € ha−1, a reduction of 14% per hectare, using the experimental system. Fennimore et al. [41] reported similar savings in broccoli and lettuce using a machine vision guidance system to control the fine movements of the cultivator. The inter-row tools were used only in the third post-emergence treatment because at the early stages of weed development between the rows, there was negligible risk of competition for nutrients, light and water between the weeds and sugar beet plants. The mechanical weed control applied at the third post-emergence treatment reduced the time spent on hand weeding from 15.32 h ha−1 to 13.19 h ha−1.

The conventional equipment cost 9,800 €, whereas the experimental equipment had an estimated cost of 20,000 €. The RTK-GPS system, which was still fairly expensive for this practice, was similar in cost to that observed by Pedersen et al. [42] who indicated that the price is expected to decrease as the technology becomes more widespread. For these early trials, a dedicated base station was used to transmit the GPS correction signal to the rover receiver. It was possible to achieve an accuracy of ±20–30 mm, but this increased the investment costs of the equipment. Currently, the Andalusian government is working on developing a network of fixed stations. In the future, the GPS correction signals may be used without having to invest in a base station (7,500 €). In this case, the experimental equipment would cost 12,500 €, a significant reduction.

The sensitivity analysis for the investment was generated with seven annual updating rates, two increases of investment payments and six farm sizes, generating 84 possible scenarios (Table 2.4). Using annual receipts and payments avoids terms that are difficult to quantify, such as depreciation, amortization and interest of fixed or circulating capital [43]. Table 2.4 shows the payback time in years and indicates that farmers with 5 ha would never recoup their investment using our experimental system. A similar situation is true for farmers with 10 ha, for whom the period of return on investment would be higher than the lifetime of the machine. At these small scales, farmers would need to form an agricultural cooperative association before either system would provide a profitable payback. This experimental equipment has sufficient degrees of freedom to allow adaptation to different row-crop species and plant growth stages.

Table 2.4. Payback time (years) for the comparative economic analysis of our experimental system compared to a conventional system.

	Increase of Investment Payments (€)											
	10,200						12,750					
	Farm size (ha)											
r ⁂ (%) †	5	10	15	20	50	100	5	10	15	20	50	100
4	†	>10	7	5	2	1	†	>10	10	6	2	1
5	†	>10	8	5	2	1	†	>10	10	6	2	1
6	†	>10	8	5	2	1	†	>10	>10	6	2	1
7	†	>10	9	5	2	1	†	>10	>10	7	2	1
8	†	>10	9	5	2	1	†	>10	>10	7	2	1
9	†	>10	10	5	2	1	†	>10	>10	7	2	1
10	†	>10	10	6	2	1	†	>10	>10	7	2	1

† Never recovers due to continuous negative cash flow; ⁂ Annual updating rate.

A single farmer would need more than 15–20 ha to recover his or her investment according to the increase in the payment of investment to consider. Additionally, 15 ha would provide the greatest variation (7 to more than 10 years) in payback recovery time. This farm size would also increase the farmer's risk by relying on low interest rates for shorter payback periods, which neglect the effects of inflation upon annual cash flows. For 20 ha, the system would be profitable even in the most unfavorable conditions of this analysis. A payback time of 6 years for the experimental system would decrease to one year or less for 100 ha farms. This increased cost-effectiveness is mainly due to savings in herbicides, which become the determining variable for the entire term of the analysis.

According to these results, the experimental equipment is recommended for areas larger than 20 ha.

Therefore, this study demonstrated the following:

(i) The side-shift frame system developed for row-position centering controlled with an RTK-GPS exhibited similar weed control efficacy as the conventional treatment. The amount of herbicide and the hand-weeding time were reduced, thereby reducing the cost of crop production. Utilization of RTK GPS equipment for other tasks in the crop production system can help disperse the equipment cost across many cultural practices, reducing the equipment cost penalty in the weed control operation and possibly making it economically viable in conventional production systems.

(ii) The sugar beet yields obtained were similar with both application methods (conventional and experimental herbicide application).

(iii) The experimental sprayer is economically profitable for farms above 20 ha of sugar beets according to the simulations.

3.2.4 Conclusions

A machine that combined six-row crop cultivators and six narrow-band sprayers with row-position centering using an electro-hydraulic side-shift frame controlled by GPS was developed for weed control in both inter-row and intra-row areas, respectively. Field tests showed that the machine was robust, adapting to the working conditions required of this type of implement. The following conclusions were drawn based upon the results of this research:

- The experimental system, equipped with GPS technology, developed and used in this work provided an herbicide band application volume targeted to the crop rows without reducing the quality of the intra-row chemical control treatment and while providing herbicide savings of approximately 50%. These reductions in applied chemicals not only reduce production costs but also reduce the environmental impact caused by the chemicals. Statistical analyses revealed no significant differences with respect to weed control efficacy between the two weed control strategies studied.

- The labor required to hand-weed was 15.3 h ha^{-1} in the conventional treatment and 13.2 h ha^{-1} in the experimental treatment, on average. At prevailing wage rates, the weeding costs were 117.00 € and 101.56 € ha^{-1}, respectively. This difference represented a 14% savings with the experimental system.

- Under normal conditions and with the technology used, a farmer with 20 ha using the experimental equipment would be profitable with respect to the conventional equipment, with a payback period of less than the life of the machine. Thus, the experimental equipment can be an affordable option for both large and small farms.

- The adoption of new procedures and technologies that optimize farm operations will help the Spanish sugar beet industry to remain competitive in the global economy.

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References

1. Slaughter, D.C.; Giles, D.K.; Fennimore, S.A.; Smith, R.F. Multispectral machine vision identification of lettuce and weed seedlings for automated weed control. Weed Technol. 2008, 22, 378–384.

2. Brandes, A. Ertrag und Qualität von Zuckerrüben in Abhängigkeit von Restverunkrautung und Standort. Ph.D. Theis, Universität Göttingen, Göttingen, Germany, 2000.

3. Naylor, R.E.L. Weed Management Handbook; Naylor, R.E.L., Ed.: Blackwell Science: Oxford, UK, 1963.

4. Jørgensen, R.N; Sørensen, C.G.; Maagaard, J.; Havn, I.; Jensen, J.; Søgaard, H.T.; Sørensen, L.B. HortiBot: A system design of a robotic tool carrier for high-tech plant nursing. CIGR J. Sci. Res. Dev. 2007, IX, 13–21.

5. Nørremark, M.; Griepentrog, H.W.; Nielsen, J.; Søgaard. H.T. The development and assessment of the accuracy of an autonomous GPS-based system for intra-row mechanical weed control in row crops. Biosyst. Eng. 2008, 101, 396–410.

6. Slaughter, D.C.; Pérez-Ruiz, M.; Gliever, C.; Upadhayaya, S.; Sun, H. Automatic Weed Control System for Processing Tomatoes. In Proceedings of the XVIIth World Congress of the International Commission for Agricultural Engineering (CIGR), Québec City, Canada, 13–17 June 2010; pp. 131–132.

7. Van Evert, F.K.; Samson, J.; Polder, G.; Vijn, M.; van Dooren, H.; Lamaker, A.; van Der Heijden, G.W.A.M.; van der Zalm, T.; Lotz, L.A. A robot to detect and control broad-leaved dock (Rumex obtusifolius L.) in grassland. J. Field Rob. 2011, 28, 264–277.

8. Karimi, D.; Mann, D. Torque feedback on the steering wheel of agricultural vehicles. Comput. Electr. Agr. 2009, 65, 77–84.

9. López-Granados, F. Weed detection for site-specific weed management: Mapping and real-time approaches. Weed Res. 2011, 51, 1–11.

10. Xue, J.; Zhang, L.; Grift, T.E. Variable field-of-view machine vision based row guidance of an agricultural robot. Comup. Electr. Agr. 2012, 84, 85–91.

11. Griepentrog, H.W.; Nørremark, M.; Nielsen, H.; Blackmore, B.S. Individual Plant Care in Cropping Systems. In Proceedings of the 4th European Conference on Precision Agriculture, Berlin, Germany, 16–18 June 2003; pp. 247–251.

12. Lampkin, N. The Living Soil; Farming Press: Ipswich, UK, 1994; Chapter 2, pp. 13–51.

13. Mohler, C.L. Mechanical Management of Weeds. In Ecological Management of Agricultural Weeds; Liebman, M., Mohler, C.L., Staver, C.P., Eds.; Cambridge University Press: Cambridge, UK, 2001; pp. 139–209.

14. Melander, B. Optimization of the adjustment of a vertical axis rotary brush weeder for intra-row weed control in row crops. J. Agr. Eng. Res. 1997, 68, 39–50.

15. Tillett, N.D.; Hague, T.; Miles, S.J. Inter-row vision guidance for mechanical weed control in sugar beet. Comput. Electr. Agr. 2002, 33, 163–177.

16. Kaya, R.; Buzluk, S. Integrated weed control in sugar beet through combinations of tractor hoeing and reduced dosages of a herbicide mixture. Turkish J. Agr. Forestry 2006, 30, 137–144.

17. Tillett, N.D.; Hague, T. Increasing work rate in vision guided precision banded operations. Biosyst. Eng. 2006, 94, 487–494.

18. Märländer, B.; Hoffman, C.; Koch, H.-J.; Ladewig, E.; Merkes, R.; Petersen, J.; Stockfisch, N. Environmental situation and yield performance of the sugar beet crop in germany: Heading for sustainable development. J. Agron. Crop Sci. 2003, 189, 201—226.

19. Dietsch, A. Rentabilität und Umweltverträglichkeit der Unkrautregulierung in gentechnisch veränderten herbizidtoleranten Zuckerrüben—ein Beitrag zur nachhaltigen Entwicklung des Zuckerrübenanbaus. Ph.D. Thesis, Universität Göttingen, Kinzel, Göttingen, Germany, 2002.

20. Cowan, T.; Alexander, K. Deregulating Genetically Engineered Alfalfa and Sugar Beets: Legal and Administrative Responses. Congressional Research Service. 2012. Available online: http://www.fas.org/sgp/crs/misc/R41395.pdf (accessed on 27 December 2012).

21. Wevers, J.D.A. Reduced Environmental Contamination by New Herbicide Formulations. In Proceedings of the 60th IIRB Congress, Cambridge, UK, 1–3 July 1997; pp. 169—176.

22. Melander, B.; Rasmussen, I.A.; Barberi, P. Integrating physical and cultural methods of weed control: Examples from European research. Weed Sci. 2005, 53, 369–381.

23. Griepentrog, H.W.; Norremark, M.; Nielsen, J.; Soriano Ibarra, J. Autonomous Inter-row Hoeing using GPS Based Side-shift Control. In Proceedings of Automation Technology for Off-Road, Bonn, Germany, 1–2 September 2006; pp. 117–124.

24. Leer, S.; Lowenberg-DeBoer, J. Purdue Study Drives Home Benefits of GPS Auto Guidance. 2004. Available online: http://news.uns.purdue.edu/UNS/html4ever/2004/040413.Lowenberg.gps.html (accessed on 16 May 2011).

25. Abidine, A.Z.; Heidman, B.C.; Upadhyaya, S.K.; Hills, D.J. Autoguidance system operated at high speed causes almost no tomato damage. California Agr. 2004, 58, 44–47.

26. Leandro, R.F.; Santos, M.C.; Langley, R.B. Analyzing GNSS data in precise point positioning software. GPS Solut. 2011, 30, 1–13.

27. Moreno, F.L.; Vaz, R.P.; Fernández, E.B.; Cabrera, F.C. Simulating the composition of the in situ soil solution by the model Expreso: Application to a Reclaimed Marsh Soil of SW Spain irrigated with saline water. Agr. Water Manag. 2004, 66, 113–124.

28. Wyse, R. Sucrose uptake by sugar beet tap root tissue. Plant Physiol. 1979, 64, 837–841.

29. Taylor, R.K.; Schrock, M.D. Dynamic Testing of GPS Receivers; Paper No. 03–1013; ASABE: St. Joseph, MI, USA, 2003.

30. R Development Core Team. R: A Language and Environment for Statistical Computing; R Foundation for Statistical Computing: Vienna, Austria. Available online: http://www.R-project.org/ (accessed on 18 June 2011).

31. Rao, V.S. Principles of Weed Science; Science Publisher, Inc.: Endfield, NH, USA, 2000.

32. Wilcox, R. Comparing robust nonparametric regression lines via regression depth. J. Statist. Comput. Simul. 2010, 80, 379–387.

33. Yuen, K.K. The two-sample trimmed t for unequal population variances. Biometrika 1974, 61, 165–170.

34. Romero, C. Evaluación Financiera de Inversiones Agrarias; Mundi-Prensa: Madrid, Spain, 1998.

35. Goering, C.E.; Hansen, A.C. Engine and Tractor Power, 4th ed.; ASABE: St. Joseph, MI, USA, 2008.

36. Srivastava, A.K.; Goering, C.E.; Rohrbach, R.P.; Buckmaster, D.R. Engineering Principles of Agricultural Machines, 2nd ed.; ASABE: St. Joseph, MI, USA, 2006.

37. Agricultural Machinery Management Data; ASABE Standards: ASABE D497.7MAR2011; ASABE: St. Joseph, MI, USA, 2011.

38. Ballestero, E. Contabilidad Agraria; Mundi-Prensa: Madrid, Spain, 1996.

39. Hembree, K.J. Sugarbeet Integrated Weed Management. In UC Pest Management Guidelines; UC ANR Publication 3469; UC Cooperative Extension: Fresno, CA, USA, 2010.

40. Wanternberg, G.; Dammer, K.H. Experiences in developing technologies in site-specific herbicide spraying in real time. J. Plant Diseases Protect. 2002, 18, 443–450.

41. Fennimore, S.A.; Tourte, L.J.; Rachuy, J.S.; Smith, R.F.; George, C.A. Evaluation and economics of a machine-vision guided cultivation program in broccoli and lettuce. Weed Technol. 2010, 24, 33–38.

42. Pedersen, S.M.; Fountas, S.; Have, H.; Blackmore, B.S. Agricultural robots-system analysis and economic feasibility. Prec. Agr. 2006, 7, 295–308.

43. Bermejo, J.L.; Ayala, J.; Morillo-Velarde, R. Recommendations for sugar beet production. J. Res. AIMCRA 2001, 71, 22–31.

III. Publications: Chapter 3

Assessing GNSS correction signals for assisted guidance systems in agricultural vehicles

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Abstract

Accuracy levels achieved with DGPS (Differential Global Positioning System) receivers in agricultural operations depend upon the quality of the correction signal. This study has assessed differential signal error from a dedicated base station (DBS), OmniSTAR VBS, EGNOS (European Geostationary Navigation Overlay System), EUREF-IP (European Reference Frame – IP for Internet Protocol) and RASANT (Radio Navigation Satellite Aided Technique). These signals were utilized in guidance assisting systems for agricultural applications, such as tillage, harvesting, planting and spraying, in which GPS receivers were used under dynamic conditions. Simulations of agricultural operations on different days and at different time slots and simultaneously recording the tractor´s geo-position from a DGPS receiver and the tractor´s geo-position from a real-time kinematic (RTK) GPS allowed the comparison of the GPS correction signals. The hardware used for tractor guidance was a lightbar (Trimble model EZ-Guide Plus) system. ANOVA statistics showed a significant difference between the accuracy of the correction signals from different sources. GPS correction signal recommendations to farmers depend upon the accuracy required for the specific operation: a) Yield monitoring and soil sampling (<1 m) are possible with all the GPS correction signals accessed in any time slot. b) Broadcast seeding, fertilizer and herbicide application (<0.5 m) are possible for 80 % of time with OmniSTAR VBS, 40% of time with RASANT and EUREF-IP and 100% of time with a dedicated base station. c) Transplanting and drill seeding (<0.04 m) are not possible with the accuracy correction provided by any one of the systems used in this study.

Keywords. DGPS, assisted guidance systems, EGNOS, RTK-GPS.

3.3.1. Introduction

Guidance of agricultural machinery has been a manual task since the 1920's. Today, there are an increasing number of Global Navigation Satellite Systems (GNSS) and the North American Global Positioning System (GPS) that are fully operational and commercially available to provide all-weather guidance virtually 24 hours a day. Its many agricultural applications to the decision-making process include; positioning of operating machines, soil sampling, variable rate application and vehicle guidance. However, GPS technology used without correction signals is limited to an accuracy range no greater than ±5 m for 95% of time thus restricting its usage (Griepentrog et al., 2006). In the last two decades, the ability of DGPS to provide real-time sub-meter- or even decimeter-level accuracy has revolutionized the agricultural industry (Bauer and Schefcik, 1994; Petersen, 1991; Wilson, 2000; Pérez et al., 2004).

The assisted guidance system works as follows: The driver makes manual steering adjustments to minimize the displayed cross-track error. The cross-track error is typically displayed with a device using LEDs and is called a lightbar. Typically, GPS pass-to-pass accuracy used for assisted guidance systems ranges from 50 mm or 100 mm to 300 mm. Drivers usually are not able to follow guidance more accurately than 10 mm. Therefore, a GPS source that is more accurate than this is not justified. However, at least 300 mm accuracy is needed in order for GPS guidance to provide better accuracy than that of traditional methods such as row markers (Heraud and Lange, 2009).

High (~10 mm range) geo-positioning accuracy and precision is available using real-time kinematic (RTK) GPS. For example, Abidine et al. (2004) demonstrated the application of RTK GPS auto-guidance technology for precision inter-row cultivation and deep tillage operations in close proximity to buried drip-irrigation tubing (50 mm target distance between crop row or drip-tape and cultivation or tillage tools) without damage to crop plants or the drip-tape. This level of precision is not needed for general site-specific farming, but it does permit treatment of specific small locations such as a plant-specific operation and is essential for precision guidance (Larsen et al., 1994) and controlled traffic farming (Chamen et al., 1992; Chamen et al., 1994).

DGPS technology employs two (or more) GPS receivers simultaneously tracking the same satellites to determine their relative co-ordinates. Of the two receivers, one is selected as a reference, or base, which remains stationary at a site with precisely known fixed co-ordinates. The co-ordinates of the other receiver, known as the rover or remote receiver, are not restricted to a fixed location. The rover's co-ordinates are determined using the reference location and measurements generated from both receivers. The rover receiver may or may not be stationary, depending on the type of the GPS operation (El-Rabbany 2006; Lechner and Baumann, 2000).

The level of precision achieved with DGPS technology depends largely on the origin of the correction signals and quality of the GPS receiver. In addition, the level of precision required depends upon the application. Automatic guidance systems for use between rows cannot tolerate errors larger than 50 mm (Keicher and Seufert 2000) but errors up to 1 m may be acceptable for yield maps (Arslan and Colvin 2002).

Agricultural use of GPS has significantly expanded due to the increased availability of differential correction. Today there are three main types of differential correction available:

DGPS radio beacons (e.g., U.S. Coast Guard DGPS beacons along major waterways). These services can provide sub-meter DGPS accuracy. Reliable coverage is available on land, sea and air. This service is free and available in more than 40 countries, however, coverage depends upon the beacon location.

SBAS supports regional, such as WAAS within the United States, EGNOS within Europe, and MSAS within Japan and Southeast Asia, or wide-area (L-band DGPS) augmentation through the use of additional satellite-broadcast messages. The accuracy of these free satellite services varies. The WAAS service within the U.S. is fully operational for safety-critical operations such as aircraft navigation and is specified at 7 m absolute accuracy. Agriculture users have found WAAS to be a reliable source of correction, with an absolute accuracy of better than 1 m and a much better pass-to-pass accuracy (Heraud and Lange, 2009). EGNOS in Europe and MSAS in Japan are services that are designed to provide performance in their regions similar to that of WAAS in North America. The two major commercial L-band satellite providers are Fugro (OmniSTAR service) and Deere (Starfire service). OmniSTAR provides almost complete worldwide coverage. The Starfire service is based on the NASA Jet Propulsion Laboratory correction system. Both of these commercial service providers have a high-accuracy service that uses dual-frequency receivers and antennas for performance in the decimeter range (100 to 300 mm). OmniStar and Starfire are subscription services .

Dedicated-use RTK base station and RTK networks. Real–time kinematic (RTK) base stations provide a high level of geo-position accuracy (~10 mm range) and precision for agricultural tasks like mechanical intra-row weed control or thinning of crop plants (Sun, et al., 2010).

Spanish agriculture utilizes a large variety of GPS correction signals such as; OmniSTAR L-band, EGNOS, EUREF-IP and RASANT. However, the exact precision of the GPS receivers utilizing those signals has yet to be adequately evaluated.

The EUREF Protocol Network is a service of GPS corrections via Internet, created by the European subcommittee of the IAG and is supported by the EU. It is known as Networked Transport of RTCM via Internet Protocol (NTRIP) (it was designed to improve accuracy in a local area). It only uses RTCM code from the nearest base station, with the consequent loss of precision from positions further away from it. However, the wide availability of base stations provides a sufficiently broad coverage (González-Matesanz et al., 2004).

Weber and González-Matesanz (2003) presented a study that detailed information obtained using a computer and bi-frequency RTK correction signal belonging to the base station in Madrid (Spain). Using RTCM correction signals, sub-meter accuracies were obtained in both latitude, longitude and altitude about 20 km from the base station.

RASANT is a real-time DGPS system which is broadcast on an FM sub-carrier by FM radio stations within Spain using the FM Radio-Data-System (RDS). It uses the RTCM code and can be used by anyone with an appropriate receiver. It is a completely free public service.

Talaya et al, 1997 obtained submeter accuracies in planimetry (altitude slightly less accurate) by correction from RASANT. The accuracy degrades by an order of 0.2-0.4 m per 100 km. The recommended reference station distance for this system is less than 500 km.

The objective of this research was to determine the accuracy of available sources of GPS correction signals at different time periods in assisted guidance systems used in agricultural applications. The specific objectives were:

(i) To establish a methodology to compare the dynamic position accuracy of different GPS correction signals and to order them in terms of accuracy.

(ii) To generate GPS correction signal recommendations to farmers, depending upon the accuracy required for each of their operations.

3.3.2. Materials and methods

Receiver configuration and Test platform

Both GPS receivers (Trimble model AgGPS 252 and AgGPS 132) were mounted on a tractor (model 6420, Deere & Company, IL, USA) (Figure 1). The first, mounted on the roof of the cab, was set to RTK (Real Time Kinematic) mode. It communicated with the base station through a radio-modem (Trimble model SiteNet 450) and determined the location of the tractor accurately (~25mm) in the field. This AgGPS 252 receiver provided the vehicle location with an accuracy <50 mm in practice and it was used as reference.

The AgGPS 132 differential GPS receiver utilizes a technology that combines a GPS receiver, a beacon differential receiver and satellite differential receiver in the same housing. The satellite differential receiver can use OmniSTAR VBS and EGNOS correction signals by external input, from any source that transmits it in RTCM, ASCII or TSIP format. The RTK-GPS, RASANT and EUREF-IP correction signals were captured and transmitted to the receiver through an external port (Figure 2): a) RTK-DGPS (model MS750, Trimble Navigation Ltd., Sunnyvale, CA, USA), the station is configured to produce CMR-RTK correction signals (Compact Measurement Record-Real Time Kinematic) when communicating through a radio-modem (SiteNet 450MHz) with the RTK receiver (AgGPS 252) and was mounted above the tractor. The CMR-RTK is a compressed communication code that uses the RTCM format. b) RASANT, a receiver tuned to the desired radio frequency through a conventional FM antenna. This receiver subsequently decodes the RTCM signal that is in the RDS band of a tuned radio station and makes it available through the RS232 port connected to a radio-modem (model 406 MHz, Satel Spain, S.L., Spain). c) EUREF-IP consists of two basic elements: a computer with internet access that acts as a decoder of the signal and a pair of radio-modems (Satel model 869 MHz) for transmission to the rover GPS receiver. Figure 1 shows the equipment scheme used in the field experiments.

A field computer (Trimble model AgGPS 170) was used to record data from the AgGPS 252 which reported the location of the tractor at all times. This computer contained a removable memory card, which records locations, time, date and number of satellites. A handheld control unit (Trimble model Racon 400 MHz) recorded all data generated from the AgGPS 132 receiver and modified it using different correction signals. The Ez-Guide Plus (from Trimble) was connected directly to the AgGPS132 receiver and was used as a guidance system aid.

Field Experiments

Field tests were performed during the summer of 2007 at the Rabanales Field Experiment site, on the University of Córdoba campus (Latitude: 37.9192028 N, Longitude: 4.7207889 W). The three criteria used for choosing the test area were- (i) a plot that was almost flat, (ii) a plot big enough for six 600 m rows, and (iii) a plot that was in range of all base stations used in the experiment.

Each test consisted of six parallel passes of approximately 600 m long following a straight line (parallel swathing). The swath width was constant at 6 m in all the experiments so that it would create realistic usage conditions and would generate enough data.

GPS satellite constellation affects position accuracy (El-Rabbany, 2006); we sought to provide a test that accounted for this inconsistency. We decided to use five days for the test block (Table 1). The test block was evaluated twice with a two week separation between each evaluation. Two types of correction signal were used within a day. A correction signal was tested for 45 minutes before alternating to the other correction signal with a 15 minute setup period between each test. Thus each was repeated five times within a day. Two different types were tested the following day. One type of signal was tested again either two or three days later with a plus one hour offset. This enabled each of the five different correction signals to be tested twice with a 49 or 73 h time period between each test. It was speculated that this testing procedure would provide enough satellite constellation averaging to account for this inconsistency. All the passes were conducted at a travel speed of 6 km/h.

Data Analysis

The UTC time, longitude, latitude, height, velocity, quality of GPS, PDOP, heading and number of satellites received were recorded for the AgGPS 132 and the RTK-DGPS receiver. Only the UTC time, longitude, latitude and velocity were utilized for the accuracy analysis. The rest of the data were used for the data quality check. The data output rate was set to 5 Hz for the AgGPS 252 (RTK unit) receiver and 1 Hz for the AgGPS 132.

A program called "Analysis_Passes", was developed in Visual Basic to convert geographic data into UTM and perform- (a) calculation of distances to the ideal line (A-B line), (b) calculation of errors (GPS error, driver and total error), (c) calculation of statistical values (mean, standard deviation and RMS), and (d) presentation of results. Errors were calculated from the instantaneous co-ordinates of the tractor´s position along a precisely measured length of the A-B line.

Figure 3 shows graphically the calculation of error by the driver (eH), the total error (eTOTAL) with respect to the ideal virtual line and the difference with the previous GPS error (eGPS) due to the loss of accuracy by the latest GPS receiver correction signal.

Adjustment of GPS Antenna Offset

Since the GPS antenna of the AgGPS 132 was not located at the same position as the reference RTK unit (Figure 3), the GPS data string from AgGPS 132 antenna must be first compensated for the antenna offset.

Assume Ex and Ey are the antenna offset values of AgGPS 132 antenna in a vehicle co-ordinate system in the x and y directions, where the origin of the vehicle co-ordinate system is defined at the center of the reference RTK unit, the y direction is defined as the current vehicle travel direction (AB), and the x direction is perpendicular to the y direction (Figure 4). At any time t=ti, the adjusted position of the AgGPS 132 is given by (Han et al., 2004):

$$X'_i = X_i - \left[E_x \cos(\beta) - E_y \sin(\beta)\right] \quad (1)$$

$$Y'_i = Y_i - \left[E_x \sin(\beta) + E_y \cos(\beta)\right] \quad (2)$$

where

(Xi´,Yi´)= adjusted co-ordinates

(Xi, Yi)= original co-ordinates

β = angle between the x-axis of the local (vehicle) co-ordinate system and the x-axis of the global co-ordinate system.

The global co-ordinate system needs to be a plane and the UTM co-ordinate system was chosen. As such, the GPS position string, reported in longitude and latitude, should be projected in the UTM co-ordinate system before equations 1 and 2 are applied.

The β in equation 1 and 2 is the vehicle heading angle, and can be approximated by the following equation:

$$\beta = \alpha - 90° = \tan^{-1}\left(\frac{y0_i - y0_{i-1}}{x0_i - x0_{i-1}}\right) - 90° \quad (3)$$

where (x0i, y0i) and (x0i-1, y0i-1) are the UTM co-ordinates of the RTK unit at time ti and ti-1, respectively.

Determination of the Cross-Track Error

In many agricultural applications such as tillage, planting, spraying and harvesting, the vehicle pass should be parallel and separated by a constant distance H. If the actual distance is greater than H, there could be a skip, and if the actual distance is less than H, there is an overlap.

The single point cross-track error (XTEi) was defined as the perpendicular distance from the straight AB line to each recorded RTK GPS system point (Pi). Total XTE has been calculated using the RMS value of all the single point XTEs along the full length of the AB line (Taylor and Schrock, 2003). Cross-track error is an important variable that affects the potential skip or overlap. The real distance of segment PQ in Figure 4, can be calculated from the simple analytic geometry shown in Equation 5.

For each pass, a root mean squared (RMS) error was then calculated with the following equations:

$$\varepsilon \, \mathrm{RMS}_t = \sqrt{\frac{1}{N_t} \sum_{i=1}^{N_t} e_{it}^2} \quad (4)$$

$$e^2{}_{it} = (x_i - x_t)^2 + (y_i - y_t)^2 \quad (5)$$

RMSt= the RMS error for the t th pass

Nt= total number of measurement point for the t th pass

eit= distance from the point i th to the t th pass

For the statistical analysis, the errors were calculated for each point, so they were grouped by type of correction signal and time slot. The SAS general linear models procedure (SAS 2008) was used to test for significant differences between both the GPS error and driver error using ANOVA. Tukey-Kramer method was used to compare the different correction signals with respect to their mean accuracy.

3.3.3. Results and Discussion

Of the 178000 events that were recorded in 6 different passes in the study, 35.000 of which corresponded to each GPS correction data. Significantly more data was collected in this study compared to previous studies (Ehsani et al. 2002; Han et al. 2004; Karimi et al. 2006), although this study is limited to a single manufacturers´ implementation of DGPS.

Two different types of errors were analyzed. Total error (eTOTAL) is the distance between the vehicle's actual position and reference pass at each moment. This error is the sum of the error due to the guidance system (eGPS) and the error made by the driver (eH). The GPS receiver error (eGPS) is the transverse deviation from the travel direction. This error is caused solely by the use of the GPS guidance system supplemented by each of the correction signals (Figure 3).

Two graphs of cumulative frequency (Figure 5 & 6) show the position error and driver assisted guidance error. These graphs can be used to choose a system based on the error that is acceptable for the application.

GPS receiver error for the set of correction signals

The data in Table 2 shows the mean, standard deviation and RMS values for the GPS receiver error when using different GPS correction signals. The base station had an accuracy of 30 mm, which was expected because the GPS receiver uses the RTK technique that can determine the position within a few centimeters (Trimble, 2007). The small RMS error for this correction signal system indicates that the measured passes were very straight. The RMS error for the rest of the GPS correction signals ranged from 0.50 to 2.00 m. It should be noted that the error from the EGNOS system was expected because during the test period, EGNOS was working in test mode and signals reflect quality and continuity disturbances by ESA. From October 1, 2009 the EGNOS system became fully available, with an expected accuracy of sub-meter making it suitable for use in precision agriculture. Griepentrog et al. (2006) reported that the corrections data from the EGNOS system will improve the accuracy of the GPS and GLONASS systems from about 20 m to less than 5 m.

Since the EGNOS correction signal was in test mode only and contained some errors, it was decided not to include it in the study of the cumulative frequency distribution. Figure 5 shows the cumulative frequency distribution curves of average GPS receiver error. From the correction signals, the 90% accuracy and the 0.5 m success rate can be calculated. The 90% accuracy value indicates there is a 90% chance that, if the test is repeated, the subsequent error will be less than that value. The 0.5 m success rate is the percent of chance that GPS average error will be less 0.5 m. The selection of 0.5 m as a criterion was based on the fact that 0.5 m accuracy can meet the positioning requirement for most agriculture applications.

Driver error for the set of correction signals

The data in Table 3 shows the mean, standard deviation and RMS displacement values between GPS position error and the total error measured using the AgGPS 252 antenna. The magnitudes of the RMS errors were similar for all the GPS correction signals and similar for all test plots since the same driver completed all the runs.

Figure 6 shows that driver error is virtually the same for all correction signals. The cumulative frequency distribution of average driver error can be used to calculate the 90% accuracy and the 0.3 m success rate. The 90% accuracy indicates that, if the test was repeated, there is a 90% probability that the driver error will be below that value. The 0.3 m success rate is the percent of chance that GPS average error will be less than 0.3 m.

GPS receiver error for time slots

Table 4 shows the RMS displacement values for the GPS error position for the five time slots. Using the correction signal from the base, a low RMS error between 0.10 m and 0.17 m was observed. These values are about 70-75% smaller than the corresponding errors associated with the EUREF-IP, OmniSTAR VBS and RASANT systems. For the EUREF-IP and OmniSTAR VBS RMS error are low during time slots 1 and 4, respectively. On the other hand, the RASANT system gave least error value of 0.39 m, in the fifth time slot.

The range of accuracies used in this study for agricultural applications are based on previous studies (e.g., Blackmore and Moore, 1999; Abidine et al, 2004; Van der Schans et al., 2006; Sun et al, 2010). GPS correction signal recommendations to farmers depend upon the accuracy required for each of their applications (Figure 7): a) Yield monitoring and soil sampling (<1 m) are possible with all the GPS correction signals accessed in any time slot. b) Broadcast seeding, fertilizer and herbicides application (<0.5 m) are possible for 80 % of time with OmniSTAR VBS, 40 % of time with RASANT and EUREF-

IP and 100% of time with their own base station. c) Transplanter and drill seeder (<0.04 m below) are possible only with RTK-GPS auto-guidance based systems.

3.3.4. Conclusions

For growers and farmers who are considering investing in a differential GPS system, the accuracy of the system is one of the most important factors. This study addressed two main questions- (i) what are the accuracies of five different GPS correction systems, and (ii) what are the practical implications of measured accuracies on various field operations of interest to farmers.

This study showed that there was significant variability between the five different commercially available GPS correction signals to complement assisted guidance equipment. This study also developed a testing methodology for this type of technology that allows analysis of the behavior of the GPS signals. The following conclusions were drawn based upon the results of this research:

- A tractor was successfully instrumented to monitor and record simultaneously the tractor geo-position from DGPS systems (OmniSTAR VBS, EGNOS, EUREF-IP and RASANT) and the tractor geo-position from a RTK GPS unit.

- According to the analysis of driver error, no clear differences were observed using all correction signals. Driver RMS errors were approximately 0.20 m with a mean close to zero. Although the correction signals were very good, agricultural tasks requiring accuracy greater than 0.20 m cannot be performed with the assisted guidance system.

- The RMS error of the main base station (RTK GPS) signals was approximately five times less than the RMS errors in the RASANT, OmniSTAR VBS and GPS correction via Internet.

- This study has developed a recommendation for the GPS correction signal to be used based upon the agricultural operation to be performed.

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References

Abidine, A.Z., Heidman, B.C., Upadhyaya, S.K., & Hills, D.J. (2004). Autoguidance system operated at high speed causes almost no tomato damage. California Agriculture, 58(1), 44-47.

Arslan, S., & Colvin, T. S. (2002). An evaluation of the response of yield monitors and combines to varying yields. Precision Agriculture, 3, 107-122.

Bauer, W.D., & Schefcik, M. (1994). Using differential GPS to improve crop yields. GPS World, 5 (2), 38-41.

Basso, B., Sarori, L., & Bertocco, M. (2007). Manual de Agricultura de Precisión "Conceptos teóricos y aplicaciones prácticas" (Precision Agriculture Manual "Theoretical concepts and applications"). Ed. Eumedia. ISBN: 978-84-930738-7-9 Madrid, Spain.

Blackmore, S., & Moore, M. (1999). Remedial correction of yield map data. Precision Agriculture, 1, 53-66.

Chamen, W.C.T., Watts, C.W., Leede, P.R., & Longstaff, D.J. (1992). Assessment of a wide span vehicle (gantry), and soil and crop responses to its use in a zero traffic regime. Soil and Tillage Research, 24, 359-380.

Chamen, W.C.T., Dowler, D., Leede, P.R., & Longstaff, D.J. (1994). Design, operation and performance of a gantry system: experience in arable cropping. Journal of Agricultural Engineering Research, 59, 45-60.

Ehsani, M. R., Sullivan, M., Walker, J.T., & Zimmerman, T.L. (2002). A method of evaluating different guidance systems. Paper No. 021155. ASABE, St. Joseph, MI 49085, USA

El-Rabbany, A. (2006). Introduction to GPS: the Global Positioning System. 2nd ed. Boston, MA, USA: Artech House.

González-Matesanz, F. J., Weber, G., Celada, J., Dalda, A., & Quiros, R. (2004). El proyecto EUREF-IP. Resultados con GPRS (EUREF-IP project. Results with GPRS). 4ª Asamblea Hispano-Portuguesa de Geodesia y Geofísica. (ed.) National Institute of Meteorology Madrid, Spain.

Griepentrog H.W., Blackmore, B.S., & Vougioukas, S. (2006). Positioning and Navigation. In: CIGR Handbook of Agricultural Engineering. Volume VI-Information Technology, (pp. 195-204) Chap. 4.2, (ed. Munack, A.). ASABE, St. Joseph, MI 49085, USA

Han, S., Zhang, Q., Noh, H., & Shin, B. (2004). A dynamic performance evaluation method for DGPS receivers under linear parallel-tracking applications. Transactions of the ASABE, 47(1), 321-329.

Heraud, J.A., & Lange, A.F. (2009). Agricultural automatic vehicle guidance from horses to GPS: How we got here, and where we are going. ASABE Distinguished Lecture Series No. 33. ASABE, St. Joseph, MI 49085, USA

Karimi, D., Mann, D. D., & Ehsani, M.R. (2006). A new methodology for evaluating guidance systems for agricultural vehicles. Paper No. 06-148. Winnipeg, MB, Canada: CSBE.

Keicher, R., & Seufert, H. (2000). Automatic guidance for agricultural vehicles in Europe. Computers and Electronics in Agriculture, 25, 169-194.

Larsen, W.E., Nielsen, G.A., & Tyler, D.A. (1994). Precision navigation with GPS. Computers and Electronics in Agriculture, 11, 85-95.

Lechner, W., & Baumann, S. (2000). Global Navigation Satellite Systems. Computers and Electronics in Agriculture, 25, 67-85.

Pérez, M., Agüera, J., Gil, J., & Blanco, G. (2004). Evaluation and incorporation of a lightbar guidance system with different correction differentials. Book of Abstracts.ISBN 90-76019-258. AgEng 2004, Leuven. pp. 916-917

Petersen, C. (1991). Precision GPS navigation for improving agricultural productivity. GPS World, 2 (1), 38-44.

SAS Institute Inc. (2008). SAS/STAT® 9.2 User's Guide. SAS Institute, Inc., Cary, NC, USA.

Sun, H., Slaughter, D.C., Pérez-Ruiz, M., Gliever, C., Upadhyaya, S.K., & Smith, R. (2010).

RTK GPS mapping of transplanted row crops. Computers and Electronics in Agriculture, 71, 32-37.

Talaya, J., Mesa, J., Segarra,J., & Colomina, I. (1997). El Sistema DGPS RASANT en Cataluña (RASANT DGPS system in Catalonia). III Geomatic week in Barcelona. (ed.) Generalitat de Catalunya, Institut Cartografic de Catalunya, Barcelona, Spain.

Taylor, R. K., & Schrock, M. D. (2003). Dynamic Testing of GPS Receivers. Paper No. 03-1013. ASABE, St. Joseph, MI 49085, USA

Trimble Navigation Limited. (2007). Form 10-k annual report, Sunnyvale, California, USA.

Van der Schans, D., Bleeker, P., Molendijk, L., Plentinger, M., Van der Weide, R., Lotz, B., Bauermeister, R., Total, R., & Baumann, D.T. (2006). Practical Weed Control in Arable Farming and Outdoor Vegetable Cultivation without Chemicals. PPO Publication 532 (77 pp), Applied Plant Research, Wageningen University, Lelystad, The Netherlands.

Weber, G., & González-Matesanz, J. (2003). EUREF-IP for Wireless GNSS/DGNSS. Example Implementation in Madrid, EUREF 2003 Symposium of the IAG Subcommission for Europe (EUREF).Vol. 13. (ed.) EUREF. Brussels, Belgium.

Wilson, J.N. (2000). Guidance of agricultural vehicles - a historical perspective. Computer and Electronics in Agriculture, 25, 3-9.

Tables

Table 3.1. Test Block (5 days)

		5 Day test pattern performed twice				
		Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
Time	**Time Slot**	**Correction Signal**	**Correction Signal**	**Correction Signal**	**Correction Signal**	**Correction Signal**
9:00	1	OmniSTAR VBS	RASANT	DBS	EGNOS	EUREF-IP
10:00		EGNOS	EUREF-IP	OmniSTAR VBS	RASANT	DBS
11:00	2	OmniSTAR VBS	RASANT	DBS	EGNOS	EUREF-IP
12:00		EGNOS	EUREF-IP	OmniSTAR VBS	RASANT	DBS
13:00	3	OmniSTAR VBS	RASANT	DBS	EGNOS	EUREF-IP
15:00		EGNOS	EUREF-IP	OmniSTAR VBS	RASANT	DBS
16:00	4	OmniSTAR VBS	RASANT	DBS	EGNOS	EUREF-IP
17:00		EGNOS	EUREF-IP	OmniSTAR VBS	RASANT	DBS
18:00	5	OmniSTAR VBS	RASANT	DBS	EGNOS	EUREF-IP
19:00		EGNOS	EUREF-IP	OmniSTAR VBS	RASANT	DBS

Table 3.2. Average of GPS receiver error for each GPS correction signal

GPS Correction Signals	Data	Mean (m)	Std. Dev. (m)	RMS (m)
Dedicated Base Station	35667	0.03	0.12	0.12
OmniSTAR	36262	-0.46	0.21	0.50
EUREF-IP	35887	-0.22	0.59	0.63
RASANT	37520	0.46	0.45	0.65
EGNOS	33001	-0.40	1.96	2.00

Table 3.3. Average of driver error for each GPS correction signal

GPS Correction Signals	Data	Mean (m)	Std. Dev. (m)	RMS (m)
Dedicated Base Station	35667	-0.01	0.17	0.17
OmniSTAR	36262	0.00	0.25	0.25
EUREF-IP	35887	0.01	0.20	0.20
RASANT	37520	-0.02	0.21	0.21

Table 3.4. GPS average displacement (m) in each time slot

Slots	Data	Dedicated Base Station	EUREF-IP	OmniSTAR	RASANT
FH1	35944	0.13	0.46	0.34	0.52
FH2	37101	0.17	0.72	0.51	0.54
FH3	35686	0.11	0.57	0.67	0.70
FH4	35185	0.10	0.44	0.44	0.94
FH5	34421	0.10	0.88	0.52	0.39

Color Scale RMS (m)	0.00 - 0.25	0.25 – 0.50	0.50 – 0.75	0.75 – 1.00

Figures

Figure 3.1. Situation of receivers, antennas and radio-modems on the tractor cab

Figure 3.2. Schematic of the test platforms to get signal correction

Figure 3.3. Definitions of the measurement errors

(eTOTAL)= total error

(eH)= driver error

(eGPS)= GPS receiver error on each utilized correction signal

P252= co-ordinates of the receiver AgGPS 252

P132= co-ordinates of the receiver AgGPS 132

P´132= translating P132 according to vector d.

d= vector joining the centers of the antennas.

α = angle between y-axis of the vehicle and straight line AB.

Figure 3.4. Cross-track error (PQ) of an observed point P from the AB straight line

Figure 3.5. Cumulative frequency distribution of average GPS receiver error for all the GPS correction signals

Figure 3.6. Cumulative frequency distribution of average driver error for all the GPS correction signals

Figure 3. 7. Average of the positioning accuracy of GPS correction signal from all the time slots.

III. Publications: Chapter 4

Field sprayer for inter- and intra-row weed control: performance and labour savings

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Abstract

Studies of new tools and methods for weed control have been motivated by increased consumer demand for organic produce, consumer and regulatory demands for a reduction in environmentally harmful herbicide use, and the decreased availability of farm workers willing to perform manual tasks, such as hand weeding. This study describes the performance of a new sprayer system for commercial production that integrates two herbicide applications in a single pass, selective herbicide (SH) application in narrow bands over the crop row, and a non-selective herbicide (NSH) application between crop rows. A real-time kinematic (RTK) global positioning system (GPS) was used for auto-guidance in seeding and spraying operations. Conventional broadcast SHs and experimental herbicides were applied at a constant nominal speed of 5.5 km h-1 for comparison. Trials in commercial sugar beet fields demonstrated the following: (i) average hand-weeding time can be reduced by 53% (ii) the new sprayer system reduced SH use by 76%, and (iii) sugar beet density did not change significantly during treatment. These results demonstrate the feasibility of using the new RTK GPS-controller sprayer system for differential and efficient herbicide application in inter- and intra-row zones in row crop production.

Keywords: hooded sprayer; precision farming; herbicide application; site-specific management.

3.4.1. Introduction

Competition from weeds in row crops can cause significant losses in crop yields and impair crop quality, resulting in unnecessary economic loss for the farmer. For example, sugar beet (*Beta vulgaris* L.) yield may be reduced by as much as 95% due to shading and competition for light from weeds (Scott & Wilcockson, 1976), and tomato (*Solanum lycopersicum* L.) yield losses resulting from weed interference can reach 88% (Miyama, 1999). Carrot (*Daucus carota* L.) and lettuce (*Latcuca sativa* L.) yield reductions have been as high as 50% and 54%, respectively (Morales-Payan *et al*., 1996; William & Warren, 1975).

Overall, the selection of a weed control method is influenced by the type and condition of the crop, the type and size of the weeds, the equipment available, and the time of treatment (Bainer *et al*., 1963). However, herbicides applied by field sprayers have been used most frequently because of their ability to control a broad spectrum of weed species, their proven efficacy, and their low cost compared to manual labour, such as hand hoeing. Where weeds have evolved resistance or are naturally tolerant to herbicide, a moderate amount of hand hoeing is required to remove intra-row weeds after chemical application. The current objective of precise herbicide application is to make operating input more efficient by minimizing overlap and skip incidents and eliminating application on non-crop areas. As this objective is achieved, fewer herbicides can be used compared to conventional application, resulting in lower cost and risk for the environment (Schroers *et al*., 2010).

The sugar beet (*Beta vulgaris* L.) complex is of particular interest, as it can be found in both crop and weedy forms in western Mediterranean regions (Desplanque *et al*., 1999). The weed beet problem has been a major concern since the 1970s in Europe (Viard *et al*., 2002), as weed beets cannot be chemically weeded and compete vigorously with the crop. Hand hoeing is the primarily control method available. However, hand hoeing is also most expensive method, as it requires intensive labour, it is time consuming, and its speed and accuracy are restricted by the skills and experience of the crew.

Inter-row cultivators have been commonly used in row crops, such as sugar beets and vegetables, for many decades. In many instances, the success of these implements depends on dry weather conditions and workable soil (Rueda-Ayala *et al*., 2010). In-row weeds are more difficult to eliminate than between-row weeds due to their proximity to the crop or seed line. Standard mechanical cultivation methods generally eliminate weeds between the rows; they do not remove weeds between the crop plants within the rows. However, the research community has been working to develop different commercial machines for intra-row weeding with different costs and field capacities, including i) mechanical intra-weed control based on the real-time kinematic (RTK) global positioning system (GPS) weed knife (at 1.6 km h^{-1}) (Perez-Ruiz *et al*., 2012), ii) intelligent systems using digital cameras to view crops and a spinning disc to remove weeds (guide price $17,000/row and speed limited to 3 km h^{-1}) (Dedousis *et al*., 2007). In some cases, thermal methods, such as flame weeding and soil steaming, can be less costly than hand weeding, but there is a high machine cost ($4,700/row and €27,023 ha^{-1} yr^{-1}, respectively) (Ascard, 1998; Vidotto *et al*., 2011). Ascard (2011) suggests that constraints due to cost, low capacity, low selectivity, and time to perform all of the necessary adjustments have prevented most of these recently developed weed control systems from being widely used in practice.

During the early growth stages, when competition for nutrients, water, and radiation is critical (Slaughter *et al*., 2008), sugar beets require either continued hand labour for weed removal (Tillett *et al*., 2008), banded application of selective herbicides (SHs) on the crop row followed by between row cultivation (Kaya & Buzluk, 2006), or broadcast herbicide application. This last scenario is currently the primary method used for sugar beet cultivation in Spain.

There are three areas within crop rows that can be clearly identified for weeding: between rows, between crop plants within the row, and close to but 3-4 cm below the plant (Griepentrog *et al*., 2003). Hand hoeing can be eliminated with mechanical weeding in the area between crop rows, but intra-row weeds remain problematic (Melander, 1997; Tillett *et al*., 2002).

Typical inter-row cultivators used in sugar beet production in Spain are composed of a parallelogram, which holds a number of rigid or vibrating shanks mounted on sweeps and distributed along the toolbar. Unless an implement positioning control system is used, these cultivators generally cannot work close to the crop plant due to the danger of root pruning. Manual steering, using a second human operator, has been a common guidance method to control the toolbar to increase cultivation accuracy and reduce crop damage. A second operator is often employed to control the toolbar laterally, making adjustments by hand based on the operator's vision. However, three issues remain problematic: increased operation costs, difficulties in recruiting trained workers, and low efficiencies associated with human error, particularly when operating with poor visibility (*e.g.*, at night or in dusty conditions). Hydraulically guided systems based on computer vision and GPS technology, which aim to reduce human error caused by the tractor driver, have been introduced (Melander *et al*., 2005; Griepentrog *et al*., 2007).

A major disadvantage of using the cultivator for weed control is that it causes soil disturbance and stimulates new weed seeds to germinate. In this context, a new method of post-emergence control of in-row weeds was recently successful in a field-tested for both corn and soybeans (Forcella, 2012). This method involves the use of air-propelled abrasive grit. The grit (*i.e.*, "green grits") abrades small weed seedlings within the crop row and leaves the crop plants essentially unscathed.

Typical RTK-GPS technology has a row positioning accuracy of ±2.5 cm, which is comparable to that of machine vision guidance systems, but it manages to accomplish this accuracy without visual guidance landmarks in the field (Leer & Lowenberg-DeBoer, 2004). Visual targets may not always be possible, such as when the crop has not emerged or too small. A high level of geoposition accuracy in row crops can enhance the precision of chemical placement in narrow bands or cultivation close to the plant line (Abidine *et al*., 2004). However, one disadvantage of the RTK-GPS solution is the requirement that a base station be located within 10 km at all times. GPS service providers and government institutions are working to mitigate this issue by developing a network of base stations that can provide access to RTK correction signals over a wider geographic region via cellular or radio modems (Leandro *et al*., 2011). In the future, these networks will provide coverage to all farmers with RTK-GPS receivers, eliminating the need for multiple base stations on each farm.

Under Mediterranean climate conditions, mild winters allow the sugar beet to be sown in autumn and harvested in summer. A longer growing season contributes to higher yields in relation to the spring-sown sugar beet. However, season-long weed control is too expensive because it may require the application of a pre-emergence herbicide at planting, up to three post-emergence herbicides depending on the region and year, and one or several mechanical cultivations coupled with hand hoeing. The Research Association for the Improvement of Sugar Beet Crop of Spain (AIMCRA) has conducted economic studies of labour management and has reported values of 20% and 23% of production costs due to weed control in irrigated and rain-fed sugar beet production, respectively (Bermejo *et al*., 2008). AIMCRA is concerned with crop conditions, production costs, and crop profitability due to the impending reduction of financial support by the European Union. Accordingly, it has launched a program to improve sugar beet crop competitiveness, which could provide substantial savings in agro-chemicals with associated environmental and economic advantages for more sustainable sugar beet production systems.

Seeking to increase sugar beet competitiveness in weed control operations, AIMCRA and the University of Seville have collaborated in the development and evaluation of the performance of a RTK-GPS-guided tractor and an implement suitable for commercial production that integrates two herbicide applications in a single pass. These applications use a SH in narrow bands over the crop row and a non-selective herbicide (NSH) between crop rows. The specific objectives of this paper were as follows: (i) to develop and assess a field sprayer that combines the under-hood application of NSHs between rows and the application of SHs within crop rows; (ii) to demonstrate that a significant reduction in the current reliance on hand labour in conventional production systems can be achieved by using such combined herbicide applications.

3.4.2. Material and methods

Equipment design and fabrication

A field prototype sprayer for inter- and intra-row herbicide application was designed and built for precise weed control operation in sugar beet fields. This equipment enables a one-pass SH treatment over the seed line (band width 14 cm) and NSH treatment between crop rows (band width 36 cm). Two 100-L herbicide tanks were mounted on the implement's main frame, with one tank for each type of herbicide. At the bottom of each tank, a 12 V electric pump (model 5800, Develan Pumps, Inc. Minneapolis, MN, USA) was installed to create flow. Each tank also included an agitation system to keep the chemical mixed, a pressure regulator valve to control flow rate, a pressure gauge with the appropriate scale, and miscellaneous components, such as fittings and strainers. For the inter-row weed control application, seven hood units protected adjacent row crop foliage from NSH. NSH was then applied to six rows. The five center metal spray-hood units had a fixed spray width of 36 cm and a height of 32 cm. The two end spray-hood units had the same height but with spray widths of 26 cm. All hoods were designed to travel 1.5 cm below the soil surface and were controlled by a set of mechanical guide wheels attached to the main frame.

Fig. 4.1. presents the sprayer in three possible configurations: conventional broadcast SH application (Fig. 4.1a), a narrow band NSH intra-row application (Fig. 4.1b), and NSH inter-row and SH intra-row application (Fig. 4.1c). The configurations in Figs. 1a and 1c were employed for this study. In the broadcast application, the supply tank one fed the spray boom while six ISO110025 standard (ALBUZ, Evreux Cedex, France) flat-fan nozzles were positioned at a height of 50 cm above the crop (height adjustment) and separated by 50 cm with a spray angle of 110°. This scheme is the conventional practice of local sugar beet producers. In the experimental application, the angle of the spray pattern and the mounting height of the nozzle were critical to controlling band width. For this study, the optimal nozzle height, located at the center of the hoods, was 21 cm for a spray angle of 80° and a band width of 36 cm. Seven even ISO standard flat-fan nozzles were used to apply the inter-row NSH to provide a uniform distribution of the spray throughout the fan pattern. The six even flat-fan nozzles (angle of 80º) over the crop rows were regulated to a height of 9 cm to achieve a band width of 14 cm. There are certain disadvantages of using NSHs; for instance, they are less effective on some weeds, and thus, there is a lack of soil residual activity due to their application. However, if the farmer's most problematic weeds are not among the most resistant species, then NSHs could be adequate for the weed control issues between the sugar beet crop rows.

An initial test of the system was conducted to characterize the lateral implement movement with a forward speed of 5.5 km h^{-1}. The anti-drift hood units create a small furrow to demarcate the hood patch as it passes across the field. A hand ruler was used to characterize the lateral implement movement by measuring the ground distances between this furrow and the crop rows; a similar procedure was described and used by Griepentrog *et al*. (2006).

Global positioning system (GPS)

Precision guidance was required in this system to ensure reliable centering of the intra-row SH application about the crop stem. RTK provides the highest degree of accuracy (2 cm) for global navigation satellite system (GNSS) applications. An RTK system requires two receivers, a radio link, and an embedded navigation controller that integrates rover sensors and GPS data to compute the final position of the rover receiver (Misra & Enge, 2006). In this study, an RTK-GPS automatic guidance system (AgGPS Autopilot, Trimble Navigation Ltd., Sunnyvale, CA, USA) was used to pilot the tractor (model TS90, New Holland with category 2, three-point hitch) for all seeding operations and field trials. The GPS system included: (i) a rover RTK-GPS receiver (Trimble EZ Guide 500) with the GPS antenna mounted on top of the tractor's cabin (~3 m above the soil surface); (ii) a user interface capable of displaying cross-track error information and receiving user input, such as the desired pass spacing and the location of the first guidance line; (iii) path-planning algorithms capable of calculating cross track error relative to the desired guidance path; (iv) vehicle steering actuators; (v) manual override sensors; (vi) steering angle sensors; (vii) controller calculating steering correction algorithms; and (viii) terrain compensation sensing (*i.e.*, pitch, roll and yaw).

The system utilized an RTK-GPS correction signal from a local (~1 km from the test site) GPS base station (Trimble Model 4700) to obtain RTK fixed quality accuracy. An 8 µs clock reference pulse per second (PPS) signal was produced by the autopilot receiver to synchronize the geoposition data with external events. The autopilot receiver was set to output the "NMEA-0183 GPGGA" string containing the geographic coordinates (Latitude and Longitude) every second via an RS-232 serial connection.

The AB line used for seeding was stored internally in the tractor navigation system for future use during the weed control trials. Near the location of this study, RTK-GPS quality guidance systems are increasingly being used by commercial farming operations for automatic guidance of tractors and other types of field equipment despite the significant financial investment required.

Field experiments

Field tests were conducted during the 2011/2012 sugar beet season in southern Spain within the Seville region (36.99760754ºN, 6.03544936ºW). A total of approximately 14 ha were planted with a 12-row pneumatic drill seeder in a commercial sugar beet field. These hectares were divided into three separate sections: A (4 ha), B (6 ha), and C (4 ha). The local farmer allowed our study team to use a 1-ha area per section for our field tests. A weed control treatment was selected for each 1-ha area. The tractor used for the seeding operation was guided by an automatic steering system with cm-level precision to ensure straight seed lines and generate an AB line for use during the trials. The field trials were carried out at a constant nominal speed of 5.5 km h^{-1}. The nominal forward travel speed was controlled by the auto-guidance tractor.

A completely randomized design used 10 zones for field test "A" (30/11/11) to determine the time per square meter required for a skilled worker to hand weed. Two weed control systems, hand hoeing and herbicide application with the experimental setup, had five experimental units for each treatment. The objective of this test was to compare the cost of weed control in sugar beet fields using hand-weeding versus the hooded sprayer for intra-row SH and inter-row NSH applications. Herbicide application was performed at a rate of 225 L ha^{-1}, a pressure of 4×10^5 Pa, and a nominal tractor speed of 5.5 km h^{-1}. One post-emergence herbicide application was carried out during this test, and the banded spray over the crop row used six nozzles located 5 cm from the top of the crop. The nozzles were separated by 50 cm with a spray angle of 110°. The wetted surface using SH (Phenmedipham 9.1% + Desmedipham 7.1% + Ethofumesate11.2%) was 84 cm (six rows with a 14 cm band per row). The wetted surface width with the banded application between crop rows using NSH (glufosinate-ammonium) was 232 cm (five middle hooded spray units of 35 cm each, two end spray units of 52 cm each). In both treatments, a follow-up hand weeding operation was conducted by a volunteer worker to remove the remaining weeds in the central 14 cm band along the row centerline and the 36 cm band between rows. For this test, initial weed density, the worker's hand weeding rate, and sugar beet plant counts along the row were recorded. In this field, 90% of the weeds were wild beet (*Beta vulgaris* ssp. *maritime*, a perennial species form the Mediterranean and European Atlantic coasts), which meant that SH would not kill the weeds. The only options for post-emergence control were our prototype hooded sprayer for inter-row NSH application and hand hoeing. Sugar beet growers typically use hand hoeing, as it is currently the only viable option.

One pre-emergence (16/11/11) and one post-emergence (27/12/11) herbicide application were carried out in field test "B" to include the complete sugar beet spraying cycle in this atypical, weed-scarce year. This test was performed with a completely randomized, unbalanced design factor (weed control) and three types of treatment: (i) conventional or broadcast application (CA); (ii) experimental sprayer application (EA), in which the pre- and post-emergence treatments were applied on the crop line, leaving the remaining plot untreated, whereas a post-emergence treatment involves treating the entire surface with the experimental herbicide application; and (iii) control, without any herbicide application. Conventional broadcast herbicide applications were conducted on six experimental plots, applied uniformly on the ground (pre-emergence) or over the crop canopy (post-emergence). The experimental applications, as described earlier, were also conducted on six experimental plots. Eighteen untreated control plots of 18 m^2 each remained between the experimental plots. Each experimental plot was comprised of 2 m of crop line, which is equivalent to 1 m^2. Weeds and crop plants were then counted and recorded to compare the weed control system efficacy and crop plant phytotoxicity (dependent variables).

Field test C was performed with the experimental sprayer over 12 zones with 1 m^2 on January 24, 2012. Six zones were randomly selected to obtain a weed count, and six were selected to determine crop plant density. Three observations were made on each plot before treatment on July 2, 2012. This test was aimed at validating the proper functioning of the newly designed sprayer.

Data analysis

Field test A used the non-parametric Wilcoxon-Mann-Whitney test to compare the independent samples (one-sided). The relationship between the weed count and hand-weeding time was calculated using least-trimmed-squares regression (Rousseeuw, 1984). Robust elliptic plot (Relplot) was used to detect and study outliers (Goldberg & Iglewicz, 1992).

In field test B, univariate analysis of variance (ANOVA) was used to establish the effects of the weed treatment factor on the dependent variable (sugar beet density). This factor had three levels: conventional application, experimental application, and control. Normality was tested using the Shapiro-Wilk test, and the homogeneity of variance was tested using the Levene test. The absence of data normality motivated the use of a robust model for this condition. Therefore, the null hypothesis was used to compare the equality of 0.2-trimmed means.

In addition, a comparison of weed density (weeds m^{-2}) was performed to determine the effectiveness of CA and EA treatments; weeds were counted 10 days after the applications. The analysis was performed using a robust Wilcoxon-Mann-Whitney test (Mee, 1990), and the null hypothesis was tested at p=0.5.

Finally, regarding field test C, the comparison before and after performing a treatment using the experimental application setup in terms of the number of beet plants per unit area, as well as weed density (weed m^{-2}), was performed using the percentile bootstrap confidence interval method, with 2,000 simulated replicates to determine the difference between medians on paired data (α=0.05).

Analyses were performed using R software (R Development Core Team, 2011).

3.4.3. Results and discussion

In this study, an experimental implement that combines two herbicide applications in a single pass, allows for SH application in narrow bands over the crop row, and allows for NSH application between crop rows was successfully developed and operated for sugar beet crops (Figure 4.2).

All measurements of lateral hood movements, *i.e.*, the ground distances between the mark left by an anti-drift hood and the crop rows, were located within the intra-row bandwidth, which for this study was defined as ±70 mm from the row center line. This result is in agreement with the findings reported by Abidine *et al*. (2002), in which an implement operating 50-75 mm from the crop center line produced no crop damage, confirming that the RTK-GPS-based autoguidance system did not cause transverse damage interaction between anti-drift hood units and sugar beet plants. Applying this technology can eliminate the need for a second human operator that is employed in some implements to control the toolbar by laterally making adjustments by hand based on the operator's vision. In addition, during the trials, although a thorough evaluation was not performed, it appeared that the aim of the electronic guidance system was to reduce the concentration needed from the tractor driver, a result that was also observed by Melander *et al*. (2005).

Labour savings in follow-up hand weeding was documented by measuring the time required for experienced laborers to hoe the remaining weeds after the experimental application and compared with the time required to hand hoe the control rows. In field test A, the median hand-weeding times in the zone with post-emergence experimental herbicide application (45±6.3 s $plot^{-1}$) and the zone without post-emergence experimental herbicide application (96±2.9 s $plot^{-1}$) were significantly different (p=0.004) (Table 1). Each experimental plot was 0.5×10 m (5 m^2). The new experimental spraying system reduced hand-weeding times by 53%. Moreover, the variability in the number of weeds was much higher in the control zone (SD=25.9 weed m^{-2}) than that in the zone for which the experimental unit had been used (SD=12.8 weed m^{-2}).

Slaughter *et al*. (2012) also achieved a 52% reduction in man hours per hectare required by using a GPS-based intra-row weeding machine for a similar weed load. Assuming a hand-weeding labour cost of €7.70 h^{-1} in the study area, this level of labour reduction represents a potentially significant savings in the cost of manual labour for hand hoeing.

Figure 4.3 shows a linear relationship between hand-weeding time and weed density (R^2=0.92, p<10^{-4}). The straight-line least-trimmed squares exhibited the following relationship:

$$t = 28 + 0.27wd \qquad \text{[Eq. 1]}$$

where t is the hand weeding time (s) and wd is the weed density (weed m^{-2}).

There are few studies on the relationship between hand-weeding time and weed density because most studies focus on comparisons between weed management techniques (Gopinath *et al*., 2009) and their economic results (Harunur *et al*., 2012). However, the data from Shrestha *et al*. (2008), who compare hand-weeding times for woody crops, can be estimated similar to our study. A linear relationship was observed between the total hand-weeding time per hectare and the total number of weeds throughout the test period. The weed density was between 4 and 365 plants m^{-2}. This is a range similar to that of this study (43 and 423 plants m^{-2}). Most of the weeds were wild beet (*Beta vulgaris* ssp. *maritima*) and *Chenopodium album.* The former were in the four-leaf stage (BBCH 14), a cotyledon stage, and the latter were in a cotyledon stage of development. According to Wellmann (1999), the critical period of sugar beet competition is never before the four-leaf stage.

Field test B examined sugar beet densities as influenced by the control, EA, and CA treatments. Mean (± SE) sugar beet densities in these treatments were 12.7±0.21 (control), 12.4±0.32 (EA), and 12.1±0.34 (CA), respectively, and were not significantly different from one another (ANOVA, p=0.28). The equality of these means across treatments indicated that the new spraying system did not affect sugar beet populations adversely and that the new system could likely be used at the field level, even at times when the sugar beet is highly sensitive to broad-spectrum herbicides that could be useful when broadcasted.

Bermejo *et al*. (2008) conducted an economic study on labour management in this region and reported that an average of 21.5% of production costs were due to weed control practices. The use of this new implement reduces the equipment cost penalty for weed control operations, which could make it economically viable for conventional production systems, even with the reduction of financial support by the European Union.

In relation to the weed population, the count performed on January 17, 2012 indicated that there were no differences between CA and EA after December 27, 2011, with a confidence level of 95% with p=0.19-0.57, thus including the value p=0.5. This result is very important because: (i) this stage is the time when weeds can achieve development that significantly reduces sugar beet production and (ii) the new implement reduced the use of SH, which is considerably more expensive than NSHs containing the active ingredient glyphosate by 76%. This reduction saves approximately €54 ha^{-1} in treatment costs for crop producers (AIMCRA published the 2012 prices of SHs in the sugar beet sector in Spain, and these were used to determine operation costs and savings (Morillo-Velarde, 2012).

Finally, in field test C, an experimental application with the new implement was conducted to assess its proper operation and the crop and weed densities were checked before and after herbicide application. The median density of the sugar beets in the experimental plots was 7 plants m^{-2} (before application) and 6 plants m^{-2} (after application) (Table 2). The 95% confidence interval of the difference before and after treatment for beet density was [0, 1]. Given this interval, there was no significant difference between the data obtained on the earlier and later dates. The median density of weeds in the experimental plots decreased from 43.5 weeds m^{-2} (before application) to 12 weeds m^{-2} (after application). The 95% confidence interval was [17.5, 80]. This interval does not contain zero, indicating that there are significant differences in the weed density due to the effectiveness of the treatment. The combined treatment of SHs and NSHs reduced the median weed population by 73%.

3.4.4. Conclusions

In this study, an experimental sprayer combining SH and NSH applications was developed for weed control over six rows. Seven sprayer hoods protected the crops from the NSH, and six narrow band sprayers applied SHs within 7 cm of the seed line using

RTK-GPS technology. Field tests demonstrated that the machine adapted to working conditions required for this technique. The potential integration of NSH and SH applications in a new sprayer implement was demonstrated for agronomic management in accordance with the treatment sequence. The beet population was not adversely affected compared to conventional broadcast SH application. There were no significant differences in weed densities between the CA and EA with the new sprayer. Using both the NSH application for inter-row weeding and the SH application for intra-row weeding with band spraying along the crop row reduced the amount of SH by replacing it with NSH. In this study, the method reduced the SH treatment area, and thus the SH input, by more than 76%. The treatment area reduction accorded local producers a savings of €54ha^{-1} for herbicide application because SH was more expensive than NSH and the labor cost for hand hoeing was reduced. This method may be valuable when a farmer needs to use several applications of an expensive herbicide or when the field is infested with wild beets (*Beta vulgaris ssp. maritima*). The adoption of new technologies that optimize farm operations will assist the Spanish sugar beet industry to remain competitive in the global economy.

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References

Abidine AZ, Heidman BC, Upadhyaya SK, Hills D J, 2002. Application of RTK GPS based auto-guidance system in agricultural production. ASAE Paper No. O21152. ASAE, St. Joseph, MI, USA.

Abidine AZ, Heidman BC, Upadhyaya SK, Hills DJ, 2004. Autoguidance system operated at high speed causes almost no tomato damage. Calif Agric 58(1): 44-47.

Ascard J, 1998. Comparison of flaming and infrared radiation techniques for thermal weed control. Weed Res 38: 69-76.

Ascard J, Fogelberg F, Hansson D, Svensson SE, 2011. Weed control in vegetable-Report from a round table discussion. 9th EWRS Workshop on Physical and Cultural Weed Control. Samsun, Turkey, 28-30 March 2011.

Bainer R, Kepner RA, Barger EL, 1963. Principles of farm machinery. Wiley, NY.

Bermejo JL, Martínez JJ, Morillo-Velarde R, 2008. Memoria técnica. Plan de competitividad 2008 (Technical Report-Competitiveness Plan 2008). Research Association for the Improvement of Sugar Beet Crop of Spain (AIMCRA). Valladolid, Spain.

Dedousis AP, Godwin R J, O'Dogherty M J, Tillett ND, Grundy AC, 2007. Inter and intra-row mechanical weed control with rotating discs. Proc. 6th Eur Conf in Precision Agriculture, Skiathos, Greece. pp: 493-498.

Desplanque B, Boudry P, Broomberg K, Saumitou-Laprade P, Guguen J, Van Dijk H, 1999. Genetic diversity and gene flow between wild, cultivated and weedy forms of Beta vulgaris L. (Chenopodiaceae), assessed by RFLP and microsatellite markers. Theor Appl Genet 98: 1194-1201.

Forcella F, 2012. Air-propelled abrasive grit for postemergence in-row weed control in field corn. Weed Technol 26: 161-164.

Goldberg KM, Iglewicz B, 1992. Bivariate extensions of the boxplot. Technometrics 34: 307-320.

Gopinath KA, Kumar N, Mina BL, Srivastva AK, Gupta HS, 2009. Evaluation of mulching, stale seedbed, hand weeding and hoeing for weed control in organic garden pea (Pisum sativum subsp. Hortens L.). Arch Agron Soil Sci 55(1): 115-123.

Griepentrog H W, Nørremark M, Nielsen H, Blackmore BS, 2003. Individual plant care in cropping systems. Proc 4th Eur Conf on Precision Agriculture ECPA. Berlin, Wageningen Acad. Press, Wageningen, NL, pp: 247-251.

Griepentrog HW, Norremark M, Nielsen J, Soriano-Ibarra J, 2006. Autonomous inter-row hoeing using GPS based side-shift control. Proc. Automation Technology for Off-Road, Bonn, Germany, 1–2 September; pp. 117–124.

Griepentrog HW, Norremark M, Nielsen J, Soriano Ibarra J, 2007. Autonomous inter-row hoeing using GPS based side-shift control. Proc. Automation Technology for Off-Road Equipment (ATOE). Bonn, Germany. September 1-2, pp: 117-124.

Harunur M, Murshedul M, Rao AN, Ladha JK, 2012. Comparative efficacy of pretilachlor and hand weeding in managing weeds and improving the productivity and net income of wet-seeded rice in Bangladesh. Field Crop Res 128: 17-26.

Kaya R, Buzluk S, 2006. Integrated weed control in sugar beet through combinations of tractor hoeing and reduced dosages of a herbicide mixture. Turkish J Agric Forest 30: 137-144.

Leandro RF, Santos MC, Langley RB, 2011. Analyzing GNSS data in precise point positioning software. GPS Solutions 30(1): 1-13.

Leer S, Lowenberg-DeBoer J, 2004. Purdue study drives home benefits of GPS auto guidance. Available in http://news.uns.purdue.edu/UNS/html4ever/2004/040413.Lowenberg.gps.html. [May 16, 2011].

Melander B, 1997. Optimization of the adjustment of a vertical axis rotary brush weeder for intra-row weed control in row crops. J Agric Eng Res 68: 39–50.

Melander B, Rasmussen IA, Barberi P, 2005. Integrating physical and cultural methods of weed control: examples from European research. Weed Sci 53: 369-381.

Mee RW, 1990. Confidence intervals for probabilities and tolerance regions based on a generalization of the Mann-Whitney statistic. J Am Stat Assoc 85: 793-800.

Misra P, Enge P, 2006. Global positioning system: signals, measurements, and performance, 2nd ed. Gamba-Jamuna Press, Lincoln, MA, USA.

Miyama S, 1999. Competition between tomato and barnyardgrass in relation to nitrogen fertilizer source. M.S. Thesis. Vegetable Crops Department. University of California, Davis, CA, USA.

Morales-Payan JP, Santos BM, Bewick TA, 1996. Purple nutsedge (Cyperus rotundus L.) interference on lettuce under different nitrogen levels. Proc South Weed Sci Soc 49: 201.

Morillo-Velarde R, 2012. Recommendations for sugar beet production. Revista de la Asociación de Investigación para la Mejora del Cultivo de la Remolacha Azucarera (AIMCRA) 112: 26-31.

Perez-Ruiz M, Slaughter DC, Gliever CJ, Upadhyaya SK, 2012. Automatic GPS-based intra-row weed knife control system for transplanted row crops. Comput Electron Agr 80: 41-49.

R Development Core Team, 2011. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available in http://www.R-project.org/ [June 10, 2013].

Rousseeuw PJ, 1984. Least median of squares regression. J Am Stat Assoc 79: 871-880.

Rueda-Ayala V, Rasmussen J, Gerhards R, 2010. Mechanical weed control. In: Precision crop protection-the challenge and use of heterogeneity (Oerke EC, Gerhards R, Menz G, & Sikora RA, eds.). Springer, Dordrecht, Netherlands. pp: 279-294.

Schroers JO, Gergards R, Kunisch M, 2010. Economic evaluation of precision crop protection measures. In: Precision crop protection-the challenge and use of heterogeneity (Oerke EC, Gerhards R, Menz G, & Sikora RA, eds.). Springer, Dordrecht, Netherlands. pp: 417-426.

Scott RK, Wilcockson SJ, 1976. Weed biology and the growth of sugar beet. Ann Appl Biol 83(2): 331-335.

Shrestha A, Browne GT, Lampinen BD, Schneider SM, Simon L, Trout TJ, 2008. Perennial crop nurseries treated with methyl bromide and alternative fumigants: effects on weed seed viability, weed densities, and time required for hand weeding. Weed Technol 22: 267–274.

Slaughter DC, Giles DK, Fennimore SA, Smith RF, 2008. Multispectral machine vision identification of lettuce and weed seedlings for automated weed control. Weed Technol 22: 378-384.

Slaughter DC, Perez-Ruiz M, Fathallah F, Upadhayaya S, Gliever CJ, Miller B, 2012. GPS-based intra-row weed control system: performance and labor savings. Proc. Int Conf of Agricultural Engineering CIGR-AgEng 2012. Valencia, Spain. July 8-12.

Tillett ND, Hague T, Miles SJ, 2002. Inter-row vision guidance for mechanical weed control in sugar beet. Comput Electron Agr 33: 163–177.

Tillett ND, Hague T, Grundy AC, Dedousis AP, 2008. Mechanical within-row weed control for transplanted crops using computer vision. Biosyst Eng 99: 171-178.

Viard F, Bernard J, Desplanque B, 2002. Crop-weed interactions in the Beta vulgaris complex at a local scale: allelic diversity and gene flow within sugar beet fields. Theor Appl Genet 104: 688-697.

Vidotto F, Letey M, De Palo F, Mancuso F, 2011. Cost comparison between soil steaming and conventional methods for weed control. 9th EWRS Workshop on Physical and Cultural Weed Control. Samsun, Turkey, 28-30 March 2011, pp:83-84.

Wellmann A, 1999. Konkurrenzbeziehungen und Schadensprognose in Zuckerrüben bei variiertem zeitlichen Auftreten von Chenopodium album L. und Chamomilla recutita (L.) [Competition and yield prediction in sugar beet by occurrence of Chenopodium album L. and Chamomilla recutita (L.)]. PhD Thesis, University Göttingen, Germany.

William RD, Warren GF, 1975. Competition between purple nutsedge and vegetables. Weed Sci 23: 317-323.

III. Publications: Chapter 5

Comparison of Positional Accuracy between RTK and RTX GNSS Based on the Autonomous Agricultural Vehicles under Field Conditions

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Abstract

Currently, many systems (machine vision, high resolution remote sensing, global positioning systems, and odometry techniques) have been integrated into agricultural equipment to increase the efficiency, productivity, and safety of the individual in all field activities. This study focused upon assessing a satellite-based localization solution used in straight path guidance of an autonomous vehicle developed for agricultural applications. The autonomous agricultural vehicle was designed and constructed under RHEA (Robot fleets for highly effective agriculture and forestry management) project and is part of a three-unit fleet of similar vehicles. Static tests showed that 99% of all positions are placed within a circle with a 2.9 cm radius centered at the geo-position using real-time satellite corrections (RTX). Dynamic tests between rows demonstrated a mean (N=610) of the standard deviation for real-time base station corrections (RTK) of 1.43 cm and for real-time satellite corrections (RTX) of 2.55 cm. These results demonstrate that the tractor was able to track each straight line with high degree of accuracy. The integration of a Global Navigation Satellite System (GNSS) with sensors (e.g., inertial sensor, altimeters, odometers, etc.) within the vehicle showed the potential of autonomous tractors for expanding agricultural applications utilizing this technology.

Keywords. Autonomous tractor, GNSS, Precision agriculture, RTK-GPS, Agricultural machinery.

3.5.1. Introduction

Innovative technologies (i.e., GNSS, GIS, machine vision, sensors, agricultural machinery controller, and high resolution remote sensing) are beginning to play a vital role in agroforestry systems, as they aid in compliance with current regulations while improving system cost and efficiency (Fountas et al., 2006; Sørensen and Bochtis, 2010). In recent years, several studies have emerged suggesting that fleet of automated agricultural machinery can increase sustainability and competitiveness in agricultural production (Blackmore et al., 2005; Peleg, 2005; Bakker et al., 2011). There are, however, important challenges that must be overcome in these fleet automated systems. These challenges include lowering the control system cost, increasing production flexibility, and reducing the number of devices aboard each fleet to avoid the failure of one vehicle causing the entire fleet to be out of order. Meanwhile, new systems must also have affordable automation systems and comply with health and safety regulations.

The placement of fleet automated technology in the agroforestry sector may provide a number of benefits, including 1) reducing environmental contamination from excessive agrochemical applications by adopting Global Navigation Satellite System (GNSS) based site-specific application techniques, 2) increasing yields by optimizing site-specific input application levels and 3) decreasing necessity of skilled farm laborers required to perform agricultural tasks.

An autonomous agricultural vehicle requires a combination of several techniques (sensors, machine vision techniques, etc.) including GNSS. For real-time applications that require on-the-go corrections, a differential GNSS technique (DGNSS) is preferred to achieve very high location accuracy. As the resolution at which the geoposition improves, it increases the number of plant-specific management tasks suited for automation. A straightforward method to achieve accurate geopositioning is to use two GNSS receivers (a rover and a base) that track the same satellites. In this case, the position of the base (a stationary unit) can be accurately determined using satellite signals. The location information from the base can be used to correct the location of the rover, and this correction information can be communicated to the field GNSS receiver by a radio link (Heraud and Lange, 2009; Perez-Ruiz and Upadhyaya, 2012). This method allows for minimization of error and higher real-time accuracy (Leica Geosystems AG, 1999).

In today's agricultural processes, RTK-DGNSS (Real Time Kinematic-Differential GNSS) based auto steering provides substantial savings in agro-chemicals and reduced hand-weeding requirements, with the associated environmental and economic advantages (Griepentrog et al., 2004; Blackmore et al., 2005; Fennimore et al., 2010). Although the use of two GNSS receivers requires a significant financial investment, RTK-GNSS systems are becoming increasingly common among commercial farming operations for automatic steering of tractors and other types of field equipment.

One disadvantage of using RTK-GNSS solutions in agriculture is the requirement that a base station be located within 10 km at all times, and this results in high capital cost. Multiple reference station RTK trials have been on-going since the late 1990's (Hu et al., 2003; Ong Kim Sun and Gibbings, 2005). For example, both Leica Geo-systems and Trimble have provided such Network RTK services for the whole Great Britain since early 2006 (Edwards et al., 2010). Likewise, some government institutions are working to mitigating this challenge by developing a network of base stations, which provide access to the RTK correction signal over a wide geographic region via cellular or radio modem (Mesas and Torrecillas, 2007). In the future, this network may provide coverage to all farmers with RTK-GNNS receivers, eliminating the need for multiple base stations on each farm. However, another factor that must be considered, due to the increased use of GNSS base stations, is the lack of knowledge as to how the base station coordinates are influenced by the movement of tectonic plates (Prawirodirdjo and Bock, 2004).

Recently, a real-time positioning products has been released (i.e., RTX), claiming to bridge the gap between real-time RTK-PPP (Real Time Kinematic-Precise Point Positioning) and Network RTK-GNSS. These developments are a combination of real-time data and innovative positioning algorithms to deliver centimeter accuracy around the world and allow satellite correction to be delivered directly to the GNSS rover receiver, with no need for additional equipment such as radios and antennas. Rizos et al. (2012) reported that RTX is capable of providing real-time positioning at 4 cm level horizontally (95%), with initialization times of less than 1 min.

The aim of this study was to determine the GNSS centimeter-level accuracy, through RTK (from base station) and RTX (from satellite) signals, of the straight path provided for an autonomous vehicle developed for agricultural applications.

3.5.2. Material and Methods

Global Navigation Satellite System (GNSS)

Real-Time Differential GNSS Correction

With 2 cm accuracy, RTK systems are the most accurate solution for GNSS (Global Navigation Satellite System) applications. An RTK system requires two receivers, a radio link, and an embedded navigation controller that integrates rover sensors and GNSS data to compute the final position of the rover receiver (Misra and Enge, 2006). In this study, an RTK-GNSS receiver (BX982, Trimble Navigation Ltd., Sunnyvale, Calif.) was used to accurately locate the autonomous tractor for all field trials. The GNSS-based navigation system included:

- a rover RTK-GNSS receiver with two GPS antennas mounted on top of the tractor's cabin 2 m above the soil surface and 1.5 m apart,
- vehicle steering actuators,
- manual override sensors,
- steering angle sensors,

- controller that implement steering correction algorithms, and
- terrain compensation sensing (i.e., pitch, roll, and yaw).

The system utilized an RTK-GNSS correction signal from a local (located ~0.3 km from the test site) GNSS base station (Trimble Model BX982) to obtain RTK Fixed quality accuracy. The rover was set to output the "NMEA-0183 PTNL, AVR" string containing the geographic coordinates (latitude and longitude) and yaw angle in degree and range (m) between primary and secondary antennas at 1 Hz rate via an RS-232 serial connection.

Real-Time Extended GNSS Correction

The real-time extended (RTX) positioning is a new technology that provides users with centimeter-level real-time position accuracy. The correction signal is based on satellite information generated at processing centers and broadcast to users through satellites. Horizontal position error obtained in real-time, via a receiver acquiring the RTX correction data through the satellite link in North America (Ames, Iowa), was RMS 1.4 cm, with a 95% horizontal error of 2.4 cm (Leandro et al., 2011). Using an RTX signal is advantageous because it does not require a local base station for signal correction.

Autonomous Agricultural Tractor

The autonomous agricultural tractor was designed and constructed under a European research project and is part of a three-unit fleet of similar vehicles (RHEA, 2012). The platform of the autonomous vehicle was a conventional 38 kW tractor (New Holland model Boomer T3050, 3-point hitch, Zedelgem, Belgium) that was retrofitted for autonomous agricultural operations. Figure 1 shows the equipment setup used in the field experiments, and figure 2 shows how the GNSS correction signals were captured and transmitted to the receiver through an external port.

Figure 5.1. Autonomous tractor unit configuration.

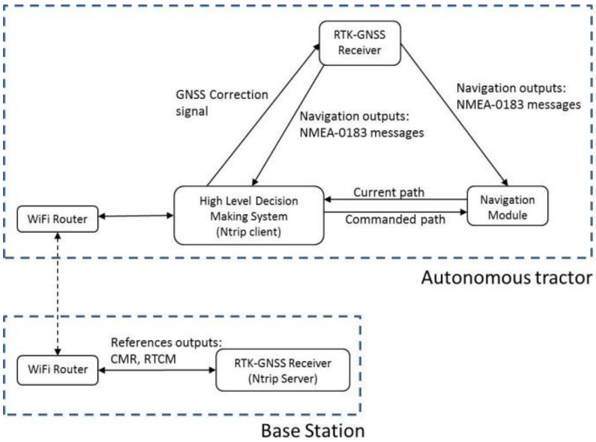

Figure 5.2. Flowchart of the location system on autonomous tractor.

A specially fabricated frame was located in the retrofitted tractor and used to mount the most necessary equipment, including the on-board computers, inertial measurement unit, modems for navigation, connector boxes, etc. The motion of the autonomous tractor had three primary degrees of freedom (longitudinal, lateral, and yaw). The tractor controller was responsible for sensing the vehicle location and heading angle.

To configure a fully autonomous agricultural system capable of ensuring precise navigation (navigation system), it is necessary to configure a framework (hardware and software) to merge perception (accurate vehicle positioning) and action (steering and speed control). The hardware framework should be modular, flexible, and robust, exhibiting real-time multitasking features and integrating modern standard communication protocols. Specifically, the vehicle controller used in this part of the experiment was based on a cRIO 9082 NI computer, and the control algorithms were developed using the LabVIEW graphical programming environment (Emmi and Gonzalez-De-Santos, 2012).

Field Experiment

Field tests were performed over a 1-week period during the winter of 2013 at the Center of Automatic and Robotic field experiment site, at the Spanish National Research Council (CISC), Madrid (latitude: 38.53894946 N, longitude: 121.7751468 W). Three criteria used for choosing the test plot were the following: (i) a plot that was almost flat, (ii) a plot large enough for five 20 m rows, and (iii) a plot that was within range of the correction base station used in the experiment.

A static test was carried out on a building of approximately 20 m in length where an open sky was visible. In this first test the RTX calculation was performed for the rover receiver and provided an accurate position of the new European correction signal using a GNSS navigation receiver. The correction signal was tested for 30 minutes on three different days, at different times of the day, within the same week as a dynamic test. Based on manufacturer recommendations (Lemmon and Wetherbee, 2005), this testing procedure would provide enough satellite constellation averaging to estimate the GNSS system accuracy.

Each dynamic test consisted of five passes of 20 m following a straight line (fig. 3). Two points ("AB") for each straight line were generated as an actual geospatial location by an RTK-GNSS receiver using a handheld surveying system interfaced to a rover RTK-GPS (Trimble model Bx982). The geographic coordinates for points "A" and "B" were obtained by placing the bottom tip of the 2 m GPS antenna survey pole against the soil surface and holding the pole vertically with the aid of a bubble level.

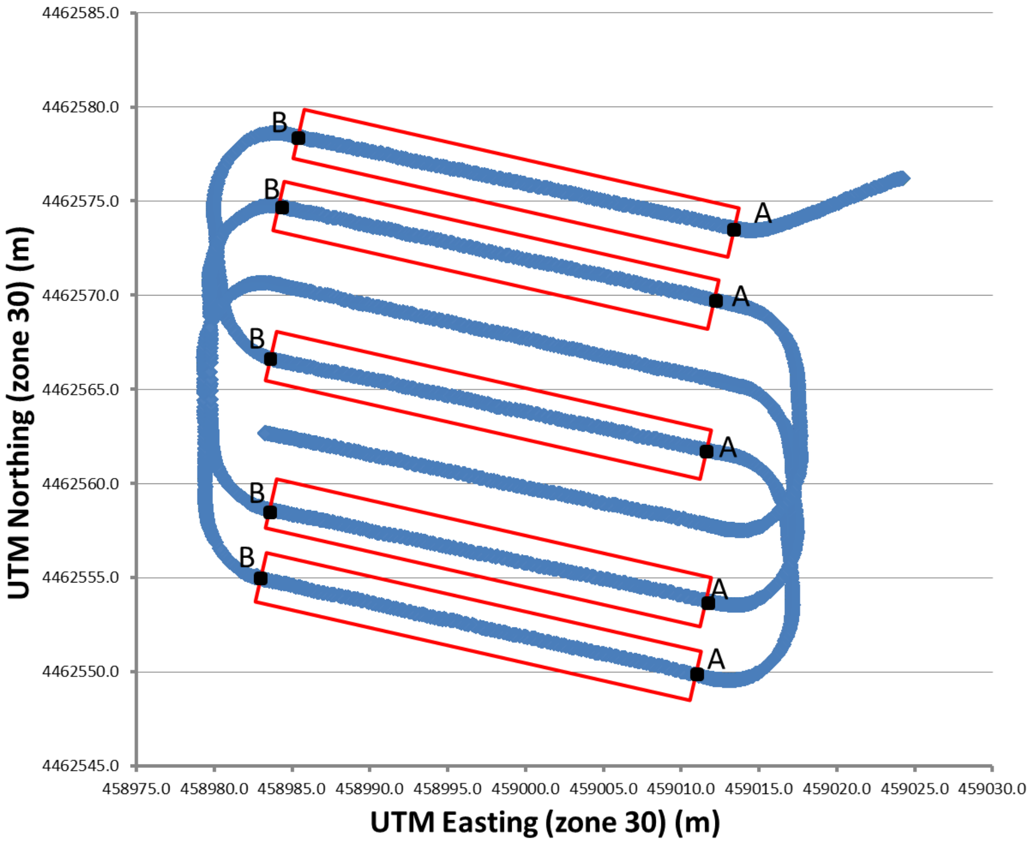

Figure 5.3. Straight mission for the autonomous tractor.

Points A and B were established for a dual-purpose: a) the straight-line mission planning for the autonomous tractor and b) a straight-line marked on the ground for accuracy measurements. All passes were travelled at a travel speed of 2.5 km h^{-1}.

Figure 5.4 shows the small tillage steel piece that was attached under the autonomous tractor, in the central axis, to mark the ground with the actual path of the autonomous tractor.

In this experiment, two types of GNSS correction signals were used: (1) RTK-GNSS signal provided by the base station and (2) RTX-GNSS based on satellite correction trough a satellite link.

Figure 5.4. Implemented steel tillage bar on the autonomous tractor.

Data Analysis

The following raw GNSS data were recorded for all the dynamic tests on the autonomous tractor: UTC time, longitude, latitude, height, velocity, signal quality indicator, PDOP, heading, and number of satellites. Only the time, longitude, latitude, and heading were utilized for the accuracy analysis. A program was created in LabVIEW (National Instruments, Austin, Tex.) to convert geographic coordinates to UTM coordinates.

To determine the accuracy of the autonomous tractor path compared to the prescribed path, the single point cross-track error (XTE) was defined as the perpendicular distance from the straight-line “AB” to each error measurements on the ground. Measurements were taken every 0.2 m between the ideal straight-line and the autonomous tractor path.

Total XTE was calculated using the root mean squared (RMS) value of all the single point XTEs along the full length of the straight-line (Taylor and Schrock, 2003). Cross-track error is an important variable that affects the potential skip or overlap.

For the *t* th pass, the RMS error was then calculated with the following equation:

$$\varepsilon\, RMS_t = \sqrt{\frac{1}{N_t}\sum_{i=1}^{N_t} e_{it}^2} \qquad (1)$$

where

N_t = total number of measurement point for the *t* th pass,

e_{it} = distance from the point *i* to the *t* th pass.

For the statistical analysis, the errors were calculated for each measurement. The SAS general linear models procedure (SAS, 2008) was used to test for significant differences between both treatments (RTK vs. RTX) using ANOVA. Statistics for the GNSS receiver (RTX satellite correction) position accuracy values in static tests were calculated using JMP (SAS Institute, Cary, N.C.).

3.5.3. Results and Discussion

RTX-GNSS Static Test

In total, 4970 GNSS data points were logged on three different days in the same week: day 1 (1220 data points), day 2 (1800 data points), and day 3 (1950 data points). Figure 5 shows the visibility of the GNSS satellite during test day 2 (10 GPS + 7 GLONASS); these conditions were similar to other static and dynamic test days. Table 1 shows the mean, standard deviation, maximum, minimum, and RMS values for the GNSS receiver error when using the RTX correction signals. The small RMS error for this test with RTX correction indicates that RTX has the potential to be used in an autonomous tractor. The magnitudes of the average circular error probable (CEP) was 2.9 cm at 99%, which means that 99% of all positions are placed within a circle with a 2.9 cm radius centred at a real position.

Table 5.1. Statistics for GNSS receiver using RTX correction signal on static, i.e. the autonomous tractor without motion.

		Statistics for RTX Position Accuracy Values									
		Easting (cm)					Northing (cm)				
Day	GNSS Data	Mean	S.D.	RMS	Max.	Min.	Mean	S.D.	RMS	Max.	Min.
1	1220	0.00	0.80	0.80	2.10	-2.50	0.00	0.90	0.90	2.80	-2.30
2	1800	0.00	1.00	1.00	2.80	-3.60	0.10	1.00	1.00	3.70	-3.30
3	1950	0.00	0.92	0.90	2.50	-3.20	0.10	1.00	1.50	3.20	-3.50
All data	4970	0.00	0.91	0.90	2.47	-3.10	0.07	0.97	1.13	3.23	-3.03

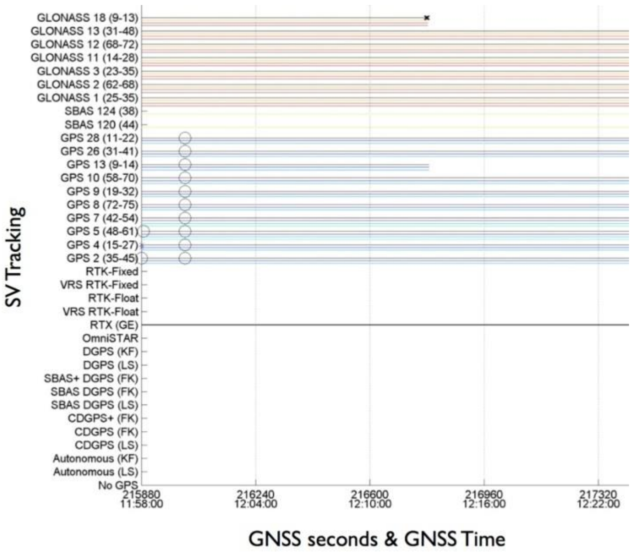

Figure 5.5. Plot of the visible GNSS satellites.

RTX-GNSS and RTK-GNSS Dynamic Test

The GNSS antennas mounting location on the autonomous tractor enabled an unobstructed view of the sky during the entire trial. This allowed for optimal signal reception regardless of satellite geometry, and the RTK and RTX-GNSS fixed quality was obtained for the recording of all data. The data in table 2 shows the RMS and standard deviation values for the GNSS receiver error mounted on the autonomous tractor when using RTK and RTX-GNSS correction signals. The rover receiver had a 2.5 cm horizontal accuracy and a 3.7 cm vertical accuracy on a continuous real-time basis. This level of accuracy was expected because the RTK technique can determine the sensor position within a few centimetres (Trimble, 2007). The average 2.4 cm for RMS cross-track error in the RTK correction signal system indicates that the passes were very straight, as was desired for the autonomous tractor. The 9.8 cm average error in the RTX correction signal system could limit the use of RTX-based autonomous tractor application in some horticultural crops and agricultural operations that require a high degree of accuracy. This unfortunate RTX accuracy was coincident with a significantly large heading error. However, fully automatic vehicles could be used for automated precision farming in many other applications such as site-specific management of weed control on extensive crops, variable rate application in orchards and vineyards using the appropriate implement, and variable-rate application of fertilizer based on yield maps. Between rows there was an error with a constant standard deviation, the average of these for RTK was 1.43 cm and for RTX 2.55 cm. These results demonstrate that the tractor controller was able to track each straight line with a standard deviation of better than 3.5 cm; the vehicle lateral position error never deviated by more than 4 cm for RTK and 10 cm for RTX.

Table 5.2. Statistics for GNSS receiver using RTX and RTK correction signals while following the straight line.

		RTK-GNSS (cm)		RTX-GNSS (cm)	
Row	Measurements	RMS	S.D.	RMS	S.D.
1	122	2.71	2.10	7.89	2.94
2	122	3.36	1.52	7.02	3.44
3	122	1.36	0.87	11.73	2.13
4	122	2.93	1.61	9.91	2.88
5	122	1.65	1.05	12.73	1.34
All Rows	610.00	2.40	1.43	9.86	2.55

3.5.4. Conclusions

There is a base of scientific research focused on achieving accurate geopositioning information through RTK-GNSS equipment mounted on an autonomous tractor using a dedicated reference station for signal correction (e.g., Nørremark et al., 2007; Sun et al., 2010; Griepentrog et al., 2005). To the best of our knowledge, however, an autonomous tractor using a DGNSS system has not been fully implemented. This study demonstrated the feasibility using a real-time RTX based on GNSS correction signal from an autonomous tractor where extreme accuracy is not required. The following conclusions were drawn based upon the results of this research:

- RMS Easting and Northing for the static tests with RTX correction showed values of 0.90 and 1.13 cm, respectively. This indicates that RTX has the potential to be used to get the location of autonomous tractors for applications that require a high degree of accuracy.
- The RMS error of the autonomous tractor using the base station (RTK-GNSS)

signals was approximately four times less than the RMS using the RTX correction signals. However, a fully automatic vehicle could be used for automated precision farming in many applications where a very high level of accuracy is not required, such as, site-specific management of weed control on extensive crops, variable rate application in orchards and vineyards using the appropriate implement, and variable-rate fertilizer application based on yield maps.

- The study has shown that the real-time extended GNSS signal could be used on an autonomous tractor, which greatly reducing the total equipment cost of the system without a large performance penalty.

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References

Bakker, T., Asselt, K. V., Bontsema, J., Muller, J., & Straten, G. (2011). Autonomous navigation using a robot platform in sugar beet field. Biosyst. Eng., 109(4), 357-368. doi:http://dx.doi.org/10.1016/j.biosystemseng.2011.05.001

Blackmore, S. B., Stout, B., Wang, M., & Runov, B. (2005). Robotic agriculture. In: J. Stafford (Ed.), Proc. of the 5th European Conference on Precision Agriculture. Uppsala, Sweden: .Wageningen Academic Publisher

Edwards, S. J., Clarke, P. J., Penna, N. T., & Goebell, S. (2010). An examination of network RTK GPS services in Great Britain. Survey Review, 42(316), 107-121. doi:http://dx.doi.org/10.1179/003962610X12572516251529

Emmi, L., & Gonzalez-De-Santos, P. (2012). Hardware architecture design for navigation and precision control in autonomous agricultural vehicles. Proc. of the First International Conference on Robotics and Associated High-technologies and Equipment for Agriculture (RHEA-2012), (pp. 217-221). Pisa, Italy: University of Pisa.

Fennimore, S. A., Tourte, L., Rachuy, J. S., Smith, R. F., & George, C. (2010). Evaluation and economics of a machine-vision guided cultivation program in broccoli and lettuce. Weed Tech., 24(1), 33–38. doi:http://dx.doi.org/10.1614/WT-09-022.1

Fountas, S., Wulfsohn, D., Blackmore, B. S., Jacobsen, H. L., & Perdersen, S. M. (2006). A model of decision making and information flows for information-intensive agriculture. Agric. Syst., 87(1), 192-210. doi:http://dx.doi.org/10.1016/j.agsy.2004.12.003

Griepentrog, H. W., Christensen, S., Søgaard, S., Nørremark, H. T., Lund, M., & Graglia, E. (2004). Robotic weeding. Proc. of AgEng 2004 Engineering the Future. Leuven, Belgium: Technologisch Instituut vzw, 2004

Griepentrog, H. W., Nørremark, M., Nielsen, H., & Blackmore, B. S. (2005). Seed mapping of sugar beet. Precision Agric., 6(2), 157-165. doi:http://dx.doi.org/10.1007/s11119-005-1032-5

Heraud, J. A., & Lange, A. F. (2009). Agricultural automatic vehicle guidance from horses to GPS: How we got here, and where we are going. ASABE Distinguished Lecture Series No.33. St. Joseph, Mich.: ASABE.

Hu, G., Khoo, H. S., Goh, P. C., & Law, C. L. (2003). Development and assessment of GPS virtual reference stations for RTK positioning. J. of Geodesy, 77(5-6), 292-302. doi:http://dx.doi.org/10.1007/s00190-003-0327-4

Leandro, R., Landau, H., Nitschke, M., Glocker, M., Seeger, S., Ghen, X., Deking, A., Tahar, M. Ben, Zhang, F., Ferguson, K., Stolz, R., Talbot, N., Lu, G., Allison, T., Brandl, M., Gomez, V., Cao, W., & Kipka, A. (2011). RTX Positioning: the next generation of cm-accurate real-time GNSS postioning. Proceeding of the ION GNSS, (pp. 1460-1475). Portland, Ore.: The Institute of Navigation

Leica Geosystems AG. (1999). Introduction to GPS (Global Positioning System). Heerbrugg, Switzerland: Leica Geosystems AG.

Lemmon, T., & Wetherbee, L. (2005). Trimble Integrated Surveying Techniques (White Paper). Westiminster, Colo.: Trimble Geomatics and Engineering Division.

Mesas, F. J., & Torrecillas, C. (2007). Andalusian network positioning. Mapping Interactivo. Retrieved from http://www.mappinginteractivo.com/plantilla-ante.asp?id_articulo=1432

Misra, P., & Enge, P. (2006). Global Position Systems: Signals, Measurements and Performance (2nd ed.). Lincoln, Mass.: Ganga-Jamuna Press.

Nørremark, M., Søgaard, H. T., Griepentrog, H. W., & Nielsen, H. (2007). Instrumentation and method for high accuracy georeferencing of sugar beet plants. Computers and Electronics in Agric., 56(2), 130-146. doi:http://dx.doi.org/10.1016/j.compag.2007.01.006

Ong Kim Sun, G., & Gibbings, P. (2005). How well does the virtual reference station (VRS) system of GPS base station perform in comparison to conventional RTK? J. of Spatial Sci., 50(1), 59-73. doi:http://dx.doi.org/10.1080/14498596.2005.9635038

Peleg, D. (2005). Distributed coordination algorithms for mobile swarms: new directions and challenges. In A. Pal, A. Kshemkalyani, R. Kumar, & A. Gupta (Eds.), Distributed Computing-IWDC 2005 (pp. 1-12). Springer-Verlag Berlin Heidelberg. doi:http://dx.doi.org/10.1007/11603771_1

Pérez-Ruiz, M., & Upadhyaya, S. K. (2012). Chapter 1: GNSS in precision agricultural operation. In F. Elbahhar (Ed.), New Approach of Indoor and Outdoor Localization Systems (pp. 1-26). InTech, under CCBY 3.0 license.

Prawirodirdjo, L., & Bock, Y. (2004). Instantaneous global plate motion model from 12 years of continuous GPS observations. J. of Geophysical Res., 109(B8), 1-15. doi:http://dx.doi.org/10.1029/2003JB002944

RHEA. (2012). A robot fleet for highly effective agriculture and foresty management. Retrieved from http://www.rhea-project.eu/

Rizos, C., Janssen, V., Robert, C., & Grinter, T. (2012). PPP versus DGNSS. Geomatic World, 20(6), 18-20.

SAS Institute . (2008). SAS/STAT 9.2 User's Guide. Cary. NC: SAS Institute, Inc.

Sørensen, C. G., & Bochtis, D. D. (2010). Conceptual model of fleet management in agriculture. Biosyst. Eng., 105(1), 41-50. doi:http://dx.doi.org/10.1016/j.biosystemseng.2009.09.009

Sun, H., Slaughter, D. C., Perez-Ruiz, M., Gliever, C., Upadhyaya, S. K., & Smith, R. F. (2010). RTK GPS mapping of transplanted row crops. Computers and Electronics in Agric., 71(1), 32-37. doi:http://dx.doi.org/10.1016/j.compag.2009.11.006

Taylor, R. K., & Schrock, M. D. (2003). Dynamic testing of GPS receivers. ASAE Paper No. 031013. St. Joseph, Mich.: ASAE.

Trimble Navigation Limited. (2007). Form 10-k annual report. Sunnyvale, Calif.

IV. General Results

4. 1. Design of a Soil Cutting Resistance Sensor for Application in Site-Specific Tillage.

A sensor-implement based on an articulated parallel linkage system, able to collect soil strength data continuously at various depths, was designed and operated.

We found a relationship between the SSPS and CI measurements (r2=0.58, 0.45 and 0.54) when the data were segmented by different depths (0-10, 10-20 and 20-30 cm)

The relationship between the profile-average measurements of the cutting force and measured profile-average soil cone index values revealed coefficients of determination greater than 0.9 when measured with the soil strength profile sensor.

4. 2. Development and Evaluation of a Combined Cultivator and Band Sprayer with a Row-Centering RTK-GPS Guidance System.

An experimental implement, which combined six-row crop cultivators and six band sprayers with row-position centering using an electro-hydraulic side-shift frame and RTK-GPS, was developed and operated for weed control within inter-row and intra-row areas.

The experimental system provided an herbicide band application volume targeted to the crop rows without reducing the quality of the intra-row chemical control treatment and while providing herbicide savings of approximately 50%. The labour required to hand-weed was 15.3 h ha^{-1} in the conventional treatment and 13.2 h ha^{-1} in the experimental treatment, on average. The manual weeding costs were reduce by 14% with the experimental system.

4. 3. Assessing GNSS correction signals for assisted guidance systems in agricultural vehicles.

A tractor was successfully instrumented to monitor and record simultaneously the geo-position from DGPS systems using OmniSTAR VBS, EGNOS, EUREF-IP, RASANT and RTK correction signals.

The RTK base station had the best results with a RMS value of 0,12 m, followed by OmniStar, 0,5 m, EUREF-IP 0,63m, RASANT 0,65 m and EGNOS 2,00m. Regarding the human error, the RMS values where quite similar for all the signals, 0,17m, 0,25 m, 0,20 m and 0,21 m, respectively.

4. 4. Field sprayer for inter- and intra-row weed control: performance and labour savings.

An experimental implement that combines two herbicide applications in a single pass, allows for SH application in narrow bands over the crop row, and NSH application between crop rows was successfully developed and operated by a GPS-RTK automated steering system.

Lateral displacement did not exceed the intra-row bandwidth, which for this study was defined as ±0.07 m from the row center line. This result is in agreement with the findings reported by Abidine et al. (2002)

The median hand-weeding times in the zone with post-emergence experimental herbicide application (45±6.3 s plot-1) and the zone without post-emergence experimental herbicide application (96±2.9 s plot-1) were significantly different (p=0.004), the experimental spraying system reduced the hand-weeding time by 53%. Moreover, the variability in the number of weeds was much higher in the control zone (SD=25.9 weed m-2) than that in the zone for which the experimental unit had been used (SD=12.8 weed m-2).

Regarding the sugar beet plant densities, we found 12.7±0.21 (control), 12.4±0.32 (EA), and 12.1±0.34 (CA), respectively, which result in not significantly differences (ANOVA, p=0.28).

4. 5. Comparison of positional accuracy between RTK and RTX GNSS based on the Autonomous Agricultural Vehicles under field conditions.

While using the dedicated RTK base station, the rover receiver had a 0.025 m horizontal accuracy and a 0.037 m vertical accuracy on a continuous real-time basis. The RMS value of 0.024 m for the cross-track error indicates that the passes were very straight.

The average error for RTX was 0.098 m, which could limit the use of RTX corrections in autonomous tractor for some specific applications.

Between rows there was an error with a constant deviation, the average of these for RTK was 0.0143 m and for RTX 0.0255 m. These results demonstrate that the tractor controller was able to track each straight line with a standard deviation better than 0.035 m; the vehicle lateral position error never deviated by more than 4 cm for RTK and 10 cm for RTX.

V. General Discussions of the Results

5.1. Design of a Soil Cutting Resistance Sensor for Application in Site-Specific Tillage.

Employment of this innovative sensor for soil cutting resistance mapping may result in a new era of site-specific tillage, which we plan to pursue through future research. Further work is also needed to provide additional insight into the SSPS and CI relationship in large commercial fields so that data obtained with the strength sensor can be related to the plethora of published research that used the CI to quantify soil strength.

5.2. Development and Evaluation of a Combined Cultivator and Band Sprayer with a Row-Centering RTK-GPS Guidance System.

Field tests showed that the machine was robust, adapting to the working conditions required of this type of implement. Under normal conditions and with the technology used, a farmer with 20 ha using the experimental equipment would be profitable with respect to the conventional equipment, with a payback period of less than the life of the machine. Thus, the experimental equipment can be an affordable option for both large and small farms.

The reductions in applied chemicals not only reduce production costs but also reduce the environmental impact caused by the chemicals. Statistical analyses revealed no significant differences with respect to weed control efficacy between the two weed control strategies studied.

5.3. Assessing GNSS correction signals for assisted guidance systems in agricultural vehicles.

For growers and farmers who are considering investing in a differential GPS system, the accuracy of the system is one of the most important factors. This study addressed two main questions- (i) what are the accuracies of five different GPS correction systems, and

(ii) what are the practical implications of measured accuracies on various field operations of interest to farmers.

This study showed that there was significant variability between the five different commercially available GPS correction signals to complement assisted guidance equipment. This study also developed a testing methodology for this type of technology that allows analysis of the behaviour of the GPS signals.

5.4. Field sprayer for inter- and intra-row weed control: performance and labour savings.

The potential integration of NSH and SH applications in a new sprayer implement was demonstrated for agronomic management in accordance with the treatment sequence. The beet population was not adversely affected compared to conventional broadcast SH application. There were no significant differences in weed densities between the CA and EA with the new sprayer. Using both the NSH application for inter-row weeding and the SH application for intra-row weeding with band spraying along the crop row reduced the amount of SH by replacing it with NSH. In this study, the method reduced the SH treatment area, and thus the SH input, by more than 76%.

5.5. Comparison of positional accuracy between RTK and RTX GNSS based on the Autonomous Agricultural Vehicles under field conditions.

There is a base of scientific research focused on achieving accurate geopositioning information through RTK-GNSS equipment mounted on an autonomous tractor using a dedicated reference station for signal correction (e.g., Nørremark et al., 2007; Sun et al., 2010; Griepentrog et al., 2005). To the best of our knowledge, however, an autonomous tractor using a DGNSS system has not been fully implemented. This study demonstrated the feasibility using a real-time RTX based on GNSS correction signal from an autonomous tractor where extreme accuracy is not required.

The error of the autonomous tractor using the dedicated base station (RTK-GNSS) signals was approximately four times less than the one using the RTX correction signals. However, the RMS error while using RTX was of 0.0113 m, which means a fully automatic vehicle using this technology could be used for automated precision farming in many applications, such as, site-specific management of weed control on extensive crops, variable rate application in orchards and vineyards, using the appropriate implement, and variable-rate fertilizer application based on yield maps.

TÍTULO DE LA TESIS:

STUDY, DEVELOPMENT AND APPLICATION OF PRECISION AGRICULTURE TECHNIQUES IN AGRICULTURAL MACHINERY

DOCTORANDO/A: D. Jacob Carballido del Rey

INFORME RAZONADO DEL/DE LOS DIRECTOR/ES DE LA TESIS

(se hará mención a la evolución y desarrollo de la tesis, así como a trabajos y publicaciones derivados de la misma).

El doctorando Jacob Carballido del Rey inició sus estudios de tercer ciclo en el anterior Programa de Doctorado "Ciencias y Tecnologías Agrarias, Alimentarias, de los recursos naturales y Desarrollo Rural" de acuerdo con la regulación establecida en el RD 778/1998 de 30 de abril (BOE de 1 de mayo). Durante el bienio 2007/2009 cursó y superó el período de docencia y el período de investigación con el tema "Aplicación, evaluación y análisis de técnicas de agricultura de precisión en cultivos extensivos cerealistas del Valle del Guadalquivir", un total de 32 créditos, obteniendo el reconocimiento de Suficiencia Investigadora con la Calificación de SOBRESALIENTE.

En 2010 inició los trabajos de investigación encaminados a la realización de sus Tesis Doctoral. Dichos trabajos se realizaron con la cofinanciación de: proyecto INIA RTA 2006-00058-C03-03 cuyo IP es el director de esta Tesis, la Asociación para la Investigación y Mejora de la Remolacha Azucarera (AIMCRA) mediante la firma de convenios con los directores, y Soluciones Agrícolas de Precisión S. L. (AGROSAP), una empresa promovida en 2007 desde la Universidad por el programa CAMPUS obteniendo varias distinciones, entre ellas el Premio UCO-UP 2016, convocado dentro de la Modalidad III: UCO - EMPRENDE del I Plan Propio Galileo de Innovación y Transferencia de esta Universidad. En esta empresa se integró el doctorando durante los primeros años de su funcionamiento en la línea de investigación de sus fundadores, los directores de esta tesis, sobre agricultura de precisión aplicada a la agricultura andaluza.

Con la modificación de la legislación sobre estudios de doctorado sin haber podido finalizar con la lectura de su Tesis Doctoral, el doctorando se ve obligado a integrarse en el nuevo Programa de la Universidad de Córdoba "Ingeniería agraria, alimentaria, forestal y de desarrollo rural sostenible" en el curso académico 2014/15 con la intención de presentar la Tesis para su lectura a lo largo de 2016 tras la realización de su estancia de investigación en la Universidad de Florencia, Italia, ya que reunía el resto de requisitos requeridos para tal fin. Por motivos puramente personales del doctorando, la redacción definitiva del documento de Tesis debió postergarse.

La labor realizada por el doctorando se inicia por tanto con anterioridad a su inscripción en el programa actual. En 2010 se publica el primer artículo científico integrante de su Tesis: "Assessing GNSS correction signals for assisted guidance systems in agricultural vehicles ", cuyos ensayos de campo son anteriores a dicho año. En este trabajo se cubren completamente los objetivos marcados del primer sub-proyecto de su Plan de Investigación según se recoge en la Memoria:

- Diseñar y validar una metodología de ensayo para realizar pruebas de comparación entre las precisiones alcanzadas con diferentes sistemas de ayuda al guiado o guiado automático.

- Determinar la precisión absoluta alcanzada, en términos de desviación con respecto a la trayectoria ideal, de un sistema de ayuda al guiado de vehículos agrícolas, utilizando diferentes señales de corrección: estación base RTK, Omnistar VBS, EUREF-IP y RASANT.

- Determinar el error humano cometido cuando se utilizan sistemas de ayuda al guiado GPS.

- Establecer recomendaciones en el uso de las diferentes señales de corrección evaluadas, en función de las necesidades de precisión que requieran las diferentes operaciones agrícolas.

Con el artículo titulado "Design of a Soil Cutting Resistance Sensor for Application in Site-Specific Tillage", publicado en 2013 se da cumplimiento a los objetivos marcados en el sub-proyecto 2 del Plan de Investigación:

- Diseñar y validar un método efectivo para la medida de la compactación de suelos a través de la resistencia mecánica que estos ofrecen al corte.

- Determinar el grado de correlación existente entre los datos recogidos con un sistema de medida de compactación tradicional, penetrómetro de punta cónica, y los datos recogidos con el sistema de medida continuo, "cuchilla", bajo las mismas condiciones.

También en 2013 publica el artículo "Development and Evaluation of a Combined Cultivator and Band Sprayer with a Row-Centering RTK-GPS Guidance System", que junto al que lleva por título "Field sprayer for inter- and intra-row weed control: performance and labor savings" cubren los objetivos marcados para el sub-proyecto 3 recogido en el Plan de Investigación:

- Diseño y fabricación de un apero que contenga los componentes necesarios para la aplicación de dos productos diferentes, sobre y entre líneas.

- Análisis comparativo de la eficacia, costes y posibles diferencias en producción, utilizando el sistema de pulverización experimental frente a las labores convencionales que se aplican en el cultivo de la remolacha azucarera en la provincia de Sevilla.

Por último, el artículo "Comparison of positional accuracy between RTK and RTX GNSS based on the autonomous agricultural vehicles under field conditions" publicado en 2014, permite concluir los trabajos de investigación previstos en su Plan cubriendo el objetivo del sub-proyecto 4:

- Determinación y comparación de la precisión de un sistema de guiado automático instalado en un vehículo autónomo, utilizando dos sistemas de corrección DGNSS, estación base propia RTK y correcciones vía satélite RTX.

Las revistas en que fueron publicados estos artículos están incluidas en el Journal Citation Reports siendo referentes en su temática.

La participación de la anteriormente mencionada empresa "Soluciones Agrícolas de Precisión S. L." en el consorcio integrante del proyecto europeo RHEA (NMP-CP-IP 245986-2) (2011-2014) permitió al doctorando completar sus trabajos de investigación además de contribuir de manera muy eficaz a su formación integral como investigador, dándole la oportunidad de establecer sólidos contactos con empresas e instituciones de investigación no sólo de España sino también de Francia, Alemania, Italia, Suiza, Austria y Bélgica. Al formar parte del Comité Científico-Técnico de dicho proyecto, asistió a las reuniones de seguimiento que se convocaban en las sedes de las instituciones integrantes del consorcio, cuyas instalaciones y líneas de investigación pudo conocer de forma directa.

Fruto de estos contactos fue la realización de su estancia de investigación como PhD Student Visiting Scholar en el "Biosystem Engineering Research Unit. Department of Agricultural and Forest Engineering. Università degli Studi di Florenze", Florencia, Italia, desde el 4 de septiembre hasta el 8 de diciembre de 2015 lo que le permite optar a la Mención Europea de su título de Doctorado. Durante esta estancia, el doctorando se incorporó en el equipo del Prof. Dr. Marco Vieri, con el que trabajó en la integración de nuevas tecnologías de posicionamiento global por satélite en maquinaria agrícola para la protección sostenible de los cultivos, lo que significó un impulso adicional en su formación al adquirir conocimientos complementarios sobre tecnologías específicas de control electrónico de maquinaria de pulverización de frutales.

Además de la publicaciones integrantes de la Tesis, el doctorando ha participado en otra publicación de carácter docente vinculada a la temática de la línea de trabajo, así como en 8 comunicaciones a congresos de gran relevancia en la agricultura de precisión.

Como resumen se puede concluir que al igual que el Plan de Investigación, puede darse por cumplido el Plan de Formación, teniendo en cuenta tanto el período de docencia ya cursado en el programa anterior, cuyos detalles pueden consultarse en la Memoria de Seguimiento, como la experiencia adquirida con su participación en el proyecto europeo RHEA.

Por todo ello, se autoriza la presentación de la tesis doctoral.

Córdoba, 25 de agosto de 2020

Firma del/de los director/es

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