Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)
Available online at www.inia.es/sjar

Spanish Journal of Agricultural Research 2011 9(2), 377-388
ISSN: 1695-971-X
eISSN: 2171-9292

# Evaluation of the use of low-cost GPS receivers in the autonomous guidance of agricultural tractors

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## Abstract

This paper evaluates the use of low-cost global positioning system (GPS) receivers in the autonomous guidance of agricultural tractors. An autonomous guidance system was installed in a 6400 John Deere agricultural tractor. A low-cost GPS receiver was used as positioning sensor. Three different control laws were implemented in order to evaluate the autonomous guidance of the tractor with the low-cost receiver. The guidance was experimentally tested with the tracking of straight trajectories and with the step response. The total guidance error was obtained from the receiver accuracy and from the guidance error. For the evaluation of the receiver's accuracy, positioning data from several low-cost receivers were recorded and analyzed. For the evaluation of the guidance error, tests were performed with each control law at three different speeds. The conclusions obtained were that relative accuracy of low-cost receivers decreases with the time; that for an interval lower than 15 min, the error usually remains below 1 m; that all the control laws have a similar behavior and it is conditioned by the control law adjustment; that automatic guidance with low-cost receivers is possible with speeds that went up to 9 km h$^{-1}$; and finally, that the total error in the guidance is mainly determined by the receiver's accuracy.

**Additional key words**: control law; fuzzy logic; inertial navigation system (INS); linear quadratic regulator; step response; trajectory tracking.

## Resumen

### Evaluación del uso de receptores GPS de bajo coste en el guiado autónomo de tractores agrícolas

Este artículo evalúa el uso de receptores de posicionamiento global (GPS) de bajo coste en el guiado autónomo de tractores agrícolas. Para ello, se instaló un sistema de guiado autónomo en un tractor John Deere 6400. Como sensor de posicionamiento se utilizó un único receptor GPS de bajo coste. Se implementaron tres leyes de control diferentes para la evaluación del guiado con el receptor GPS de bajo coste. Se realizaron pruebas de seguimiento de trayectorias rectilíneas y de respuesta escalón. El error de guiado total se obtuvo de la precisión del receptor y del error relativo instantáneo en el seguimiento de una trayectoria. Para la evaluación de la precisión del receptor, se tomaron y analizaron datos de posición de varios receptores. Para la evaluación del error en el guiado, se realizaron pruebas con cada una de las leyes de control a tres velocidades diferentes. Como conclusiones se ha obtenido que la precisión relativa de los receptores GPS de bajo coste disminuye con el tiempo; que en un intervalo de tiempo inferior a 15 min, la precisión relativa es aproximadamente 1 m; que el comportamiento de las diferentes leyes de control es similar y está condicionado por el ajuste de las mismas; que el guiado es posible a velocidades de hasta 9 km h$^{-1}$ y, finalmente, que el error total en el guiado está principalmente determinado por la precisión del receptor.

**Palabras clave adicionales**: ley de control; lógica difusa; regulador cuadrático linear; respuesta escalón; seguimiento de trayectorias; sistema de navegación inercial (INS).

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Received: 11-03-10; Accepted: 05-05-11.

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Abbreviations used: CDMA (code division multiple access), CVI (C Virtual Instrument), DC (direct current), DGPS (differential global positioning system), EGNOS (European Geostationary Navigation Overlay Service), GNSS (global navigation satellite systems), GPS (global positioning system), INS (inertial navigation system), LRQ (linear quadratic regulator), NMEA (National Marine Electronics Association), PID (proportional integral derivation), RTK-CDGPS (real time kinematic carrier phase differential global positioning system), UTM (universal transverse mercator), WAAS (wide augmentation area system).

## Introduction

Agriculture has experienced enormous advances in the past century as a result of a mechanical revolution that has made possible the replacement of animal-powered equipment with internal combustion engines. A chemical revolution has made the use of fertilizers and herbicides ubiquitous. A biological revolution has produced many varieties of plants and animals more productive and disease resistant, while an electronic revolution has allowed the optimization and automation of numerous tasks (Wilson, 2000; Auernhammer, 2001). One of the most recent modern technologies making this advance possible (Zhang *et al.*, 2002) is the global positioning satellite system (GPS), and one of the tasks to which it is being applied is the autonomous guidance of agricultural machinery (Ashraf *et al.*, 2003).

The first guidance systems were mechanical (Parish *et al.*, 1970; Kirk *et al.*, 1976; Busse *et al.*, 1977). Later, machine vision guidance systems (Billingsley and Schoenfisch, 1997; Benson *et al.*, 2003) and GPS guidance systems (Keicher and Seufert, 1999) were developed. Today, GPS guidance systems are the most popular.

Autonomous guidance systems can be divided into two groups: relative positioning systems and absolute positioning systems (Slaughter *et al.*, 2008). Relative positioning systems are those that use relative references to the current or previous position of the tractor. For example, vision systems (Subramanian *et al.*, 2006) that use the line of separation between the previous trajectory and the current one, or systems that use a laser reference (Leemans and Destain, 2007). On the other hand, absolute positioning systems use an external and global reference. Of these systems, the most widespread are those based on global navigation satellite systems (GNSS) (Stafford, 1999; Gan-Mor *et al.*, 2007).

The accuracy of autonomous GPS guidance systems depends on many variables. The most important is the accuracy of the GPS receiver. The accuracy of GPS receivers depends strongly on the employment of one or two frequencies and the use of differential corrections. Another variable that influences the accuracy is the frequency with which the GPS receiver supplies the positioning information. This frequency is usually in the range of 1 to 20 Hz. Thus, based on these variables, it is possible to reduce errors from several meters to a few centimeters with differential corrections. Precise real time kinematic carrier phase differential global positioning systems (RTK-CDGPS) have been usually used in the scientific literature (Noguchi *et al.*, 1998; Reid *et al.*, 2000; Thuillot *et al.*, 2002; Lenain *et al.*, 2006; Gan-Mor *et al.*, 2007). Positioning rates of 5 Hz or more have been used. No studies in the scientific literature analyze with detail the viability and precision of autonomous agricultural guidance systems based on low-cost single frequency GPS receivers that provide one position per second.

The tracking method or the guidance control has a great influence on the accuracy of the system. Control must allow quick approximation to the path without oscillations. Guidance control has been studied in many articles offering different control laws and technologies. One of the most common methods for the automatic guidance of an agricultural tractor, due to its simplicity and excellent results at low speeds, is the method that takes an advanced point on the path and then either points the front wheels directly at this point, or applies a steering angle proportional to the difference of orientation between this vector and the tractor (Gerrish *et al.*, 1997). A second method, also simple and commonly used, applies a proportional control to the distance and the difference of orientation between the path and the tractor trajectory (Noguchi *et al.*, 1998; Stoll and Kutzbach, 2000). However, the problem of this method is the loss of stability when the distance to the trajectory is increased. A third method is connected with the theory of state variables (Benner and Faβbender, 1999) and its derivations. Previous studies have looked at hybrid control systems (O'Connor *et al.*, 1996; Cordesses *et al.*, 1999; Thuillot *et al.*, 2002), which use «coarse» control laws when the errors are big and «thin» laws when they are small. Linear quadratic regulators (LRQ) were used for the «thin» control law. For resolving these problems, adaptive controllers have been used (Zhang *et al.*, 2003; Lenain *et al.*, 2006). Another more complex method is called chained systems. Here, a lineal model is obtained from the state model applying first order chained derivations (Lenain *et al.*, 2006). Finally, studies have also been carried out in which the control was implemented with fuzzy logic or neural networks (Blochl and Tsinas, 1994; Zhu *et al.*, 2005).

In order to obtain acceptable precision results, it is necessary to have a good steering response. Many studies have focused on the use of electrohydraulic valves in steering (Wu *et al.*, 1999; García-Pérez *et al.*, 2008), whereas others have looked at a simpler system using a direct current (DC) motor that turns the steering wheel.

The objective of this paper is to evaluate the use of low-cost GPS receivers in the autonomous guidance of agricultural tractors. For that, three different control laws were implemented and studied in order to determine the behavior of the system with this kind of receiver. For every control law the maximum tracking error for straight trajectories and the step response were analyzed by means of field automatic guidance tests. The static accuracy of the receiver was also studied experimentally. For that, horizontal position data were taken for fixed positions of the receiver at different times, evaluating the results. Global accuracy of the guidance system was determined from the precision of the GPS receiver and the precision of the tracking system.

## Material and methods

### Materials

A 6400 John Deere tractor with a maximum power of 73.5 kw was used for the experimental tests (Fig. 1a). The steering control was programmed in a microcontroller. The actuator was an RE-30 Maxon DC motor joined by means of a striated pulley to the steering wheel of the tractor (Fig. 1c). A GP 32 Maxon reducer gear adapted the motor turning speed to the steering wheel speed. The reduction rate was 14:1 for the reducer gear and 6:1 for the pulley. An MA3 US Digital magnetic encoder was used to measure the steering angle position (Fig. 1b) and an MD03 power stage was used to drive the DC motor. The power stage was controlled through an I2C bus from the microcontroller. The range of values for this control was 0 to 243. The GPS was a HI-204III Haicom, with a refreshment frequency of 1 Hz. The price of this GPS was lower than € 40. This GPS provides relative good performance with very low cost. Two other low-cost receivers were used to analyze the low-cost receiver's accuracy and its evolution with time. These receivers were a Garmin 16 and a Garmin 18 5 Hz.

A portable computer was used to control the whole system. It processed National Marine Electronics Association (NMEA) frames from the GPS receiver, calculated the error from the tractor to the desired trajectory and computed the control law for the steering. Windows XP was the operating system and LabWindows CVI was the development environment. Although this environment is not a real time system, this is not a problem due to the low processing frequency (1 Hz).

### Methods

The study was focused on rectilinear paths, since they are the most common shapes in agricultural work. In order to obtain precise and repeatable results, the guidance of the tractor was done independent of different factors such as the steering control, the navigation information measurement and the path position. Consequently, it was necessary to calibrate and obtain good conditions for these systems and to hold these configurations constant for all the tests. Within this

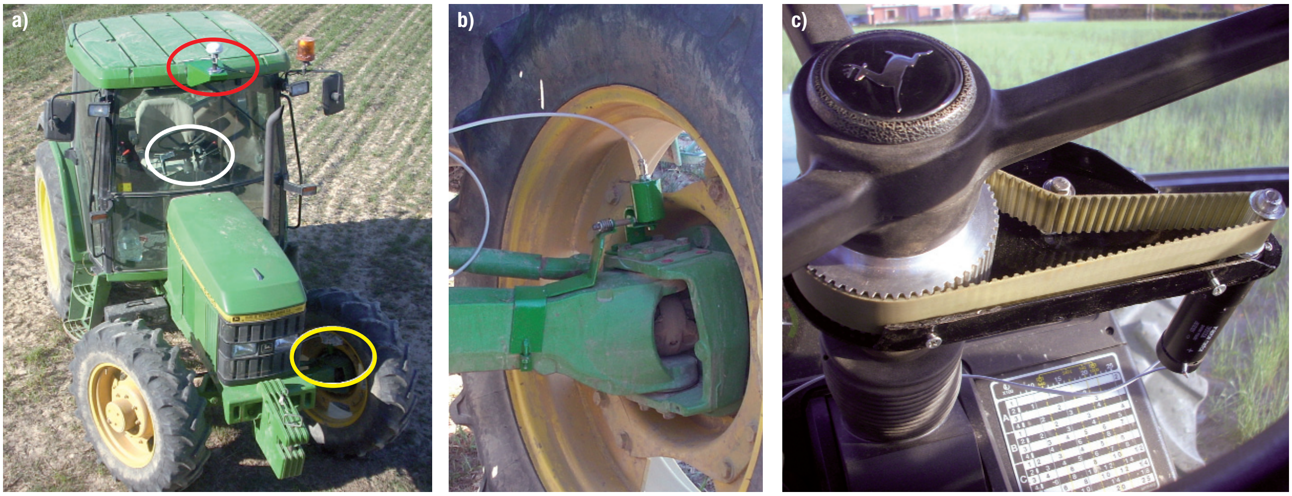

**Figure 1.** a) 6400 John Deere used in the test. The red circle indicates the position of the GPS, the white circle the DC motor for controlling the steering and the yellow circle the magnetic encoder. b) Magnetic encoder used for measuring the steering angle. c) DC motor and pulley used for moving the steering.

section the calibration and configuration of the tractor for the tests is described.

### Steering control and calibration

Steering control has a great influence on the guidance of the tractor. A very quick steering response (< 0.2 s), absence of peaks and oscillations, and a resolution lower than one half degree is necessary for a good guidance control. In this case, the control was accomplished by means of a DC motor joined with a pulley to the steering wheel. A reducer gear was used to adapt the motor speed to the steering wheel speed. The feedback for the controller was a magnetic encoder with a resolution of 10 bits that offered an effective resolution of 0.35°. The control was implemented using a microcontroller and fuzzy logic. Triangular functions were chosen for the fuzzy logic. Figure 2 shows the shape of the logic functions of this controller.

The mathematical expression of these functions is defined by equations [1] and [2]:

$$u(t) = \pm\left((PA - O_1)\,\frac{Gain_1}{Ramp} + (PA - O_2)\,\frac{Gain_2}{Ramp}\right) \quad [1]$$

$$u(t) = \pm\, Far\ Gain \quad [2]$$

Eq. [1] is used for triangular functions and 1 and 2 sub-indices are for positive and negative slopes respectively. Eq. [2] is applied in the far gain area. In these equations, *u(t)* is the value applied to the power driver, *Gain* is the maximum value for each interval, *Ramp* is the width of the interval, *O* is the origin of the interval, *PA* is the instantaneous position of the steering and *Far Gain* is the voltage for the trapezoidal function.

The adjustment of the controller parameters was done experimentally. The far gain was the saturation value of the DC motor. In our implementation it was 243. The lower gain was set to a value sufficient to correct stationary errors and move the steering with small errors quickly but without continuous current peaks. The middle value and the ramp were adjusted experimentally to a value that provided a smooth and quick response. Once the controller was implemented, the steering angle was obtained from the encoder angle and the equations of the Ackerman steering model.

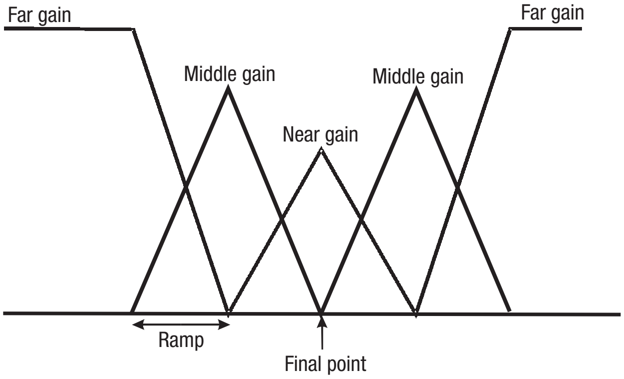

**Figure 2.** Typical triangular functions of fuzzy logic.

### GPS receiver

GPS receivers range in price from a few dozen to several thousand euros. The GPS receiver is one of the components that most affects the price and the precision of guidance system. An HI-204III Haicom low-cost receiver was chosen for this study. It is a one frequency code receiver that supports code differential corrections. In this case, European Geostationary Navigation Overlay Service (EGNOS) corrections were used to improve the navigation data.

### GPS. Principles, kinds and errors

The navigation system time and ranging (NAVSTAR) GPS is a satellite-based radio-navigation system that allows determining the position of a mobile anywhere in the world. It was developed by the United States (US) Department of Defense in 1978 and it is formed by 24 satellites turning around the earth. It calculates the position of a receiver based on the delays of the signals from the satellites (Borgelt *et al*., 1996).

Nowadays, three radio carrier frequencies are used. They are known as L1, L2 and L5. The most used for civil navigation is called L1C and it has a frequency of 1,575.42 MHz (DAF, 2008). Two codes are transmitted modulating these signals: a standard C/A (coarse acquisition) code and a precise P code restricted to US government use. The codes are transmitted using a technique called code division multiple access (CDMA). Each satellite sends a unique code.

GPS receivers can be classified as code or phase GPS receivers according to if the receiver evaluates the code or the phase of the carrier wave of the signals transmitted by the satellite.

Code receivers compare the coded signal transmitted from the satellites with an exact replica of the code generated in the receiver. The time delay between the two signals provides a measurement of the distance to each satellite. This distance is called pseudo-range. At least four pseudo-range measurements are necessary for the computation of the receiver position in three dimensions and the receiver clock offset. Code receivers have a 2dRMS accuracy of 100 m due to ionosphere effects, multipath and other effects (Borgelt *et al*., 1996). This accuracy can be improved using differential corrections. These corrections are obtained from a receiver in a static position and are used to correct mobile receiver errors. The corrections can be distributed via radio or satellite. Free satellite corrections, for example, EGNOS, can give to the receivers an accuracy of 5 m 2dRMS. Other non free corrections, such as OMNISTAR or SF2 system of John Deere, can improve the accuracy until 1 m 2dRMS. Code receivers are usually low cost and are used in a lot of applications, for example, car navigation.

Phase receivers analyze the phase of the carrier frequency. They need to know the carrier phase lag between the receiver and the base station. Phase receivers can be classified into two types according to the method used for calculating the phase lag: static carrier phase differential GPS (S-CPDGPS) and real time kinematic carrier phase differential GPS (RTK-CPDGPS). On one hand, S-CPDGPS is applied for static receivers. The number of cycles of the carrier frequency is calculated with post processing. A small amount of data is necessary in order to obtain the precise position of the receiver. On the other hand, RTK-CPDGPS is used to determine the position of mobile receivers. They resolve the ambiguity of the number of cycles supposing that they are an integer number. Then, there are only a few possible values for the equation of the number of cycles. This kind of receivers resolves the equation really quickly but they do not always obtain the optimal solution. Both the S-CPDGPS and the RTK-CPDGPS have an accuracy of a few centimeters.

## Error considerations for GPS receivers

Two kinds of errors can be defined for GPS receivers and GPS guidance systems (August *et al.,* 1994; ISO, 2008; ISO, 2009): (i) relative accuracy, precision, reproducibility or repeatability is the degree to which the measurements reported by a GPS receiver under a fixed placement of the receiver provide close positions and (ii) absolute accuracy is the degree of closeness of positions to their true value.

Figure 3 shows the difference between relative accuracy or precision and absolute accuracy.

For guidance systems, in applications where the time between pass and pass is relatively short and the trajectories must not be saved from year to year, precision or relative accuracy can be taken as the most important variable.

## Coordinates and lateral error calculation

The GPS system was developed for determining the position of a receiver on the earth.

GPS receivers usually provide their position in geodetic coordinates. This coordinate system is based on an ellipsoid. In the case of the HI 204 III Haicom GPS receiver, the ellipsoid is defined in the World Geodetic System of 1984 (WGS84) datum. However, this kind of coordinate system is not appropriate to work with tractors, because they are not Cartesian coordinates. Consequently, these coordinates were transformed to Universal Transverse Mercator (UTM) coordinates (DMA, 1989), which are Cartesian coordinates. UTM coordinates project geodetic coordinates over a cylinder perpendicular to the rotational axis of the earth. It divides the earth surface into sixty zones. Coticchia-Surace equations (Martin-Asin, 1983; Ferrero *et al*.,

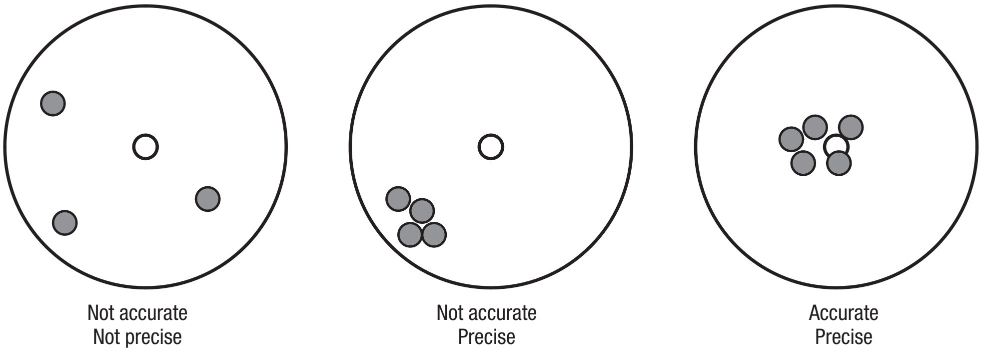

**Figure 3.** Difference between precision and accuracy.

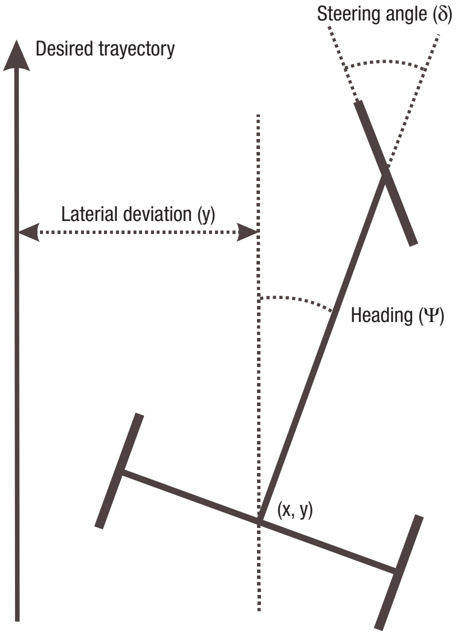

**Figure 4.** Instantaneous error from the tractor to the desired trajectory.

2009) were used to convert geodetic coordinates into UTM coordinates. With Cartesian coordinates, the representation of the straight trajectory and the calculation of the distance from the tractor to the trajectory are trivial, and this calculation was done by means of geometric relationships. Figure 4 shows how the distance from the tractor to the desired trajectory was calculated.

### *Placement of the GPS receiver on the tractor*

A delay in the heading information affects the guidance. The position of the GPS receiver influences the heading measurement (Stombaugh *et al.*, 1999). Consequently, diverse tests were done to evaluate the influence of the receiver placement in the heading measurement. From these tests, it was deduced that the placement of the GPS in an advanced position with regard to the central point of the rear axle of the tractor, produces enlargements in the heading that are as substantial as the displacement of the receiver. This is because the GPS uses the variation of position to calculate the course. Therefore, placing the GPS in an advanced position produces a bigger position variation in a turn than placing it on the tractor pivot point.

Therefore, the receiver was placed in the front of the cabin on its symmetry line because this position provides considerable stability and a quick system response (Stombaugh *et al.*, 1999).

### *Control laws*

This section provides a brief theoretical description of each one of the evaluated control laws.

#### Orientation and distance proportional control law

The steering angle is calculated as the addition of two terms. The first term is proportional to the angle difference between the heading of the tractor and the orientation of the desired trajectory. The second term is proportional to the distance from the tractor to the desired trajectory. This second term allows the correction of path deviations. However, it produces instabilities when the distance to the path increases. For this reason, the second term has been modified decreasing $K_2$ gain when the distance to the path is very large. Eq. [3] represents the control applied in this case, where $\theta_{trajectory}$ is the instantaneous path orientation, $\theta_{tractor}$ is the instantaneous heading of the tractor, $d_{trajectory}$ is the distance from the tractor to the trajectory and $K_1$ and $K_2$ are adjustable proportional constants for the orientation and the distance, respectively.

$$\delta = K_1 \cdot (\theta_{trajectory} - \theta_{tractor}) + K_2 \cdot d_{trajectory} \qquad [3]$$

The adjustment of this control law was done experimentally for every tested speed. The step response was analyzed for the adjustment. Initially $K_2$ was fixed to 0 and $K_1$ was fixed to a low value. $K_1$ was incremented up to the maximum value that did not cause instability in the system and allowed a quick response. It was done by tracking a step trajectory for each value of $K_1$ and analyzing only the heading response. Next, this maximum value of $K_1$ was decreased a bit and $K_2$ was increased until a value that kept the system stable and only small deviations over the trajectory were observed.

#### Vector pursuit control law

There are several kinds of vector pursuit control laws. All of them are based on applying a vector that goes from the tractor to an advanced point in the path (Gerrish *et al.*, 1997). The type of control depends on the point that is considered on the tractor. In this study, the vector is applied from the central point of the back axle of the tractor. The steering angle is obtained applying a proportional-integral-derivative (PID) controller over the angle formed between this vector and the orientation of the tractor. The equations used in this law are [4] and [5], where $K_P$, $K_D$ and $K_I$ are the constants of the controller and $\theta'_{tractor}$ is the angle between the tractor heading and the pursuit vector [6].

$$\delta = K_P \cdot \theta'_{tractor} + K_D \cdot \frac{(\theta'_{tractor} - \theta'_{tractor-1})}{T} + I \qquad [4]$$

$$I = I_{-1} + K_I \cdot (\theta'_{tractor} - \theta'_{tractor-1}) \cdot T \qquad [5]$$

$$\theta'_{tractor} = \theta_{tractor} - \theta_{pursuit\_vector} \qquad [6]$$

The precision of this law depends on the adjustment of its parameters. If the distance of the anticipated point decreases, a better approximation to the path is obtained, the response is quicker and the tracking error is smaller. Nevertheless, a decrease in the anticipated point distance produces bigger and quicker movements in the steering and increases sensitivity to noises in the GPS position, to pot-holes in the land or oscillations of the tractor. The adjustment of the PID controller is similar to that of any other application so that, as the proportional constant is increased, the oscillations in the steering will also be increased. The derivative part largely smoothes these oscillations, while the integral part allows for the correction of small deviations over the path produced by small calibration errors when the tractor is very close to the path.

For the experimental adjustment of this control law, the advance point distance was looked for first. To do this, $K_D$ and $K_I$ constants were fixed to zero and $K_P$ was fixed to a small value. Later, the advance point distance was changed until a value that had a good response was found. When this value was found, $K_P$ constant was incremented until the critical gain where the system started to oscillate was found. Later, this gain was decreased by half. Next, the integral constant was looked for. This value was adjusted to eliminate stationary errors. Finally, the derivative constant was not considered.

#### Linear quadratic regulator

This control law is based on linearization along with a Linear Quadratic Regulator (O'Connor *et al.*, 1996; Thuillot *et al.*, 2002). The expression for this controller is given by Eq. [7], where $\delta$ is the steering angle, $K_1$ and $K_2$ the gain constants, $L$ is the distance between the axles of the tractor, $d_{trajectory}$ is the distance to the path, and $\theta$ is the difference of orientation between the tractor and the path.

$$\delta = \arctan[(-K_1 d_{trajectory} - K_2 \tan\theta) L \cos^3\theta] \qquad [7]$$

The stability of this control law can be mathematically proven, but this control law suffers from singularities at $\cos\theta = 0$. In other words, if the heading of the tractor is oriented perpendicular to the desired trajectory, the steering angle input will be zero. In this situation, the vehicle will get stuck and will be unable to follow the desired trajectory. In addition, even near the singularity, the steering angle input is close to zero. In this situation, even though the vehicle is able to eventually converge to the desired trajectory, the actual path of the vehicle may not be desirable.

The experimental adjustment of this control law was similar to the orientation-distance control law. Initially, $K_1$ was fixed to 0 and $K_2$ was fixed to a low value. $K_2$ was incremented up to the maximum value that did not cause instability in the system and allowed a quick response. It was done by tracking a step trajectory for each value of $K_1$ and analyzing only the heading response. Next, this maximum value of $K_2$ was decreased a bit and $K_1$ was increased until a value that kept the system stable and only small deviations over the trajectory were observed.

## Results

Two types of tests were done in order to evaluate the accuracy of the autonomous guidance system using a low cost GPS as unique positioning receiver. On one hand, the static relative horizontal GPS receiver accuracy was measured. On the other hand, automatic guidance errors were evaluated. Total guidance error can be calculated taking into account the static error of the receiver and the guidance error.

### GPS positioning errors

One of the most evaluated variables of guidance systems is pass to pass accuracy (ISO, 2008). The tests for obtaining this variable must be done in passes spaced out less than 15 minutes. Consequently, accuracy of guidance systems is mainly important in short periods of time.

In order to evaluate GPS accuracy, positioning data were taken for three different low-cost receivers at a fixed position in three consecutive days. Figure 5 shows

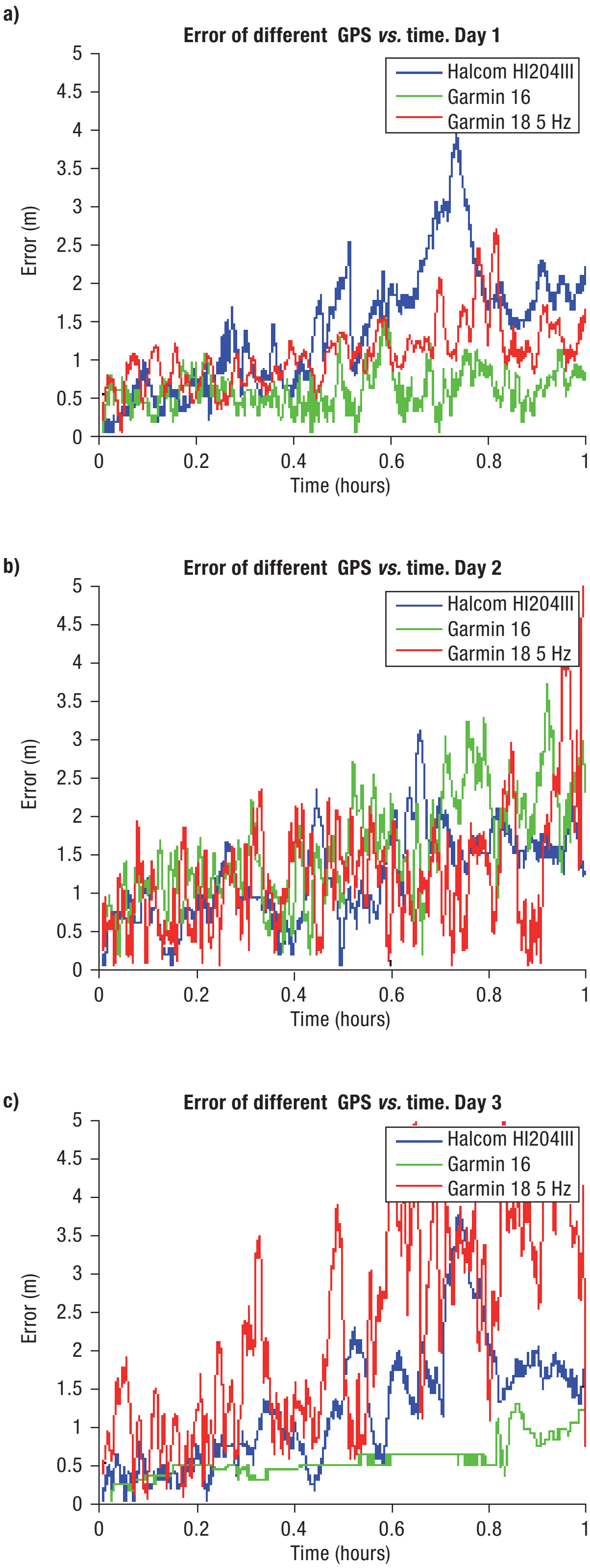

**Figure 5.** Instantaneous relative accuracy for three low-cost receivers during one hour on three different days. a) First day. b) Second day. c) Third day.

the error of each GPS during one hour for the three days. Error was calculated as the distance between the initial position reported for the receiver and the rest of the positions, and it had an upward trend with the time. In the first 15 min, error was less than 1 m.

## Trajectory tracking errors

Real guidance tests were carried out in order to evaluate guidance error. Tests were done with the three different control laws described before. Straight tracking and step response were evaluated. The reference trajectory was taken for each test from the first and the last position of the trajectory marked on the ground. These points were taken directly from the positions reported by the GPS. The total length of the trajectory was 200 m. The step was placed at 50 m from the beginning of the trajectory and the remaining 150 m were used to study the step response and the continuous tracking error. All the tests were done at three speeds: 3, 6 and 9 km h$^{-1}$. The control laws were experimentally adjusted for each speed as is described in the Methods section. Table 1 shows the adjustment parameters for the tests.

Figure 6 shows the step response and the instantaneous error for the three control laws at a speed of 3 km h$^{-1}$.

The step response was similar for the three control laws. The instantaneous error was similar too. The

**Table 1.** Adjustment parameters for the control laws used in the study. Parameters were adjusted for every tested speed (3, 6 and 9 km h$^{-1}$). Each control law has its own parameters (explained earlier in the control laws section)

| Parameter | Speed (km h$^{-1}$) | | |
|---|---|---|---|
| | 3 | 6 | 9 |
| Orientation-distance | | | |
| $K_1$ | 900 | 750 | 500 |
| $K_2$ | 0.5 | 0.4 | 0.35 |
| Pursuit | | | |
| Advance point distance (m) | 4 | 8 | 10 |
| $K_P$ | 0.5 | 0.35 | 0.3 |
| $K_D$ | 0 | 0 | 0 |
| $K_I$ | 0.01 | 0.01 | 0 |
| O'Connor | | | |
| $K_1$ | 0.1 | 0.06 | 0.03 |
| $K_2$ | 0.35 | 0.25 | 0.18 |

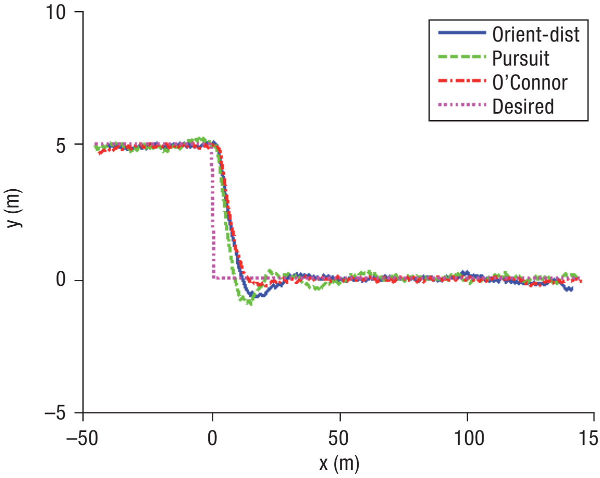

**Figure 6.** Step response and instantaneous error for Pursuit, O'Connor and Orientation-distance proportional control laws at 3 km h$^{-1}$.

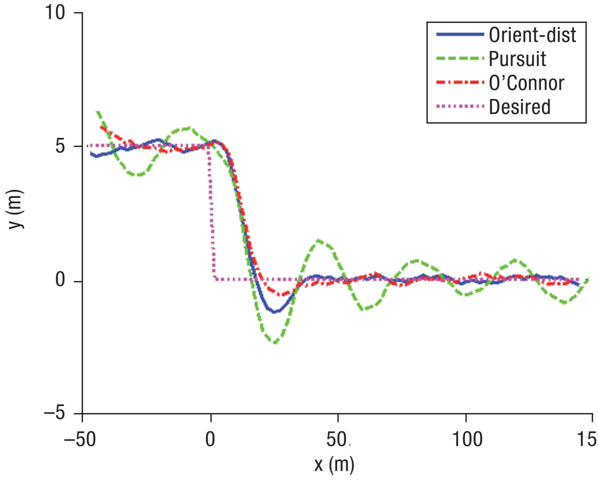

**Figure 8.** Step response and instantaneous error for Pursuit, O'Connor and Orientation-distance proportional control laws at 9 km h$^{-1}$.

distance that the tractor needed to reach the trajectory after the step was applied was approximately 40 m. The movement of the tractor was lightly underdamped. The instantaneous error was constant along the trajectory. The pursuit law had more oscillation. The three control laws were adjusted to be very slow. The control law that presented the best behavior in the step response and in the continuous guidance was the O'Connor control law.

Figure 7 shows the step response and the instantaneous error for the three control laws at a speed of 6 km h$^{-1}$. In this case, it is possible to see how the instantaneous error was very similar to that obtained for 3 km h$^{-1}$. The system was stable with all the control laws and it was capable of driving the tractor at this speed. All responses were very similar, but the O'Connor control law was a little faster.

Finally, Figure 8 shows the step response and the instantaneous error for each control law at 9 km h$^{-1}$. In this figure, the differences were greater. The pursuit control law was slower reaching the trajectory and it had some oscillations. These oscillations were constant along the trajectory. The orientation and distance proportional law was faster, although it had a larger over peak than O'Connor. The tractor advanced several meters between the step and the achievement of the trajectory.

Finally, a histogram is presented in Figure 9 for analyzing the errors of the three control laws at the three

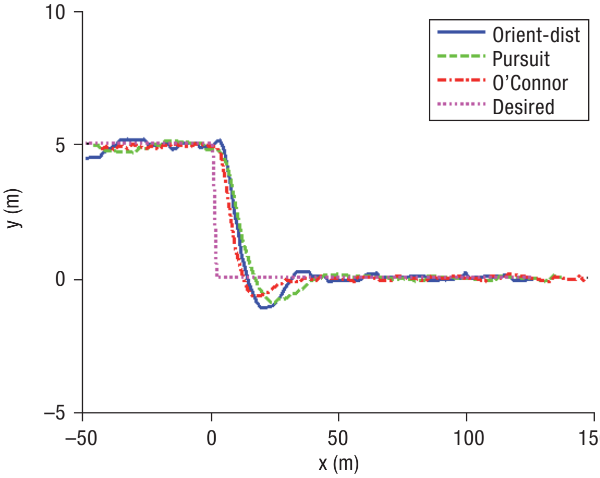

**Figure 7.** Step response and instantaneous error for Pursuit, O'Connor and Orientation-distance proportional control laws at 6 km h$^{-1}$.

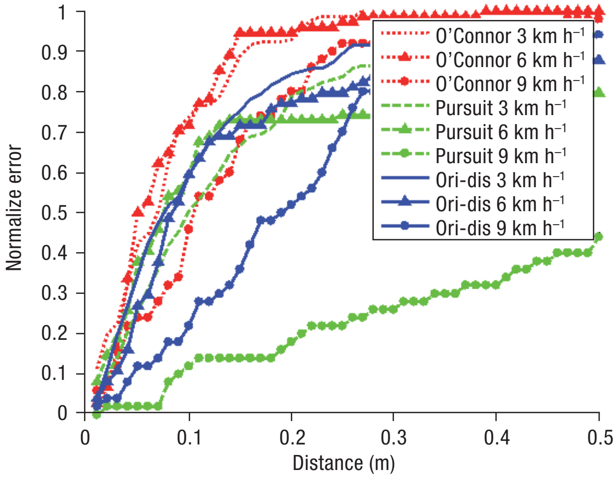

**Figure 9.** Accumulative histogram for the instantaneous error of the O'Connor, the Pursuit and the Orientation-Distance control laws at 3, 6 and 9 km h$^{-1}$.

speeds in the continuous tracking of the trajectory. This histogram was obtained from the instantaneous error when the trajectory was stable; it is between 50 and 150 m. The histogram represents the normalized accumulated error for each distance.

From this histogram it is possible to deduce that the O'Connor control law produced the lowest errors independent of speed and the Pursuit control law was the worst. Moreover, it is possible to observe that error was very similar for 3 and 6 km h$^{-1}$ and it was increased for 9 km h$^{-1}$.

### Total guidance error

Total guidance error was calculated from the previous tests. This error is the result of adding GPS error and guidance error. The total guidance error for all the control laws and for all tested speeds was lower than 1.25 m in 75% of the trajectory, except in the pursuit vector control law at 9 km h$^{-1}$, which was unstable. This error will increase with time, due to the relative accuracy of the receiver which grows with time and it is the main component of the total guidance error.

## Discussion

This paper describes the implementation of an autonomous guidance system for an agricultural tractor and analyzes the use of a low-cost GPS as the only positioning sensor for guidance. This article covers a gap in the scientific literature in the field of precision agriculture because there are no articles in the scientific literature that study the guidance of a tractor using only a low-cost GPS receiver as a positioning sensor. Usually, expensive RTK-CDGPS are used in the scientific literature (Noguchi *et al*., 1998; Reid *et al*., 2000; Thuillot *et al*., 2002; Lenain *et al*., 2006; Gan-Mor *et al*., 2007). Only few articles (Guo and Zhang, 2004; Peters and Evett, 2005; Keskin and Say, 2006) have used this kind of receiver for obtaining the position of an irrigation system (Peters and Evett, 2005), measuring the speed of a vehicle (Keskin and Say, 2006), or the guidance of an off-road vehicle (Guo and Zhang, 2004; Price and Nistala, 2005). In this article, the complete guidance system has been implemented and static and relative errors have been studied obtaining clear results. Several articles (Devlin *et al.,* 2007; Gan-Mor *et al.,* 2007) have studied GPS errors or guidance tracking errors, however, none have applied and studied a low-cost guidance system.

GPS accuracy can range from 1-2 cm to 100 m (Czajewski, 2004; Gan-Mor *et al.,* 2007; Valbuena *et al.,* 2010) depending on the kind of GPS receiver employed. For low-cost GPS receivers using wide augmentation area system (WAAS) corrections, position accuracy of 95% can be less than 3 m (Peters and Evett, 2005). In contrast, relative accuracy or pass to pass accuracy (ISO, 2008) is the variable that is really important for multiple agricultural applications. Experimental tests carried out in this article have demonstrated that for a short period of time of 15 min this relative accuracy can be reduced to approximately 1 m. This relative accuracy could be enough for applications where wide width of work is used, for example, fertilizer application.

Novelty guidance systems and control laws have been employed in a multitude of scientific articles (Gerrish *et al*., 1997; Stoll and Kutzbach, 2000; Thuillot *et al*., 2002; Lenain *et al*., 2006). However, all of them have been developed and analyzed with expensive RTK-CDGPS receivers and, in several cases, combined with expensive INS systems (Noguchi *et al*., 1998). In contrast, this article studied the behavior of these control laws with low-cost receivers. Three control laws were implemented and analyzed by means of real tests. A soft adjustment of the control laws was done in order to avoid making the system unstable. In contrast to other articles (O'Connor *et al*., 1996; Steinz *et al*., 2002) where big differences were found between control laws, in this article a similar behavior for all the control laws was obtained and it was determined by the control law adjustment and by the receiver accuracy.

In summary, it is possible to guide autonomously an agricultural tractor with a low-cost receiver as positioning sensor. No more sensors are necessary for the autonomous guidance of the tractor. The maximum speed for the automatic guidance is approximately 9 km h$^{-1}$. Higher speeds make the autonomous guidance system unstable.

The behavior of the different control laws is similar with low-cost GPS receivers and it is conditioned by its adjustment. With a proper adjustment of the control laws, all of them obtain similar results.

Errors in pass-to-pass trajectories can usually be less than 1 m. This error is composed by the guidance error, typically less than 20 cm, and the positioning error relative to a previous pass that increases with time.

## Acknowledgments

This work was supported partially by the regional 2010 Research Project Plan of the *Junta de Castilla y León* (Spain), under project VA034A10-2 and partially by the 2009 ITACyL project entitled «Realidad aumentada, Bci y correcciones RTK en red para el guiado GPS de tractores (ReAuBiGPS)». J. I. Arribas work was supported by the *Comisión Interministerial de Ciencia y Tecnología* under grant TEC2007-67037 and by fellowship JC-2009-00255 under «Programa Nacional de Movilidad de Recursos Humanos de Investigación, *Ministerio de Educación,* Spain».

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