International Journal of Engineering and Technical Research (IJETR)
ISSN: 2321-0869 (O) 2454-4698 (P), Volume-6, Issue-1, September 2016

Automatic Steering Systems Based on Relative Position

Rodrigo F. G. Baldo, Timothy S. Stombaugh, Paulo. S. G. Magalhaes, Rodrigo S. Zandonadi

***Abstract*— All mechanical sugar cane harvesting uses a separate wagon to receive the material from the harvester. This wagon is usually pulled by another vehicle, which must follow a parallel path with respect to the harvester. Substantial harvest losses are caused by the lack of vehicle synchronization. This issue can be addressed by using automated guidance systems on both vehicles; however, the costs associated with equipping all the fleet vehicles with the required high accuracy GNSS (Global Navigation Satellite System) receivers are prohibitive. By using local distance sensors between the operating vehicles, their relative position could be determined based on the harvester's, which is the leading vehicle in the process, and the only vehicle carrying the high accuracy GPS receiver. This paper presents the development, and the Field testing of steering control system based on relative position determined by distance sensors installed in the vehicle. The tests were conducted at the University of Kentucky, USA; by varying the offset of the parallel distance between the machines and measuring the settling time. The results were considered positive since the average settling time was about 7 seconds, and the maximum steady state error was 0.12 m.**

***Index Terms*— Autopilot, GPS, Precision Agriculture, Sensors.**

I. INTRODUCTION

Raw material losses during harvest is caused in part by the lack of synchronization between the harvester, and the tractor that pulls the biomass collection wagon, especially in harvesters with no storage capacity, such as forage, coffee and sugarcane harvesters. Beyond the raw materials losses, there is also a decrease in the effective operational capacity when the wagon travels ahead of the harvester, forcing the tractor operator to realign the equipment in the ideal position.

In the last two decades, the use of electronic control systems in agricultural machinery has seen an increase, thanks to the wide use of GNSS (Global Navigation Satellite System), and the advances in computing and electronics. There is a growing interest in the adoption of automatic steering systems (auto steer) which reduces the operator's stress and provide higher reliability during night work [1]. The mental fatigue on these operators is not only caused by the work's monotony, but also by the stress caused by the need of precision driving inside narrow lanes without any damage to surrounding vegetation: thus, maintaining a suitable work pace. As technology advances, more complete and accurate information is being incorporated into the intelligent systems for agricultural vehicles, demanding for the control information to be quickly treated to ensure a reliable and rapid response from the system. Agricultural automatic operations are regulated by feedback control systems, containing loop control sensors [2]. [3] described a positioning control system for the synchronization between the sugarcane harvester and the wagon, using ultrasonic sensors to identify the vehicles positioning, and radio frequency transmitters for communication between the operators who manually, controlled the machines' speed. The system reduced the raw material losses by about 60kg.ha-1. However, this system did not take in consideration the parallelism between machines.

Most commercial auto steer are programmed to parallel copy a pre-defined AB line. The most accurate auto steer systems consists of a high-accuracy RTK (Real Time Kinematic) GNSS, a tractor wheel positioning sensor, a gyroscope, and a steering actuator. There are two types of automatic guidance systems available on the market. The universal system, which can be used in various models and types of vehicles, it comprises of a steering actuator with an electric motor that controls the steering wheel; thus, keeping the vehicle on the desired path during operations. The other is the integrated autopilot control, where the vehicle's steering is performed by a set of hydraulic and electronic components attached to its steering system [3]. According to the author, the integrated system has better accuracy in the field work, compared to the universal system, by acting directly at the vehicle's steering wheel; thus, decreasing the settling time to correct the path.

However, the existing autopilots are not designed to mimic the movements of another vehicle. This is relevant in several systems involving two synchronized agricultural machines, as in the case of the vehicles receiving the outputs from grain and forage harvesters, and more specifically, from the sugarcane harvester where a high volume of biomass is transferred from the harvester to the wagon [4].

The objective of this study was to develop an automatic steering control system for a slave vehicle, based on the positioning of a master vehicle, to be used in agricultural field operations requiring synchronization, such as material transfer; thus, avoiding losses and physical exhaustion in the operators.

II. MATERIALS AND METHODS

A. *System Description and Operation*

Currently, the commercial autopilot system operates as follows: point A is created by the operator, and then it moves to a final destination and creates point B. Thus, the system generates the AB line, which is the reference line for the autopilot controller. This system is capable of work in parallel to this line at a spacing determined by the operator, Figure 1.

Rodrigo F. G. Baldo, State University of Campinas, Pedro Zaccaria, 1300 - Limeira – SP, 13484-350 Brazil
Timothy S. Stombaugh, University of Kentucky, 128 Charles E. Barnhart Building – Lexington – KY 40546-0267 USA
Paulo. S. G. Magalhaes, State University of Campinas, Zeferino Vaz - Campinas – SP, 13083-865 Brazil
Rodrigo S. Zandonadi, University of Mato Grosso, Sinop – Mato Grosso – SP, Sinop Brazil

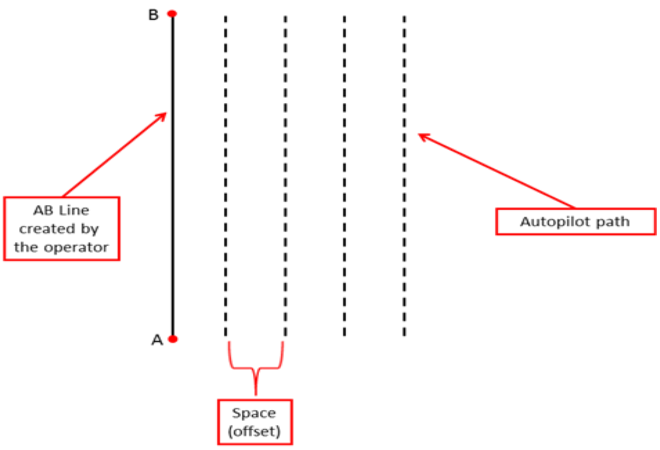


Figure 1 - AB line created by the auto steer operator.

In the control system proposed in this work, the auto steer starts to receive the position information from the master vehicle, modifying the coordinates sent by RTK GNSS. For this, the control system captures the position values sent by RTK, creates a new position based on the difference between the desired parallelism and the one measured by the sensor installed on the side of the slave vehicle, and sends this new coordinate the slave vehicle's auto steer. Thus, the slave vehicle's position depends on the master vehicle position, thereby copying its movements. The developed algorithm uses polar coordinates to calculate the point displacement. The following items describe the system in more detail.

B. *System Instrumentation*

Master

A van was fitted with a Trimble (Trimble Navigation, California, USA) Model 5800 RTK GNSS receiver and a notebook computer to store the instant positions of the vehicle (Figure 2).


Figure 2 - Van used as the master in the steering control.

Slave

A John Deere tractor model 7220 was used as the slave vehicle for the steering testing (Figure 3).


Figure 3 - John Deere tractor used as the slave vehicle.

The tractor was equipped with a Trimble (Trimble Navigation, California, USA) model AgGPS 214, RTK GNSS receiver, and a notebook computer responsible for storing the tractor's positioning, and for running the program developed in this work. Furthermore, it was also installed, a Trimble EZ Steer assisted steering system (Trimble Navigation, California, USA) (Figure 4).

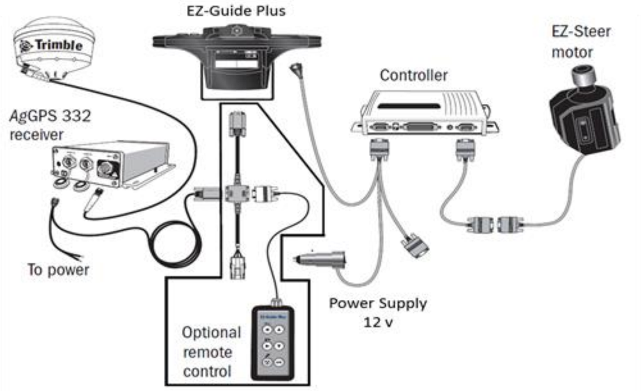


Figure 4 - Trimble EZ-Steer Autopilot (Trimble Navigation, California, USA).

The EZ-Guide Plus guidance system (Trimble Navigation, California, USA) was connected to the EZ-steer (Figure 5).

Figure 5 - EZ - Guide Plus (Trimble Navigation, California, USA).

RTK Base Station

In Figure 6 are presented the base station was composed by: a Trimble AgGPS 214 RTK receiver (Trimble Navigation, California, USA), a Trimble Trimmark3 radio transmitter (Trimble Navigation, CA, USA), and a communication antenna responsible for sending the corrections to the mobile RTK GPS.

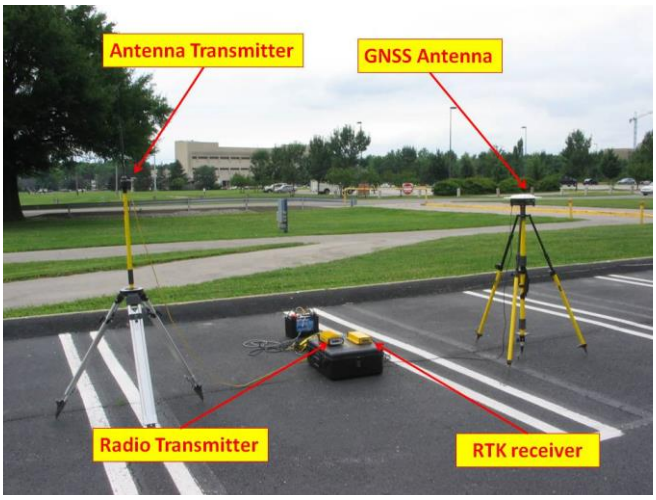


Figure 6 - RTK base station.

C. *Program Manager*

A Visual Basic .NET program manager was developed, to copy the Van's movement, and installed in a notebook computer mounted next to the Trimble auto steer. In Figure 7 are presented differences between the commercial system, and the system developed in this work.

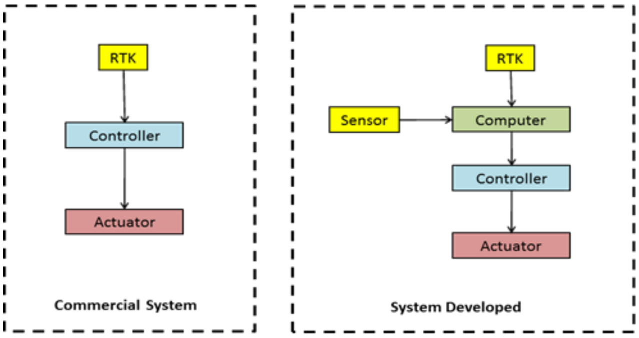


Figure 7 - Hardware differences between the commercial and the developed system.

The developed Algorithm captures the position information sent by the RTK receiver, receives the laser sensor readings which gives the relative distance of the slave vehicle with respect to the master machine, and compares it with the desired parallel distance between the machines (offset). With this information, a new position was created and sent to the auto steer controller for decision in the path correction.

Program Calculations

The tractor's new position was computed as follows:

After receiving the NMEA signal from the RTK receiver.

It stores the point A in addition to the point B, which was created by the tractor operator when the autopilot was turned on.

The program calculated the line AB angle with respect to the North (Figure 8) using Equation 1

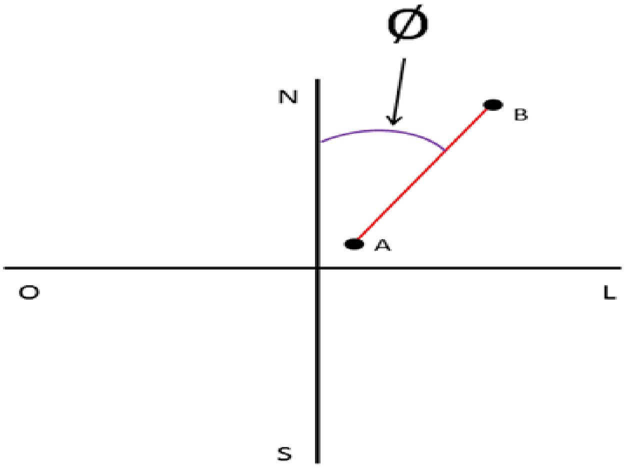


Figure 8 - AB angle relative to the North.

$$\emptyset = Atan2(\cos(latA) * \sin(latB) - \sin(latA) * \cos(latB) * \cos(longB - longA), \sin(longB - longA) * \cos(latB)) \quad (1)$$

Where:

Atan2(x,y) returns the angle (in radians) from the x-axis to a line containing the origin (0,0) and the point (x,y)

$\emptyset$= Angle (in radians) between the AB line and the North

latA = Point A latitude

latB = Point B latitude

longA = Point A longitude

longB = Point B longitude

When starting the route, the program stores both the latitude and longitude from the initial position, and calculates the angle of the vehicle's actual position with respect to the North (Figure 9) using Equation 2.

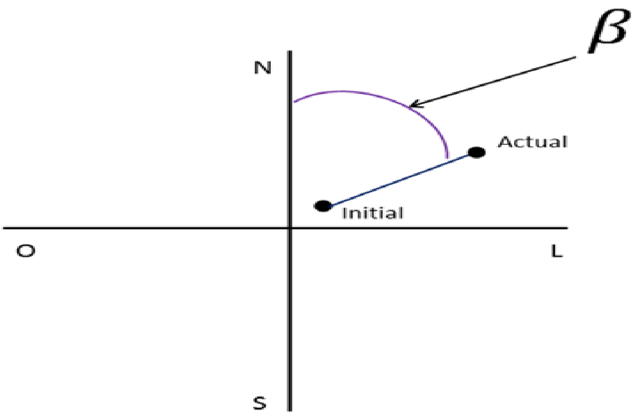


Figure 9 – Path angle relative to the North.

$$\beta = Atan2(\cos(latinic) * \sin(latatual) - \sin(latinic) * \cos(latatual) * \cos(longatual - longinic), \sin(longatual - longinic) * \cos(latatual)) \quad (2)$$

Where:

Atan2(x,y) returns the angle (in radians) from the x-axis to a line containing the origin (0,0) and the point (x,y)

β = Angle (in radians) between the actual line and the North
latinic = Initial point latitude
latatual = Initial point latitude
longinic = Initial point longitude
longatual = Initial point longitude

The program calculates the distance (in meters) from the actual point, to the initial point (D), Figure 10 using Equation 3.

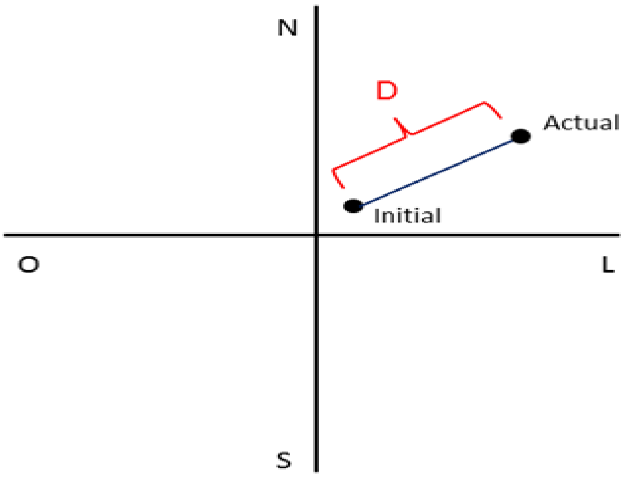


Figure 10 - Calculation of the distance from the actual point to the initial point.

$$D = R * \cos^{-1}(\cos(longinic - longatual) * \cos(latinicial) * \cos(latatual) + \sin(latinicial) * \sin(latatual)) \tag{3}$$

Where:
$R = 6371 * 10^3\ m$ that is the approximate radius of the earth

latinic = Initial point latitude
latatual = Initial point latitude
longinic = Initial point longitude
longatual = Initial point longitude

The program also calculates the distance from the actual point to the AB line (Dpr),

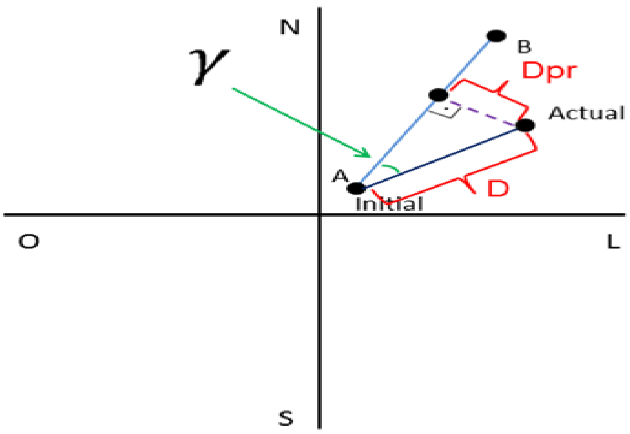


Figure 11 using Equation 4. The Dpr is used on the new point calculation.

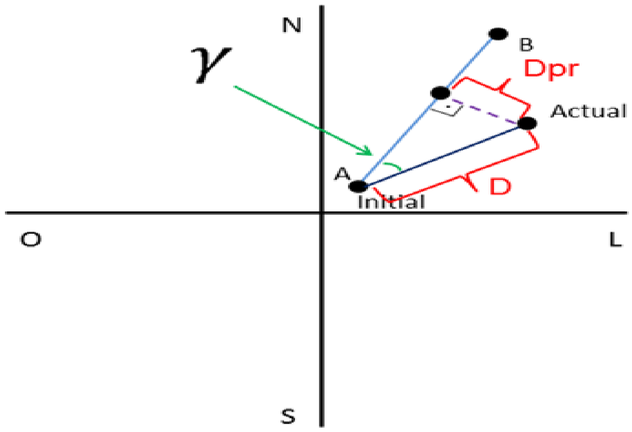


Figure 11 - Distance computation from the actual point to the AB line.

$$Drp = D * \sin(\gamma) \tag{4}$$

Where:
$\gamma = \beta - \emptyset$ (in radians)
Drp = distance (in meters) from the actual point to the AB line
Finally, the program calculates the new latitude and longitude (Figure 12), using Equations 5 and 6.

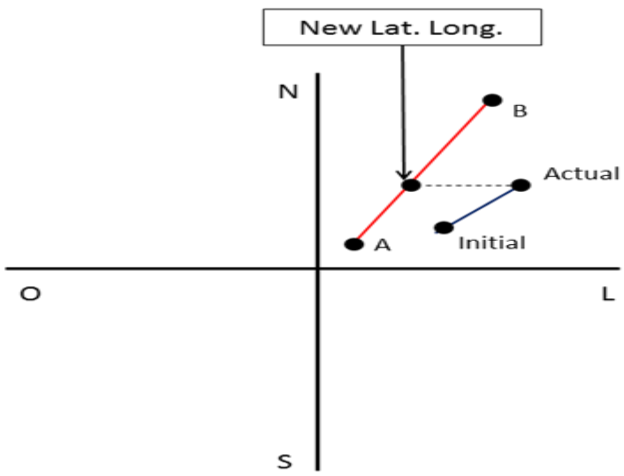


Figure 12 - Calculation of the new Latitudes and Longitudes.

$$Latnova = \operatorname{asin}\left(\sin(latatual) * \cos\left(\frac{S}{R}\right) + \cos(latatual) * \sin\left(\frac{S}{R}\right) * \cos(\alpha)\right) \tag{5}$$

$$Longnova = longatual + \operatorname{Atan2}\left(\cos\left(\frac{S}{R}\right) - \sin(latatual) * \sin(Latnova), \sin(\alpha) * \sin\left(\frac{S}{R}\right) * \cos(latatual)\right) \tag{6}$$

Where:
$R = 6371 * 10^3\ m$ that is the approximate radius of the earth
S = Distance that the point should be moved (in meters)
latatual = Actual point latitude
longatual = Actual point longitude
α = The steering angle that the point should be created with respect to the North (in radians)
$Latnova$ = New latitude
$Longnova$ = New longitude

After calculating the actual position of the vehicle, the program recreates a GPGGA (Global Positioning System Fix Data), and the GPVTG (Track Made Good and Ground Speed) strings, and sends them to the controller.

Besides the above computation, the algorithm also defines how much the point should be moved. For this, the algorithm measures the distance between the machines, the distance from the AB line (Dpr), and the values from past performances. If the distance measured by the sensor was equal to the offset, the new position was coincident with AB line; thereby there was no correction to be made in the vehicle course If the measurement was different from the offset, the new position was displaced from the AB line with a value equal to the difference between the measured value and the offset; thus, causing the controller to correct the vehicle trajectory bringing it back to the AB line, thereby the difference between the sensor's reading and the desired position is subtracted.

The vehicle position was updated at 5 Hz which was the frequency set for the GNSS receiver.

In the Figure 13 are presented the screen shot of the Visual Basic.NET developed algorithm.

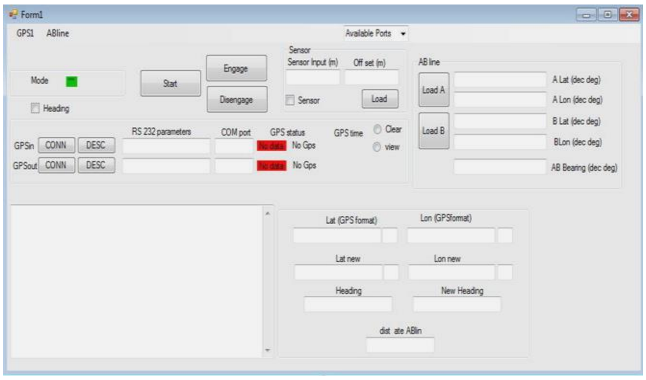


Figure 13 - Program developed in Visual Basic. NET.

D. *System Evaluation*

To evaluate the developed system, the laser sensor was affixed to the tractor (slave vehicle), and a van was used as the master vehicle, Figure 14.

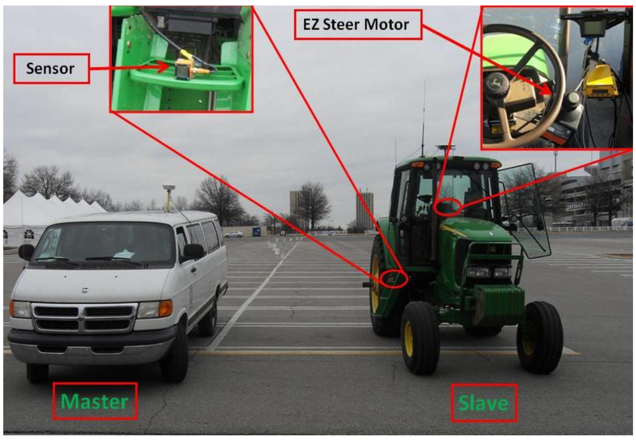


Figure 14 - The assessment test assembly.

First, the two vehicles were placed side by side. Then, the master vehicle (van) performed a straight line path while the offset in the main program was changed once during the journey, causing the tractor to move away from Van towards to the new path determined by the change in the offset distance. Therefore, the settling time and steady state error was determined. The offsets were changed as follows: in the first test, the offset was changed from 2.00 m to 2.40 m, in the second from 2.00 m to 2.60 m, in the third from 2.00 m 2.80, and in the last from 2.00 m to 3.00 m. The tests were conducted in the parking lot located at the University of Kentucky, USA and were repeated five times at an average speed of 4.5 km.h-1.

Testing was performed to verify if the slave tractor would follow the master in a curvilinear path. For that, the van performed a curved path where the slave vehicle followed. These tests were also carried out in the parking lot at the University of Kentucky, USA at an average speed of 4.5 km.h-1. The sensor readings and the offset desired were stored and plotted on a graph.

III. RESULTS AND DISCUSSION

Figure 15 presents the results from laser sensor readings (red line) when the offset (blue line) was changed from 2.00 to 2.40 m.

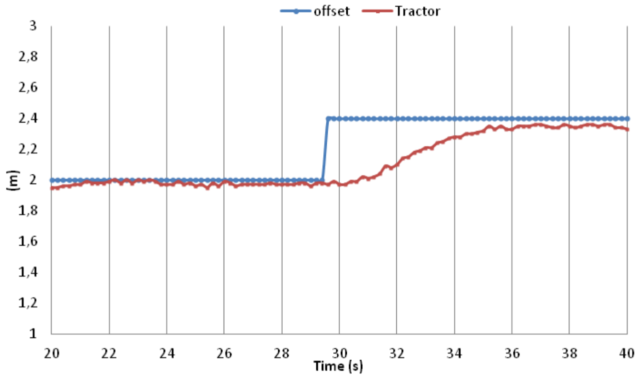


Figure 15 - Control system test when the offset was changed from 2.00 m to 2.40 m.

In Figure 15 it can be observed that tractor followed the offset variation. The average settling time for the five repetitions at this variation was 7.4 seconds with a delay time of 1.7 seconds.

Table 1 shows the descriptive statistics analysis of the real difference between the distances of the two vehicles, and the desired distance for the offset variation from 2.00 m to 2.40 m. The results are presented before and after the excitation.

Table 1 - Descriptive statistics of five repetitions for the 0.4m offset variation

System in steady state	Before the excitation	After the excitation
Average	0.01 (m)	0.02 (m)
Median	0.01 (m)	0.02 (m)
Standard Deviation	0.03 (m)	0.03 (m)
Minimum	-0.06 (m)	-0.07 (m)
Maximum	0.07 (m)	0.07 (m)
Count	218	220

Table 1 Shows that the average values and the median are close to zero, which is the desired value. The absolute average was 0.02 m, and the largest parallelism error found was of 0.07 m.

The Figure 16 presents the results from laser sensor readings (red line) when the offset (blue line) was changed from 2.00 to 2.60 m.

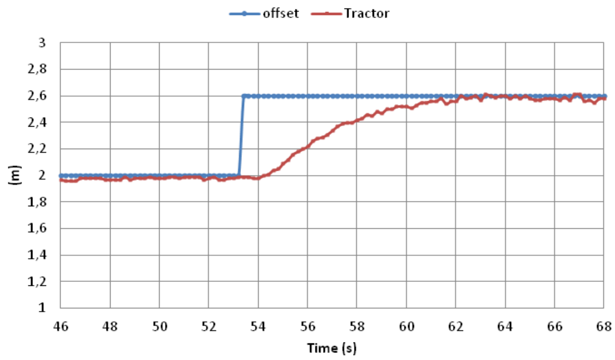


Figure 16 - Control system test when the offset was changed from 2.00 m to 2.60 m.

The average settling time for the variation presented above was of 7.8 seconds with a delay time of 1.7 seconds.

Table 2 presents the descriptive statistics for the five repetitions varying the offset from 2.00 m to 2.60 m.

Table 2 - Descriptive statistics of five repetitions for the 0.6 m offset variation

System in steady state	Before the excitation	After the excitation
Average	0.02 (m)	-0.01 (m)
Median	0.02 (m)	0.00 (m)
Standard Deviation	0.04 (m)	0.04 (m)
Minimum	-0.08 (m)	-0.10 (m)
Maximum	0.10 (m)	0.07 (m)
Count	166	297

In
Table 2 it can be observed that in this case the values of the average and the medians are also close to zero. The absolute average was 0.02 m, and the largest parallelism absolute error found 0.10 m.
In Figure 17 are presented the results from sensor laser readings (red line) when the offset (blue line) changed from 2.00 to 2.80 m.

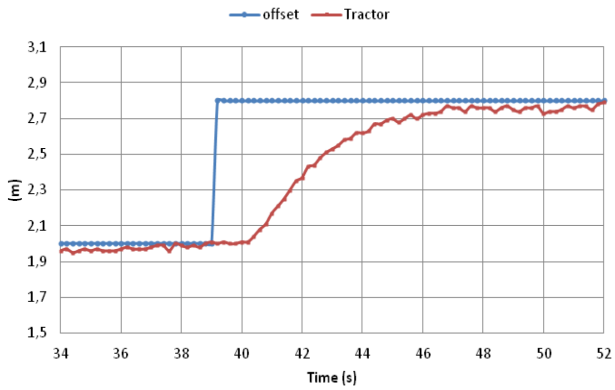


Figure 17 - Control system test when the offset changes from 2.00 m to 2.80 m.

The average settling time for the variation from the Figure 17 was of 7.9 seconds with a time delay of 1.2 seconds.

Table 3 presents the descriptive statistics for the five repetitions varying the offset from 2.00 m to 2.80 m.

Table 3 - Descriptive statistics of five repetitions for the 0.8 m offset variation.

System in steady state	Before the excitation	After the excitation
Average	0.03 (m)	-0.01 (m)
Median	0.03 (m)	-0.01 (m)
Standard Deviation	0.03 (m)	0.04 (m)
Minimum	-0.04 (m)	-0.08 (m)
Maximum	0.09 (m)	0.12 (m)
Count	292	382

The higher absolute average was of 0.03m, and the largest parallelism absolute error found was 0.12 m.
Finally, in the Figure 18 are presented the system response when the offset changed from 2.00 to 3.00 m.

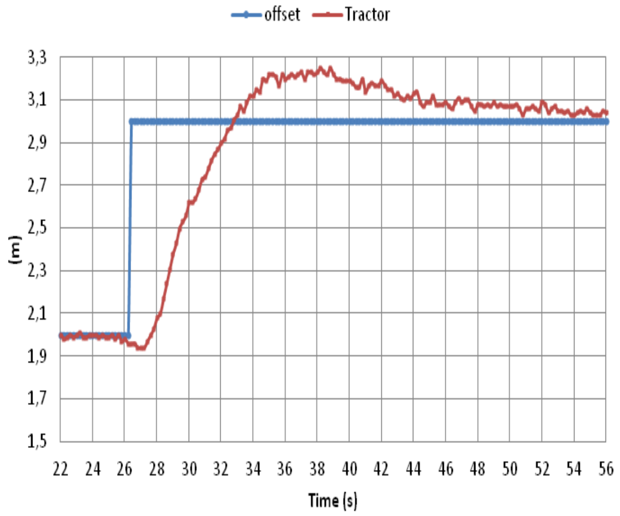
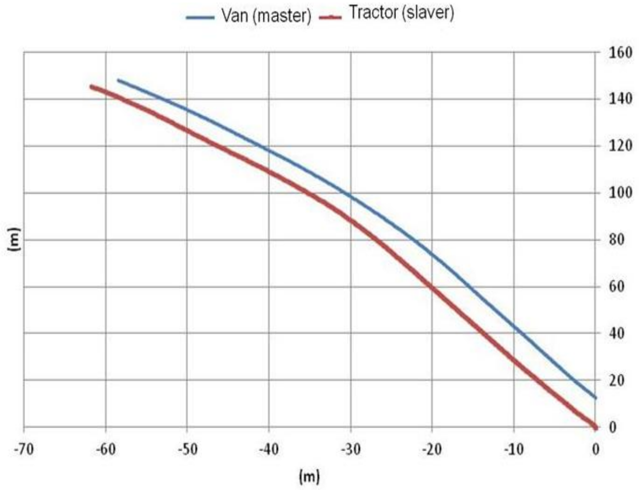


Figure 18 - Control system test when the offset changes from 2.00 m to 3.00 m.

In this case the average settling time was 18 seconds. In this situation, the timing was higher because the system took time to recognize an increase over a meter. Upon recognizing it, the action was very sharp; thus, generating an overshoot that increased the settling time.
All tests performed with degree excitation showed delay time of around a second. This reaction time was caused by the Trimble controller software, which follows a set routine to recognize an unexpected point. In preliminary tests the delay time was even greater; this problem was alleviated by changing the first value of the GPVTG string, which is responsible for the information from the vehicle's steering angle. This value was changed along with the new point; thus, the newly created latitude and longitude became more reliable for the autopilot controller.
Figure 19 (a) presents the graph of the tests performed with the master vehicle in a curvilinear trajectory where the Van (blue line) followed a curve path with the tractor (red line) following its trajectory. The Figure 19 (b) illustrates the two vehicles trajectory, held in the parking lot at the University of Kentucky.



(a)

(b)

Figure 19 - Control system response in curved paths.

In the Figure 20 are presented the differences between the distance measurements captured by the laser sensor and the desired offset.

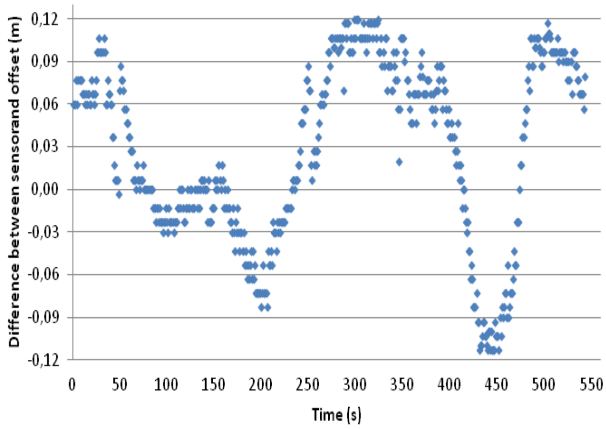


Figure 20 - Difference between the distance measurements captured by the laser sensor and the desired offset.

Note that the developed steering system's attempt to maintain the distance between the vehicles in the offset value. Ideally for this graph, the points would stay close to zero.

Table 4 shows the descriptive statistics of the differences concerning the distances measured by the sensor, and the desired parallelism between the machines (offset).

Table 4 - Descriptive statistics of the difference between the distances measured by the sensor and offset

Difference between the sensor readings and the offset	
Average	0.028 (m)
Standard Err	0.003 (m)
Median	0.037 (m)
Standard Deviation	0.063 (m)
Sample Variation	0.004 (m)
Minimum	-0.113 (m)
Maximum	0.120 (m)
Count	543

Note that the average values stayed close to zero, which was the desired value, and the maximum parallelism error during the course was of 0.12 m. Whereas the average value of a wagon's tire width is of 0.6 m and the sugarcane crop is planted with 1.5 m of space between the sugarcanes, 0.9 m is left for the tractor's tire movement between the plants. Therefore it is assumed that the tire has a total of 0.3 m room for steering errors, with 0.15 m on each side. With these data it can be considered that the 0.12 m maximum error is acceptable, since it is within the allowable error.

IV. CONCLUTION

It was concluded that the objective was successfully achieved, once the slave vehicle's autopilot began to operate based on the master vehicle's position. The average settling times were of 7.7 seconds, and the maximum steady state error average was of 0.07 m and maximum steady state error during all the trajectories was of 0.12 m. One can consider this error as acceptable for farming operations, e.g., during the sugarcane mechanical harvesting, where the deviation up to 0.15 m does not affect the operational performance of the harvester/wagon combination. Moreover, both the settling time and the steady state error were limited to the response from the autopilot system itself.

REFERENCES

[1] BERGLUND, S.; BUICK, R. Guidance and automated steering drive resurgence in precision farming. In: EUROPEAN CONFERENCE ON PRECISION

[2] MAGALHÃES, P. S. G.; BALDO, R. F. G.; CERRI, D. G. P. Sistema de sincronismo entre a colhedora de cana-de-açúcar e o veículo de transbordo. Engenharia Agrícola, v.28, n.2, p.274-282, 2008. Disponível em: <www.scielo.br/scielo.php?script=sci_arttext&pid=S0100-69162008000200008> Acesso em: 28 out. 2011. doi: 10.1590/S0100-69162008000200008

[3] OLIVEIRA, T. C. A. Estudo sobre desempenho de sistemas de piloto automático em tratores. 2009. 68 f. Dissertação (Mestrado) - ESALQ, Piracicaba, 2009

[4] BALDO, R. F. G.; MAGALHÃES, P. S. G. Sistema de controle de velocidade sincronizada entre dois veículos agrícolas. Ciência Rural, Brazil, v.42, f.2 p.298-304, 2012. doi: 10.1590/S0103-84782012005000001

[5] ROVIRA-MÁS, F. Sensor architecture and task classification for agricultural vehicles and environments. Sensors, v.10, n.12, p.11226-11247. Disponível em: <http://www.mdpi.com/1424-8220/10/12/11226> Acesso em: 28 out. 2011. doi: 10.3390/s101211226.