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Guidance Directrix Generation Using Laser Sensors

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Abstract. *A sensor array consisting of two laser sensors was utilized to determine the guidance directrix (offset distance-d, heading angle-ø) that are required as reference inputs for an automated guidance system. The sensor array was evaluated in both laboratory and field conditions. Under laboratory conditions the sensor array replicated the physical profile of the target surface with a 4% error in determining the heading angle. Field tests were conducted in two types of crops; corn and alfalfa. The sensor array identified the cut-crop edge profile ahead of the tractor and replicated distinct shapes of the cut-crop edge. RMSE values in determining the offset distances and heading angles of the cut-crop edge in corn were within 5.5 cm and 4.39^{o}. In the case of alfalfa cut-crop edge the RMSE values were within 6.6 cm and 4.32^{o}.*

Keywords., , **Automated Guidance, RTK-GPS, Cut-Crop Edge, Agricultural Combines, Forage HarvestingIntroduction**

A key component of contemporary agriculture is the deployment of automated guidance for accomplishing improved application of inputs and crop harvesting. Depending on the type of sensor used, automated guidance systems can be classified into satellite based systems and non-satellite based systems. These systems use the Global Position System (GPS) and vision or ranging sensors (cameras, infra-red, ultrasonic sensors), respectively

O'Connor et al. (1995) utilized a satellite based system where he used a four antenna carrier phase GPS system for guiding a John Deere 1880 tractor on prescribed straight row courses with headland turns. For a typical farmer, the most significant limitation to implement automated guidance is the availability of accurate horizontal positioning information (< 2 cm absolute). Real time kinetic (RTK) GPS systems provide high levels of accuracy and they cost in excess of $25 K (U.S.). RTK GPS requires the end user to locate and maintain a GPS base station to generate real-time correction information for the roving receivers. Availability of the correction information is further complicated by the need to communicate this data wirelessly. For producers that rely on RTK GPS anything less than 99.9% availability hampers their ability to complete field operations in a timely fashion. Providing the RTK GPS availability is resolved, concerns remain with regard to the horizontal accuracy of tractor guidance, especially over rough terrain.

Non-satellite based systems came in to existence for implementing automated guidance particularly in row crops and to reduce the cost by eliminating the dependency of guidance system on satellites. Some researchers used machine vision sensors in combination with low cost GPS systems to improve the accuracy of their automated guidance system. Special purpose cameras developed from standard sensors with optical filters were used by Reid and Searcy (1987) to implement automated guidance. Image processing techniques were applied to the output signals of vision sensors to obtain useful information for guidance (Gerrish and Surbrook, 1984; and Gerrish and Stockman, 1985). Machine vision systems act as heading sensors which provide information about the relative positioning between the vehicle and a row of crop. Specifically, machine vision systems are used to generate guidance parameters (heading angle, ø, and offset distance, d) which act as target or reference inputs for an automated guidance system. Although, machine vision systems have a good potential to either replace or complement satellite based guidance systems, they were found to be computationally complex and time consuming which eventually added to the existing costs of the sensors.

One approach to solve the above noted problems is the adoption of off-the-shelf, low-cost sensing technologies to generate guidance parameters by sensing the cut-crop edge. The sensing technologies considered for this project are mature technologies in the manufacturing sector.

Objectives

The main objectives of this study were:

- To evaluate the utility of off-the-shelf low cost laser sensors for automated guidance
- To test the laser sensor array in laboratory and field conditions
- To generate guidance parameters (heading angle, ø; offset distance, d) which are used as desired reference inputs for automated guidance systems
- To evaluate the performance of laser sensor array in generating guidance parameters in two types of crops (corn and alfalfa) at different speeds of operation.

Materials & Methods

Guidance parameters are the reference inputs required to implement a typical row-crop automated guidance. For the autonomous vehicle to follow a target crop row, two parameters have to be known; the distance from the datum crop row and the heading angle (Tillet, 1991). Accurate estimation of these parameters namely, Ooffset distance (d) of the machine from a datum crop row and heading angle (ø) are critical parameters to accurately guide the autonomous vehicle. An off-the-shelf laser sensor which is predominantly used in the manufacturing sector is considered for this study. An array of two laser sensors was used to determine the guidance directrix for both laboratory and field investigations. The laser sensor used was O1D100 manufactured by Ifm-efector, Inc. (Exton, PA) which had a sensing range of 20 to 1000 cm.

Sensor Calibration & Evaluation

The laser sensor operates on the time-of-flight principle; the travel period for reflected light returned from the object is directly proportional to distance. The light source is a 4.1 mW, class 2 laser with a wavelength of 650 nm pulsed at 1.3 ns. This sensor is priced at $350 (U.S.) retail and has an accuracy of 3.5 cm within the operating range of the sensor. Calibration of the sensor was accomplished by aligning the sensor perpendicular to a solid surface target at distances ranging from 50 cm to 900 cm in steps of 50 cm. Sensor voltages were averaged over a 5 s period at each distance and plotted as a function of the actual distance. The resulting calibration curve was linear with a coefficient of determination of r^2 =0.999 and can be seen in figure 1.

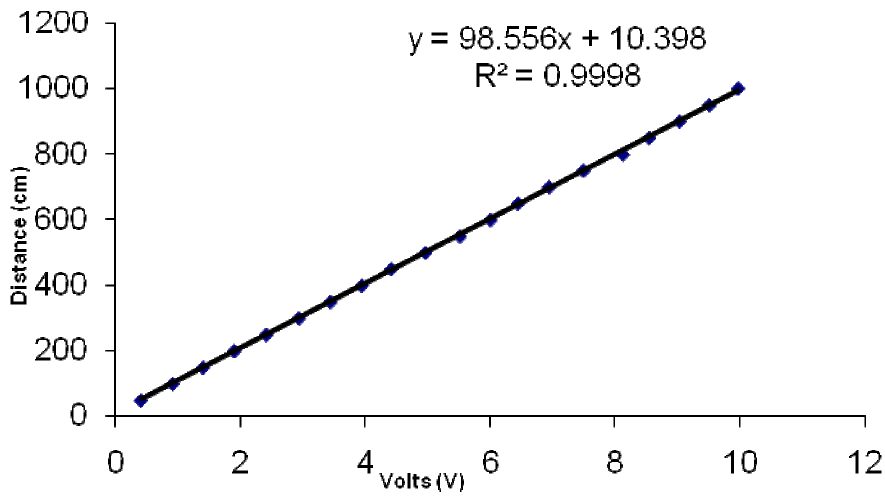

Figure 1. Calibration of the model O1D100, Ifm-efector, Inc. laser sensor.

Laboratory Testing

Procedures

Two laser sensors were spaced 30.5 cm (1.0 ft) apart and mounted on a rectangular steel bar which in turn was attached to a movable test fixture (fig. 2). The test fixture moved the sensor array along the track in a straight line at a constant speed of 0.6 km/hr perpendicular to the laboratory target. The laboratory target was made with cardboard which had parallel and nonparallel surfaces with respect to the sensor path.

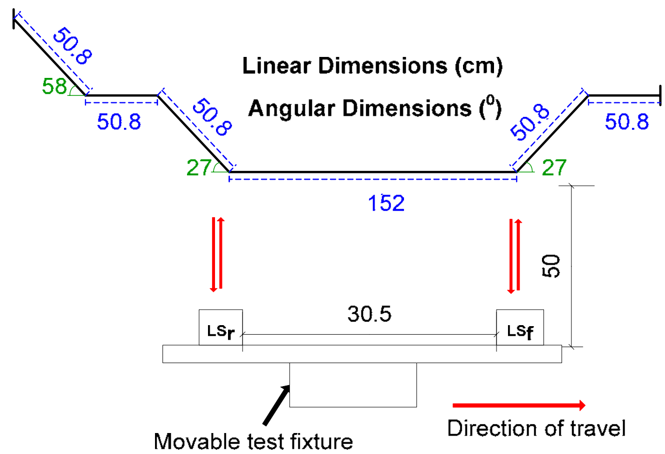

Figure 2. Laboratory test set-up.

The ranging output d_f from the front sensor (LS_f) and d_r from the rear sensor (LS_r) were digitized and stored using a 12-bit A/D card at a sampling frequency of 1000 Hz for each test run. The sensor was spaced at a distance of 0.50 m from the nearest parallel edge of the laboratory target. The intent was to detect different angled surfaces and reproduce the physical profile. The orientation of the non-parallel surfaces was at an angle 27.0° to the primary parallel surface.

Guidance Directrix Estimation Method

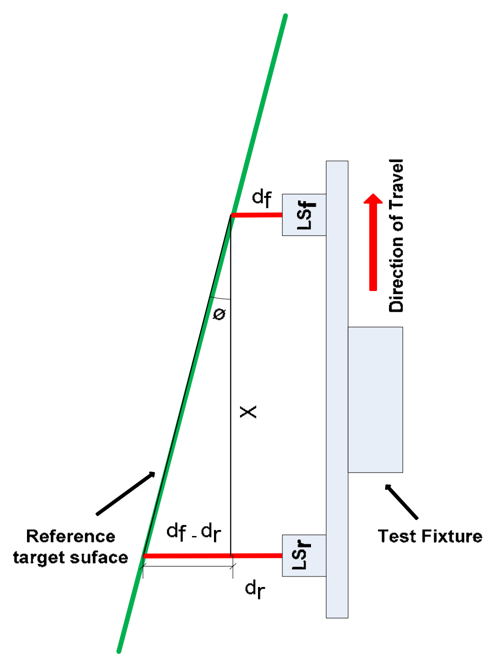

Figure 3. Guidance directrix estimation

To determine the guidance directrix, distance output (d_f) from front laser sensor (LS_f) and distance output (d_r) from rear laser sensor (LS_r) were used. The two sensors provide distance outputs d_f and d_r, respectively upon sensing a target surface. The distances given by two sensors are approximately equal when the test fixture is traveling parallel to the target surface. When the test fixture is non-parallel (fig.3) to the reference target surface and vice versa, the distance outputs are not equal and the difference of the distance outputs from the two sensors can be used to determine the heading angle (ø) using equation 1.

$$\text{Tan}(ø) = (d_f - d_r)/X \qquad (1)$$

Where,

ø = Heading error angle (deg)

d_f = Offset distance output (cm) given by LS_f

d_r = Offset distance output (cm) given by LS_r

The numerator of equation (1) becomes negative when the target surface is closer to the front sensor (LS_f) than the rear sensor (LS_r). The text fixture was mounted to a garage opener for conducting the test run in the laboratory and was placed at a constant distance of 50 cm from the parallel straight edge of the target as shown in fig. 2. Distance outputs ($d_{f,}$ d_r) were collected at a frequency of 1 kHz.

Field Testing Procedures

The laser sensor setup used for laboratory testing was attached to the mounting bracket (fig.4) on the tractor to provide ranging measurements perpendicular to the direction of travel in the field.

Figure 4. Sensor setup (top-left); Corn cut-crop edge (top-right); Sensor with RTK-rover vertically above the sensors (bottom-left); RTK-Base station (bottom-right)

A modification to the orientation of the front sensor (LS_f) was made for field testing. The front laser sensor (LS_f) was oriented at an angle $\alpha = 45^0$ with respect to the direction of travel. This modification to the orientation of the sensor was made to predict the profile of the cut-crop edge ahead of the tractor. Hence for the entire field tests the front sensor (LS_f) was placed at $\alpha = 45^0$ to the direction of travel and the rear sensor (LS_r) was placed perpendicular to the direction of travel (fig.4 –lop left). Cut-crop edges were created in two types of crops; corn and alfalfa, to evaluate the performance of laser sensors. RTK-GPS antenna (fig.4 bottom left) was mounted directly above the sensors to record the actual path of sensors for each test run. The sensor path was a straight line located at a constant offset distance from the nearest straight cut-crop edge. The offset distance was 0.38 m for corn and 0.30 m alfalfa. The sensor response was evaluated at tractor speeds of 3.2, 6.4 and 9.6 km/h. A pole–mounted RTK GPS receiver was used to record the spatial coordinates of the actual cut-crop edges (corn and alfalfa). GPS coordinates from the tractor path and cut-crop edge were projected from decimal degrees to Cartesian coordinates to compare sensor response to the profile of the cut-crop edge.

Directrix Estimation from Forward Sensing Array

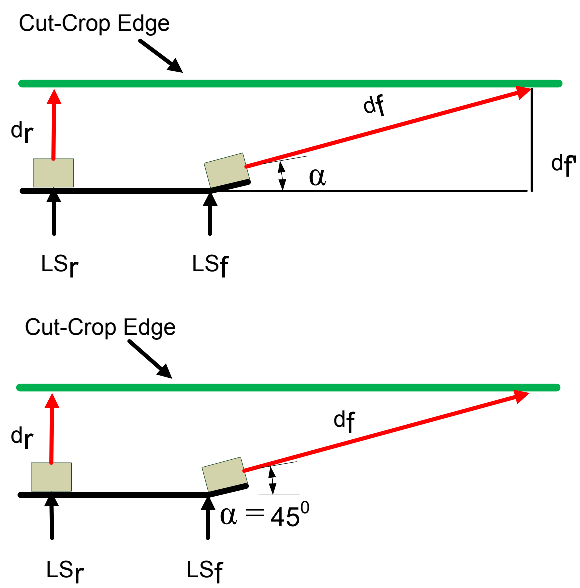

Figure 5. Forward sensing laser array.

Corrected offset distance,

$$\mathbf{df' = df\sin(\alpha)}$$

(2)

Heading Angle

$$\phi = \tan^{-1}\left[\left(\frac{\mathbf{df' - dr}}{\mathbf{X}}\right)\right] \qquad (3)$$

d_f = distance output (cm) given by sensor in front (LS_f)

$\mathbf{d_f'}$ = corrected offset distance

d_r = offset distance output (cm) given by rear laser sensor (LS_r)

α = angle of operation of the front sensor (LS_f)

x = spacing between the sensors = 0.3 m

Since the front laser sensor is oriented at angle of 45^o with respect to the direction of travel , the expression to determine the heading angle (equation (1)) is replaced by equation (3). The front laser sensor output ($\mathbf{d_f}$) needs to be corrected to determine the heading angle of the cut-crop edge ahead of the tractor. From simple geometric analysis (fig. 5) the corrected offset distance ($\mathbf{d_f'}$) is given by equation (2). The corrected offset distance ($\mathbf{d_f'}$) is the offset distance of the cut crop edge ahead of the tractor. Thus, $\mathbf{d_f'}$ and offset distance output (d_r) given by the rear laser sensor (LS_r) will be utilized to calculate the heading angle of the cut crop edge ahead of the tractor.

Data Processing and Filtering

The laser ranging device measurements for all the cut-crop edges were recorded at 1000 Hz and hence there were 1000 measurements corresponding to one set of RTK GPS (1 Hz) coordinates acquired from the tractor mounted rover GPS. The RTK GPS coordinates of the cut-crop edge profile were collected with a pole-mounted receiver moved manually along the cut-crop edge. Data were logged at a frequency of 1Hz. The cut-crop edge profile and tractor paths were rotated with respect to a common reference point on the tractor path to simplify analyses. The origin of the coordinate system was aligned on the tractor path with x-axis oriented along the direction of travel of the tractor and y-axis perpendicular to the direction of travel. Comparison of the sensor's distance output (d) with the actual cut-crop edge profile required interpolation of the x coordinates of the tractor path to equal the x coordinates of the cut-crop edge. The distance output from the sensor can be compared to the y' coordinate of the cut-crop edge only if the magnitude of x coordinate on the tractor path is same as the magnitude of x coordinate on the cut-crop edge.

Fewer GPS coordinates were recorded for the tractor path because of the higher speeds of operation when compared to the number of coordinates recorded for the cut-crop edge. The cut-crop edge data were collected by walking along the track and hence there were two data arrays with different sizes to be compared. Also, each GPS coordinate pair on the tractor path had 1000 laser sensor measurements tagged to it. Thus, Interpolation was done between successive GPS coordinate pairs along the tractor path to obtain unique x-coordinates for each distance measurement recorded from the ranging devices. After interpolation, to eliminate laser sensor measurements with high magnitudes, the ranging data were first clipped using a threshold distance of 700 cm. In addition to clipping, a moving window of size 50 was considered and minimum distance measurement within this window was stored in a separate array along with the corresponding RTK-GPS coordinates. The resultant array from the tractor path was then compared to the RTK-GPS coordinates of the cut-crop edge to match the x' coordinates. Finally, a comparison was made between the sensor's distance output and the y' coordinates of the cut-crop edge profile using the common 'x' coordinates. .

After the successful comparison of actual cut-crop edge profiles with the response of laser sensors, heading angles were calculated by utilizing d_f' and d_r. The calculated heading angles were compared to the actual heading angle of the cut-crop edge.

Results & Discussion

Lab Testing

Figure 6 provides the ranging output from the laser sensor array (d_f (red), d_r (blue)) and heading angle profile (green) after performing a moving average filter with a window size of 10. The sensors were able to detect both the angled and the straight surfaces. The straight edge profile and the two angular edge profiles were replicated by the sensor and were comparable to the actual target cardboard surface.

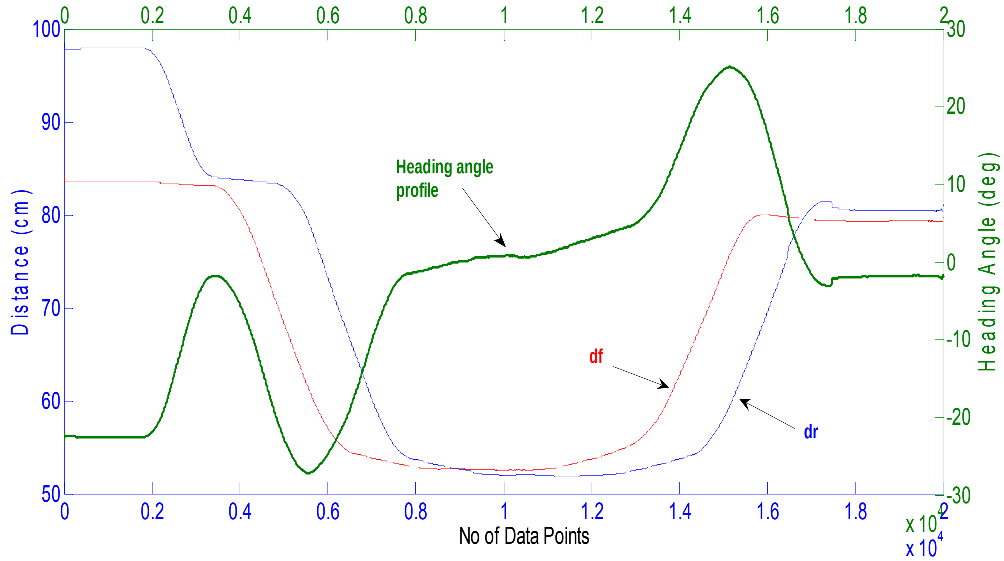

Figure 6.Offset distance outputs **(**$d_{f,}$ d_r**)** and heading angle profile of the target surface generated by the laser sensors

Figure 7. depicts the sensor array output and desired heading angle for the left angled surface of the laboratory target. The distance outputs (d_f (red), d_r (blue)) between the dotted straight lines (fig. 7) were considered to calculate the heading angle. The average heading angle (ø) thus obtained (in green) was close to 28°. The percent error in measuring the angle of the left angled surface was approximately 4%. The right angled edge of the target surface can be seen in fig. 8. Similarly, the percent error in measuring the heading angle of the right surface (fig. 8) was approximately 4%.

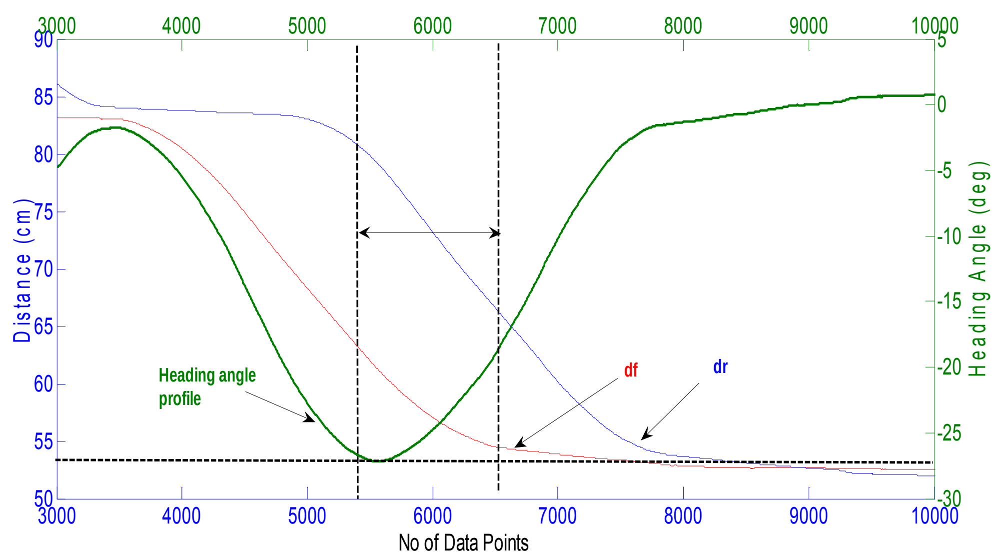

Figure 7. Offset distance outputs ($d_{f,}$ d_r) and heading angle profile of the left angled segment of target surface generated by the laser sensors.

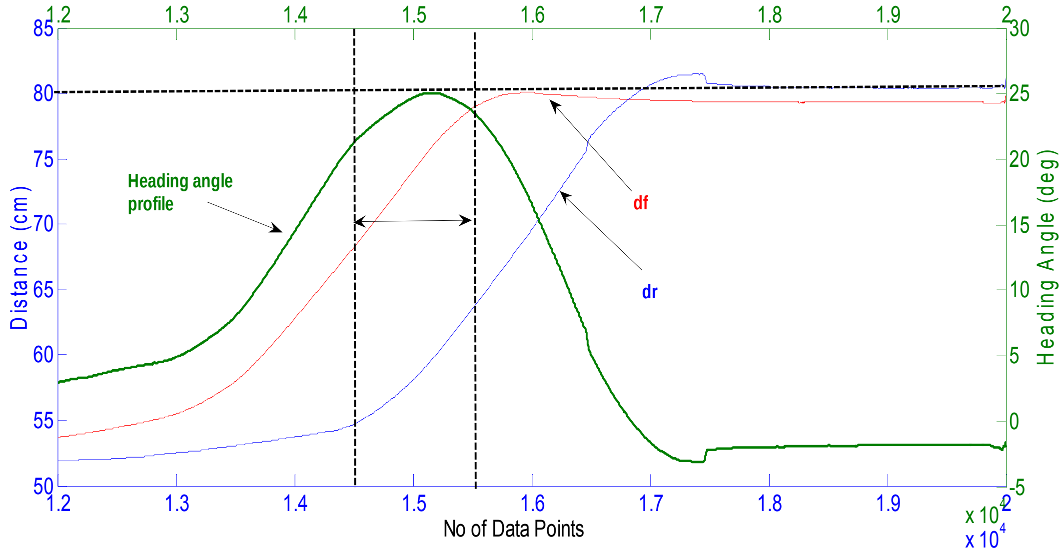

Figure 8. Offset distance outputs (d_f , d_r) and heading angle profile of the right angled segment of target surface generated by the laser sensors.

Field Testing

RTK-GPS coordinates from the cut-crop edge and the sensor path were exported to GIS and shape files were created to compare the location of the sensor path to the cut-crop edge location. GPS coordinates of cut-crop edge were rotated with the tractor path as the reference axis. A sample shape file created from corn cut-crop edge can be seen in fig. 9. It is evident that the density of data is high for the cut-crop edge as the data was collected manually by walking along the crop edge whereas the data for sensor path was collected by a rover receiver mounted on a tractor moving relatively at high speeds.

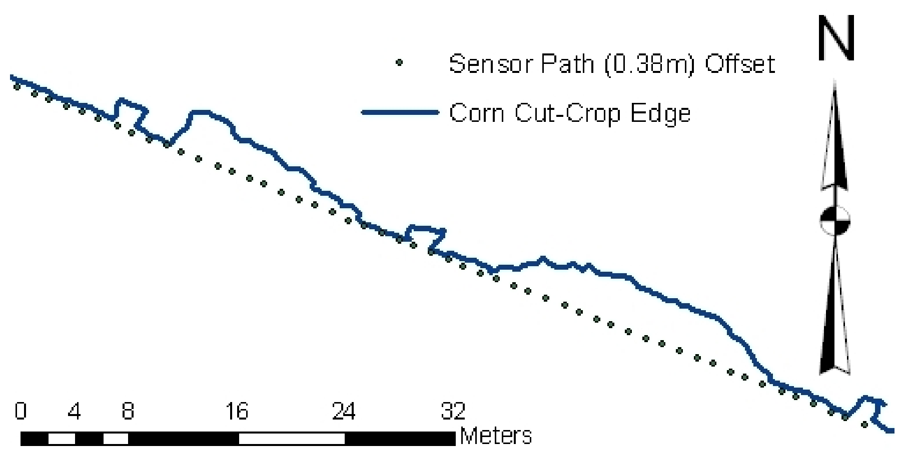

Figure 9. Actual cut-crop edge and sensor path obtained from RTK-GPS coordinates.

Sensor Response Evaluation

Crop type: Corn

Before evaluating the response of the sensor it is important to know if the front sensor placed at an angle of $\alpha = 45^o$ is able to identify the cut-crop edge ahead of the tractor. To determine this, the corrected offset distance d_f' is compared to the actual cut-crop edge. Figure 10 provides a comparison of the corrected offset distance d_f' (red) and the actual cut-crop edge (blue). This comparison clearly indicates that the response of forward looking sensor resembles the actual cut-crop edge profile ahead of the tractor.

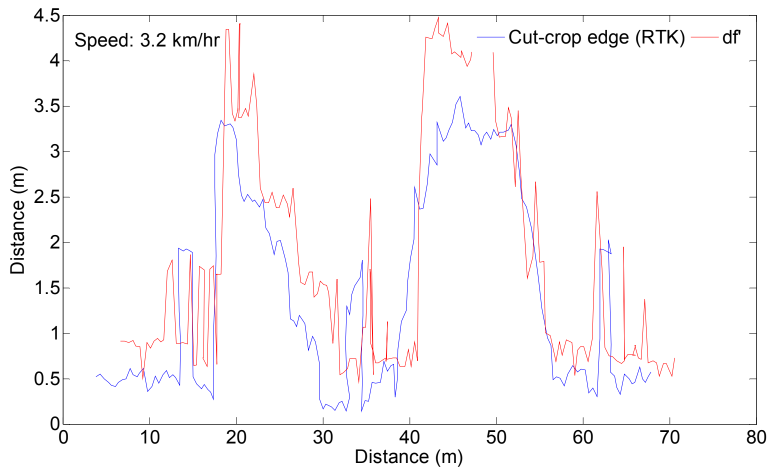

Figure 10. Comparison of d_f' ($\alpha = 45^0$, 0.38 m offset at 3.2 km/h) and actual corn cut-crop edge.

A moving average filter was applied to smooth the corrected offset distance d_f' and the resultant sensor output profile d_f' (mvg) (red) and the actual cut-crop edge (blue) is provided in fig. 11.

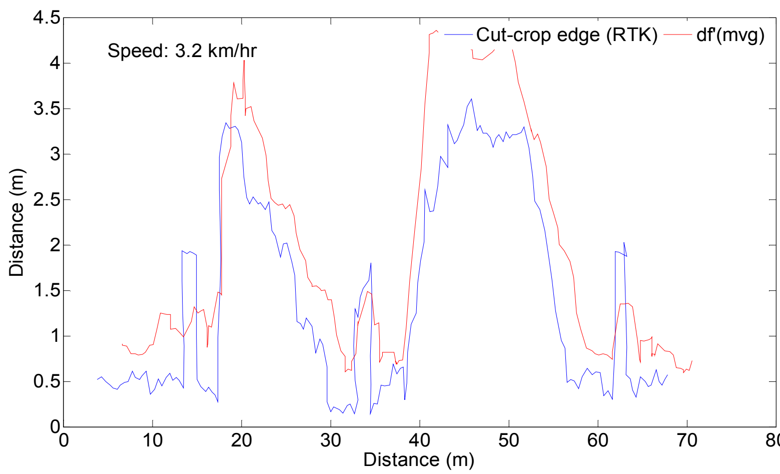

Figure 11. Comparison of d_f' moving average d_f' (mvg) ($\alpha = 45^0$, 0.38 m offset at 3.2 km/h) and actual corn cut-crop edge.

The corrected offset distance (d_f') and the offset distance output given by the rear laser sensor (d_r) were utilized to determine the heading angle using equation (3). The heading angle HA - s determined from d_f' and d_r is compared to the heading angle (HA - RTK) determined from RTK-

GPS coordinates of the cut-crop edge. A comparison of HA - s (red) and HA - RTK (blue) for corn cut-crop edge at a tractor speed of 3.2 km/h can be seen in figure 12.

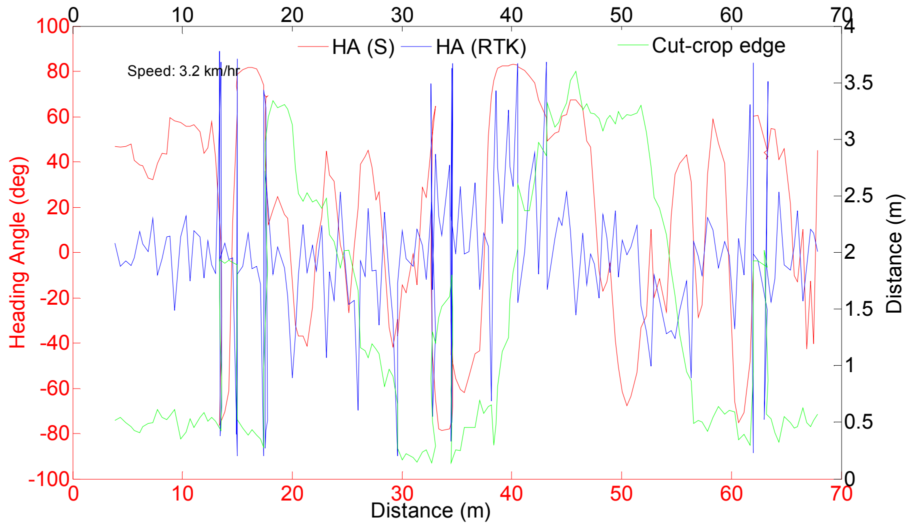

Figure 12. Comparison of heading angle (HA - s) determined from d_f' and d_r to the heading angle HA (RTK) determined from actual corn cut-crop edge (α = 45^0**,** 0.38 m offset at 3.2 km/h).

Offset distance (d_f' **)** and heading angle (HA - s) profiles were determined for different speeds of operation. Root mean square error (RMSE) between d_f' and actual cut-crop edge (RTK), Heading angle HA - s and HA - RTK was found and tabulated in table 1. Tractor speed of 9.6 km/h yielded the least RMSE offset distance of d_f' = 4.0 cm whereas tractor speed of 6.4 km/h yielded the least RMSE heading angle of ø = 3.75^0**.** No particular trend in RMSE values of heading angle (ø) was observed in the RMSE values with increasing tractor speed. A decrease in RMSE values of offset distance (d_f') was observed with increase in speed.

Table 1. RMSE values: Corn cut-crop edge

Sensor Speed (km/h)	0.38 m Sensor Offset	
	RMSE Offset distance, d_f' (m)	RMSE Heading angle, ø (deg)
3.2	0.055	4.39
6.4	0.045	3.75
9.6	0.040	4.10

Similar procedure for calculating the offset distance (d_f') and heading angle (HA - s) was followed for evaluating the sensor response in alfalfa crop.

Crop type: Alfalfa

In the case of alfalfa crop the forward looking sensor was able to identify the cut-crop edge ahead of the tractor. Figures 13 and 14 provide a comparison of the corrected offset distance d_f' (red) and the actual cut-crop edge (RTK) (blue), corrected offset distance with moving average and the actual cut-crop edge (RTK) (blue).

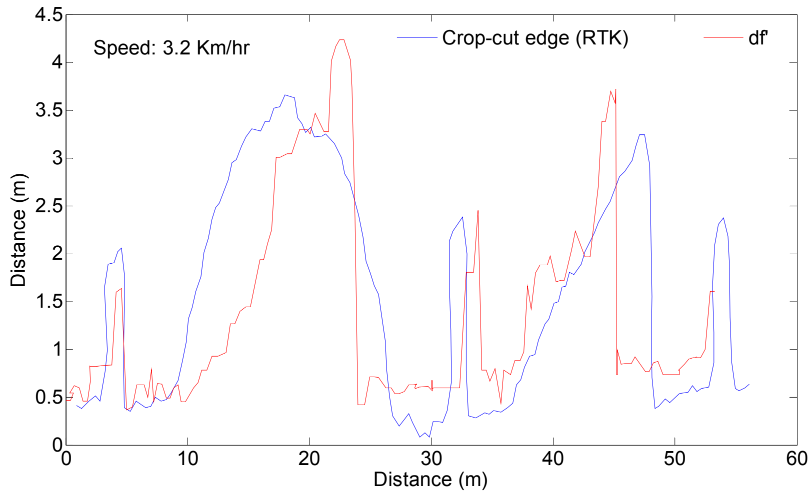

Figure 13. Comparison of d_f' (α = 45°, 0.38 m offset at 3.2 km/h) and actual alfalfa cut-crop edge.

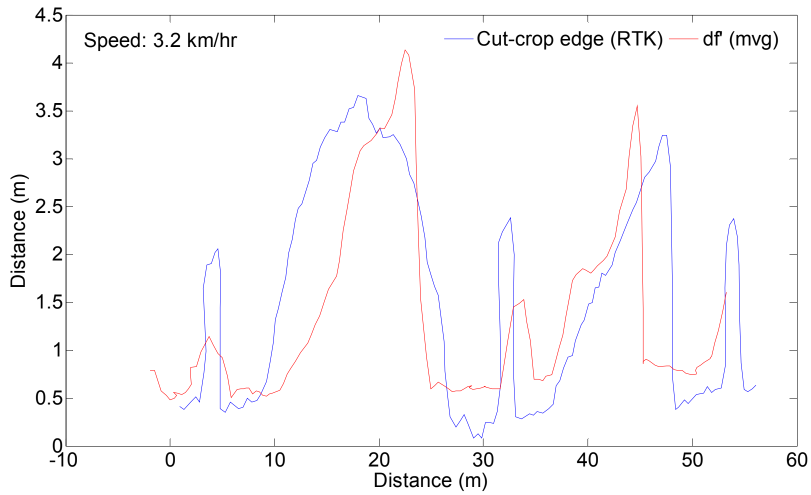

Figure 14. Comparison of d_f' **with** moving average d_f' (mvg) (α = 45^0, 0.38 m offset at 3.2 km/h) and actual alfalfa cut-crop edge.

Offset distance (d_f' **)** and heading angle (HA - s)) profiles were determined for different speeds of operation. Root mean square error (RMSE) between d_f' and actual cut-crop edge (RTK), Heading angle HA - s and HA - RTK were found and tabulated in table 2.

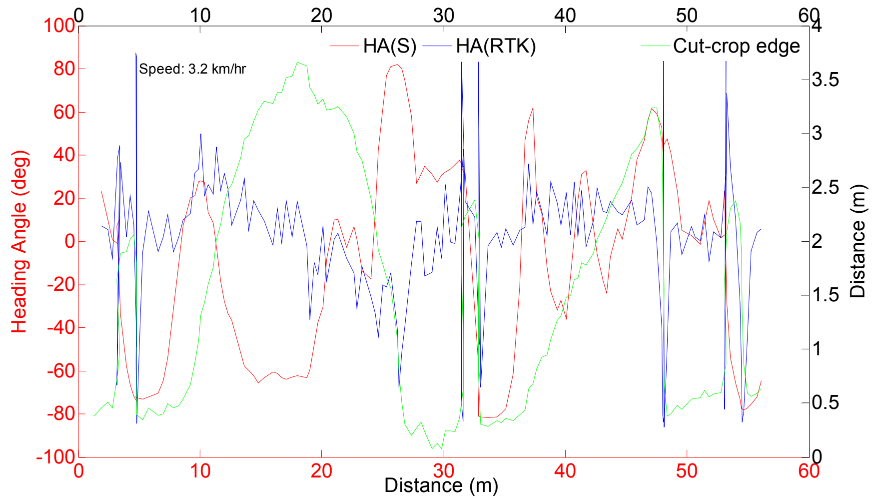

Figure 15. Comparison of heading angle (HA - s) determined from d_f' and d_r to the heading angle HA (RTK) determined from actual corn cut-crop edge (α = 45^0, 0.38 m offset at 3.2 km/h).

Tractor speed of 6.4 km/h yielded the least RMSE offset distance value of d_f' = 4.9 cm whereas tractor speed of 9.6 km/h yielded the least RMSE heading angle value of ø = 3.25^0**.** No particular trend in RMSE values of offset distance (d_f') was observed in the RMSE values with increasing tractor speed. A decrease in RMSE values of heading angle (ø) was observed with increase in speed.

Table 2. RMSE values: Alfalfa cut-crop edge

Sensor Speed (km/h)	0.3 m Sensor Offset	
	RMSE Offset distance, d_f' (m)	RMSE Heading angle, ø (deg)
3.2	0.061	4.32
6.4	0.049	3.82
9.6	0.066	3.25

Conclusion

The low cost off-the-shelf laser sensor was evaluated under both laboratory and field conditions. The sensor array sensed the physical profile of the cardboard target surface (laboratory conditions) yielding a heading angle with 4% error. The sensor array was tested under field conditions with corn and alfalfa cut-crop edges at varying ground speeds. The forward looking sensor at an orientation of α = 45^0 identified the cut-crop edge profiles in both corn and alfalfa, making it possible to generate a reasonably accurate guidance directrix. RMSE values in determining the offset distances (d) and heading angles (ø) for the entire field test were within 6.6 cm and 4.39^o, respectively. The sensor array proved to be an effective sensing element for development of a low-cost row crop automated guidance system. The laser sensor array may have the potential to improve the accuracy of automated guidance systems based on low-cost GPS.

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