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Research article

Development of a low-cost driver assistance system for tractors in sugarcane fields using a scanning-laser range finder

Pawin Thanpattranon*, Sirisak Chertkiattipol, Watcharapol Chayaprasert, Wanrat Abdullakasim, Prathuang Usaborisut

Department of Agricultural Engineering, Faculty of Engineering at Kamphaeng Saen, Kasetsart University Kamphaeng Saen Campus, Nakon Pathom 73140, Thailand

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Abstract

Importance of the work: For off-road vehicles, different guidance or positioning systems present different sets of challenges. Scanning-laser rangefinders (SLRs) possess many advantages over other systems, for example the ability to operate in different light conditions, providing high resolution positioning data, robustness against vapor and dust interferences, not requiring many accessories or peripherals and lower equipment costs.
Objectives: To develop and test a low-cost driver assistance system for a tractor.
Materials & Methods: The driver assistance system primarily consisted of a sensor, a guidance algorithm and a graphic user interface display. In principles, the algorithm identified obstacle objects from the laser beams reflected back to the SLR and then recommended steering directions to the driver via the display. In the preliminary trial and first test, the tractor was driven parallel to a straight reference furrow located on the right side of the tractor, simulating a ploughing operation. In the second test, the tractor travelled along a straight path between rows of sugarcanes, simulating a harvest operation.
Results: In the furrow detection test, the system yielded maximum and root-mean-square errors in the ranges 15.80–41.40 cm and 4.55–20.86 cm, respectively. The tracking errors of the sugarcane row detection test were in a satisfying range similar to those found in the furrow slice detection results.
Main finding: With further refinement, the driver assistance system could potentially be used in practice.

* Corresponding author.
E-mail address: fengpwt@ku.ac.th (P. Thanpattranon)

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Introduction

Agricultural practices in Thailand have long relied extensively on heavy machinery, such as for cultivation of sugarcane for the sugar industry that utilizes machinery in every step, from land preparation to harvest. The global positioning system (GPS) was one of the first guidance systems to be implemented for open-field farming equipment and it has been continuously improved until the present day.

Simple GPS systems can be used to guide a human driver manually steering the vehicle along a desired route. The differential GPS (DGPS) system developed by Van Zuydam (1999) guided a drive's steering through a planned path by measuring the actual coordinates of the agricultural implement installed behind the tractor. This DGPS system yielded errors of within 12 cm of the planned path at a speed of 5.2 km/hr. Inoue et al. (1999, 2009) developed a guidance system for a tractor with a rotary tiller based on DGPS, gyroscope sensors and a Kalman filter algorithm. When testing by performing tillage on a 30 m × 100 m plot of land at a speed of 1.25 m/s, a driving accuracy of ±20 cm was maintained. On the other hand, autonomous vehicles require more sophisticated GPS systems. O'Connor et al. (1996) and Bell (2000) successfully developed GPS systems for automatic tractor steering where the deviation for the desired trajectory was less than 2.5 cm. The GPS guidance system developed by Stombaugh et al. (1999) incorporated a feedback controller and was able to steer the vehicle at speeds up to 6.8 m/s with a tolerance of less than 16 cm from the desired path. A real-time kinematic (RTK) GPS system with optical fiber gyroscope sensors has been integrated into an automated rice transplanter (Nagasaka et al., 2004). When tested on a 10 m × 50 m plot of land (6 rows with a 1.8 m gap between rows), the machine finished transplanting rice seedlings in 15 min with a maximum deviation from the desired path of less than 12 cm.

At present, new tractors available in many countries around the world are equipped with steering controls or accessories for automatic steering using GPS. However, the limitations of many GPS systems include their rough resolution. With a nominal GPS signal receiver, the resulting coordinates could have an error of up to 15 m. In order to maintain any errors in a vehicle's coordinates to below 5 cm, an RTK-GPS system, which requires base stations, is needed to accurately measure the vehicle's position. These base stations are located on the ground around the field, sending and receiving coordinate signals to the GPS unit on the vehicle. Then, these signals are used for correcting the vehicle's coordinates in real time before being implemented in the steering algorithm. Nowadays, GPS guidance systems do not cost as much as in the past due to the increased interest in related applications, such as agricultural drones. However, the operating environment of agricultural tractors involves many unpredictable interferences, for example uneven land surfaces, greater vibration or varying loads due to attached implements. Developing steering assistance systems for agricultural tractors based on other sensor technologies is still a compelling alternative.

For off-road vehicles, other types of positioning techniques present different sets of challenges. For tractors in agricultural operations, positioning data obtained by the dead reckoning method are prone to accumulated errors due to vibration and tire/track slips. A guidance system based on image processing often suffers from inconsistent natural light, while ultrasonic sensors are also affected by vapors and dust. Scanning-laser rangefinders (SLRs) have many advantages over other technologies, including: being capable of effectively operating under different light conditions; providing high resolution positioning data; being robust against vapor and dust interference; not requiring many accessories or peripherals; and lower equipment costs (Ahamed et al., 2016).

Ahamed et al. (2006a, b) developed a tractor navigation system using the time-of-flight (TOF) method. An SLR was mounted on a tractor. The researchers measured the time it took for pulse waves to travel from the SLR and then get reflected by surrounding objects back to it. At a test speed of 0.1 m/s on a concrete surface, the system was able to maintain lateral and directional errors below 2 cm and 1°, respectively. Subramanian (2006) tested an SLR-based autonomous guidance system against another system based on image processing installed on the same tractor. The systems controlled the tractor to automatically travel along straight and curved paths made of hay bales. The SLR and image processing systems produced average lateral errors of 2.5 cm and 2.8 cm, respectively, at a speed of 3.1 m/s. The autonomous tractor guidance algorithm developed by Thanpattranon et al. (2015) utilized data from a SLR to calculate safe distances from the tractor to surrounding landmarks along the travel course. The algorithm automatically steered the tractor by following the center line of the course. When tested in straight and curve courses constructed using traffic cones on a concrete surface, the tractor successfully navigated the courses autonomously at a speed of 0.18 m/s. In a follow-up study (Thanpattranon et al., 2016), the algorithm was improved by adding a control scheme for a tractor with a trailer. The improved algorithm maintained lateral errors of both the tractor's and the trailer's positions within 0.275–1.094 m from the desired path. Clearly, these studies on SLR guidance systems had promising results. Thus, the present study aimed to develop a low-cost driver assistance system using an SLR for tractor operations in sugarcane fields.

Materials and Methods

The driver assistance system primarily consisted of an SLR sensor, a guidance algorithm and a graphic user interface (GUI) software window displayed on a screen. The SLR sensor (UTM-30LX; Hokuyo Automatic Co. Ltd.; Japan) used in the present study emits laser beams in a sweeping pattern, namely scanning (Fig. 1A). It has a sweeping angle of 270°, resolution of 0.25° per step (1,080 steps per scan), a scanning frequency of 10 scans/s and a maximum detection distance of 30 m. After the guidance algorithm and GUI window had been completed, the system was installed on a tractor and its performance was tested. The SLR was installed at the front of a 4-wheel drive tractor with a maximum power of 86 HP (Massey Ferguson 390; AGCO Corp.; USA). The base of the SLR was 0.8 m above the ground and the angle of depression (AOD) was adjusted according to the test condition (Fig. 1B). A preliminary trail was conducted and then the system's performance was evaluated in two tests. In the preliminary trial and first test, the tractor was driven parallel to a straight reference furrow located on the right-hand side of the tractor, simulating a ploughing operation. In the second test, the tractor had to travel along a straight path with rows of 2.5–3 m high sugarcane plants on both sides, simulating a harvest operation. All the trial and test replicates were conducted in a sugarcane field belonging to the Department of Agricultural Engineering, Kasetsart University, Kamphaengsaen campus, Thailand (14.03 °N, 99.96 °E). The tractor was operated by the same human driver throughout the study.

Algorithm

Fig. 2 illustrates a flow diagram of the guidance algorithm of the driver assistance system. In brief, the algorithm received distance data from the SLR, identified a suitable travel path and then suggested the turning direction to the driver as a left or right arrow on the GUI window. Both the algorithm and the GUI software window were written in Borland C++ (Version 6.0; Micro Focus International PLC; UK).

The algorithm started with the "Acquire distance data" process. Empty distance data taken from the SLR were in the form of linear distances between the SLR and points from which the laser beams reflected back at all angular steps. By specifying the position of the SLR as the origin on an X-Y plain, these distance data were essentially polar coordinates of all the points in front of the tractor that reflected the laser beams. Then, the polar coordinates were then converted into Cartesian coordinates. Next, the algorithm classified the coordinate data into obstructing objects ("Cluster data and extract objects" process). When at least five adjacent angular steps had empty linear distances within 70 mm of each other, the coordinates associated with these angular steps were grouped together and classified as an obstructing object. Data points that did not adhere to these criteria were not considered an object and omitted from the classification process.

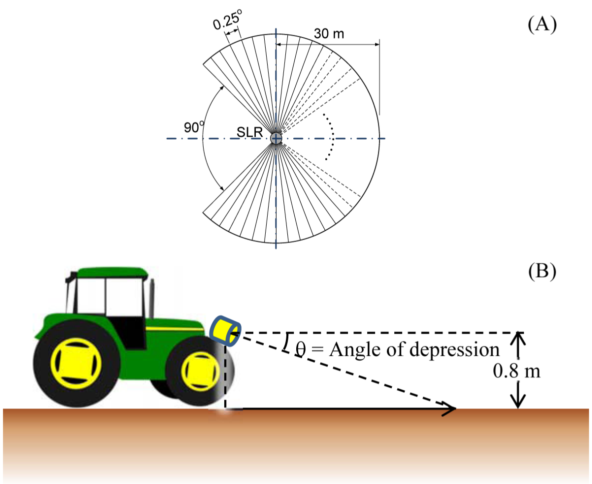

Fig. 1 Diagrammatic representation of: (A) swiping area of a scanning-laser rangefinder (SLR); (B) installation location of SLR

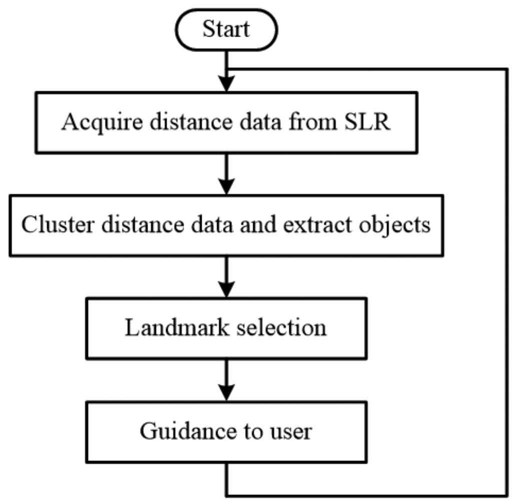

Fig. 2 Flow diagram of guidance algorithm of driver assistance system

Obstructing objects that were too far away could potentially cause inaccurate guidance. In cases when the tractor had to travel straight ahead with a furrow on the right, only four obstructing objects closet to the SLR were assigned as landmarks ("Landmark selection" process). In order to obtain the four closet objects, a bubble-sorting procedure (Stelovsky, 2011) was utilized. After that a linear regression was performed on the coordinate data points of the four landmarks, resulting in an equation describing the reference landmark line. The driver was supposed to steer the tractor while trying to maintain a constant perpendicular offset distance from the furrow within a certain tolerance limit. Thus, in the "Guidance to user" process, two guiding lines, which were parallel to and equidistant from the reference landmark line by the tolerance limit, were displayed on the GUI window. In addition, a left or right arrow was shown when the tractor deviated too close or too far away from the landmark line. The driver had to turn the tractor according to the shown arrow, keeping the landmark line in between the two guiding lines.

In cases when the tractor had to travel in between the rows of sugarcanes, the bubble sort procedure was performed on the coordinate data from both sides of the tractor, resulting in eight landmarks (four on the left and four on the right). Two parallel reference landmark lines were generated, signifying the left and right sugarcane rows. Then, the algorithm determined the middle path between the two landmark lines and displayed it as the guiding line on the GUI window. An arrow was shown when the middle of the tractor deviated from the guiding line by more than the tolerance limit.

Preliminary trial

A preliminary trial was conducted to determine suitable operating conditions for the driver assistance system. A 60 m long straight reference furrow was constructed using the Massey Ferguson 390 tractor equipped with a 3-disc plough. Following the suggestion of the assistance system, the driver had to steer the tractor parallel to the reference furrow, which was situated on the right side of the tractor (Fig. 3). The operating conditions consisted of three factors, namely the tractor's speed, the SLR's AOD and the perpendicular offset distance between the furrow slice and the middle of the tractor. Each of the three factors was divided into three levels: 1) three gear positions (tractor's speeds), namely L2 (below practical speed), L3 (practical speed) and H1 (above practical speed) operated at 1,300 revolutions per minute engine speed; 2) three AODs, namely 10°, 15° and 20°; and 3) three offset distances, namely 1.5 m, 2.5 m and 3.5 m (tolerance limit = ±0.75 m).

Each of the 27 combinations of operating conditions was conducted once. The coordinate data collected from each combination were manually graded and the corresponding combination was given a score from 1 to 5 for each of three categories: 1) detecting distance, so that a combination that could detect further coordinates was given a higher score (weighing factor = 0.35); 2) variability in the coordinate data, so that a combination associated with less varying data was given a higher score (weighing factor = 0.40); and 3) quantity of the detected landmarks, where a combination with a higher number of detected landmarks was given a higher score (weighing factor = 0.25).

$$S = \sum_{i=1}^{3} s_i w_i \quad (1)$$

The final suitability score (S) of each combination of operating conditions was calculated using Equation 1:

where s_i and w_i are the score and weighing factor of each category. All combinations of the operating conditions were rated based on the final suitability score as follows: 1) a score between > 3.8 and 5.0 indicated "suitable"; 2) a score between ≤ 3.4 and ≤ 3.8 indicated "potentially suitable"; and 3) a score between 0 and < 3.4 indicated "potentially unsuitable".

Furrow detection test

The furrow detection test one of the two tests conducted to evaluate the performance of the guidance system. The equipment setup was the same as that in the preliminary trial (Fig. 3). The test conditions consisted of the same three factors as in the preliminary trial; however, the treatment levels of the AOD and offset distance were reduced from three to two levels, so the parameters were: 1) three gear positions (L2, L3 and H1); 2) two AODs (15° and 20°); and 3) two offset distances (1.5 m and 3.0 m) with a tolerance limit of ±0.75 m.

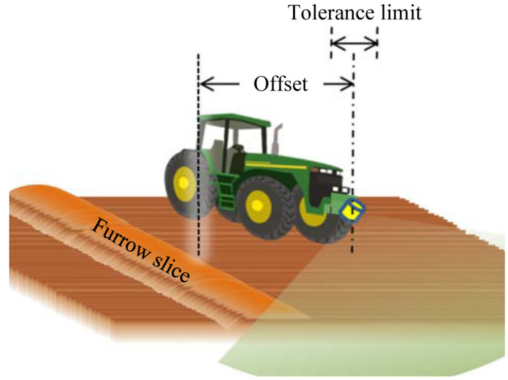

Fig. 3 Schematic diagram of equipment setups for preliminary trial and furrow detection test

Each combination of the test conditions was conducted with three replicates. In each replicate, the driver had to steer the tractor parallel to a reference furrow 30 m in length. The data from the first and last 5 m were not collected as these distances were used for the tractor to reach its constant travelling speed and to slow down at the end of the row, respectively. Thus, the data were collected only for 20 m. As the tractor traveled the 20 m, markings indicating the actual trajectory of the SLR and thus the tractor were made by manually placing a wooden pole on the ground every 1 m behind the tractor. At each interval, the actual perpendicular offset distance from the furrow was measured using a measuring tape and recorded. Thus, the error for each interval was the difference between the actual and desired offsets. Notably, the desired offsets in this test were either 1.5 m or 3.0 m. The performance of the guidance system was evaluated based on the absolute maximum and root-mean-square (RMS) errors calculated from all the interval errors for each replicate.

Sugarcane row detection test

The second performance evaluation test involved driving the tractor along a straight path in the middle between rows of 2.5–3 m high sugarcane (Fig. 4). It was found in the preliminary results that at the 3.5 m offset, the performance of the driver assistance system decreased substantially. Thus, the desired offset distance in the sugarcane row detection test was fixed at 3.0 m with a tolerance limit of ±0.10 m as the distance between the two rows was about 6 m. Since in this test the ground surface was relatively flat and the sugarcane rows formed virtually straight walls on both sides of the tractor, the AOD of the SLR was also fixed at 0° in order to ensure a horizontal line of sight. Therefore, the single factor of the test conditions was the tractor's gear position which had three levels (L2, L3 and H1). The test was conducted with three replicates for each gear position. The travel length for each replicate remained 20 m. The absolute maximum and RMS errors were calculated in a similar manner as in the furrow slice detection test.

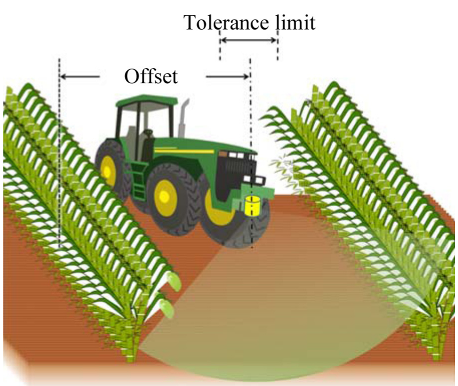

Fig. 4 Schematic diagram of equipment setup for sugarcane row detection test

Results and Discussion

Fig. 5A presentss a photograph of the tractor during the preliminary trial traveling along the reference furrow at an offset distance of 1.5 m. Fig. 5B shows the display located in front of the tractor driver showing the GUI software window during the sugarcane row detection test. An example of the GUI window of the driver assistance system when the tractor traveled parallel to a furrow is illustrated in Fig. 6. The operating conditions were L2 gear, 15° AOD and 2.5 m offset.

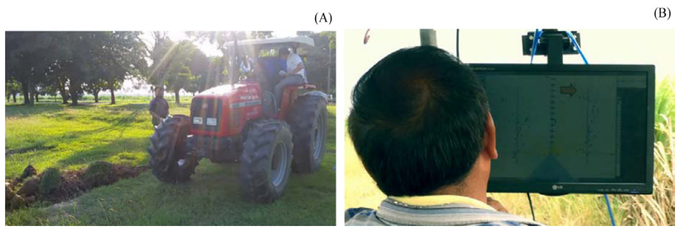

Fig. 5 Photographs of: (A) tractor with SLR being driven along a furrow at 1.5 m offset distance; (B) display located in front of driver showing GUI software window

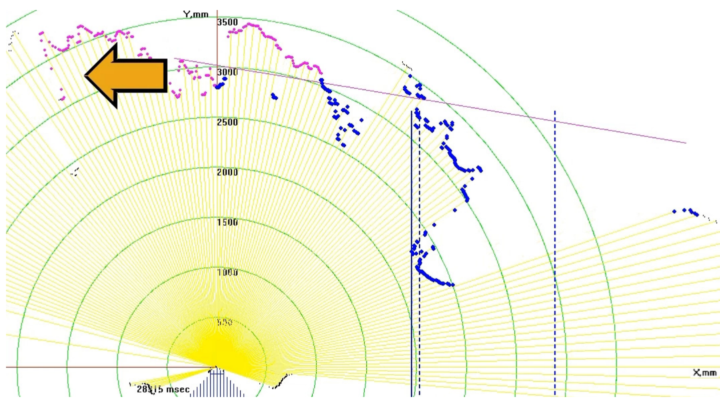

Fig. 6 Example of GUI window of driver assistance system detecting a furrow, where origin (X = 0, Y = 0) is location of scanning-laser rangefinder, blue dots are coordinates of detected obstructing objects, solid blue line is the reference landmark line, dotted blue lines are the guiding lines, Y-axis is the actual forward direction of tractor and orange left arrow indicates suggested steering direction

Notably, from this figure: 1) the tractor was too close to the furrow beyond the tolerance limit; 2) the orange arrow was suggesting the driver to turn left, steering away from the furrow so that the reference landmark line would shift to the right, back between the two guiding lines; and 3) the pink dot and the line indicate the coordinates of the level ground surface in front of the tractor that were omitted by the algorithm.

Preliminary results

The suitability scores of all operating condition combinations are summarized in Table 1. Notably, using L2, L3 and H1 gears, the measured forward speeds of the tractors were approximately 2.0 km/hr, 2.8 km/hr and 5.5 km/hr. Based on the scores in Table 1, the following findings were made: 1) at 3.5 m offset, the operating condition combinations were considered either potentially suitable or potentially unsuitable; 2) using the H1 gear, the combinations were considered either potentially suitable or potentially unsuitable; 3) using the L2 gear (speed ≈ 2.0 km/hr), the scores were in the range 3.80–4.30 which were higher than those using the L3 and H1 gears, however, a typical ploughing speed of a tractor is between 3 and 5 km/hr; 4) using the L3 gear, the tractor traveled close to the typical range of ploughing speeds and several of the combinations were considered either suitable or potentially suitable; 5) at 10° AOD, the scores tended to be lower than those at 15° and 20°.

Consequently, it was concluded that the L2, L3 and H1 gears, the 15 and 20° AODs and the 1.5 m offset were suitable operating conditions and they were further used in the furrow detection test. In addition, an offset of 3.0 m was added as an operating condition in the furrow detection test.

Furrow detection results

As an example, the measured offset distances along the furrow slice for the parameters offset = 1.5 m, gear = L3 and AOD = 15° are plotted in Fig. 7. It can be seen that from

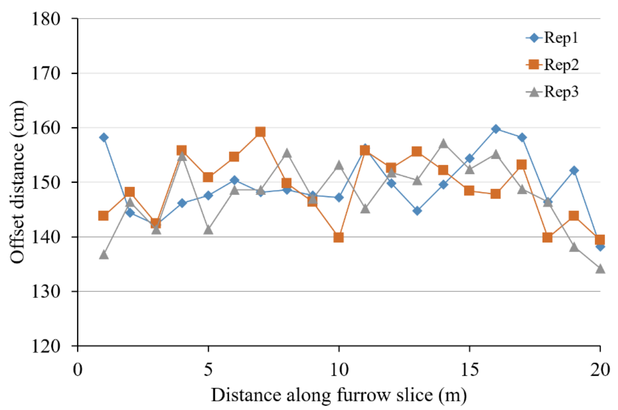

Fig. 7 Example of measured offset distances from the furrow detection test for the three replicates (Rep) for desired offset = 1.5 m, gear = L3 and AOD = 15°

Table 1 Suitability scores of operating condition combinations for driver assistance system

Gear [Speed (km/hr)]	Offset (m)								
	1.5			2.5			3.5		
	AOD (°)			AOD (°)			AOD (°)		
	10	15	20	10	15	20	10	15	20
L2 [2.0]	4.20	4.25	4.30	3.95	4.00	4.05	3.70	3.75	3.80
L3 [2.8]	3.80	3.85	3.90	3.55	3.60	3.65	3.30	3.35	3.40
H1 [5.5]	3.40	3.45	3.50	3.15	3.20	3.25	2.90	2.95	3.00

AOD = angle of depression

Green, yellow and red marks indicate suitable, potentially suitable and potentially unsuitable operating conditions, respectively

Table 2 Absolute maximum and root-mean-square (RMS) errors (in centimetres) (mean ± SE based on three replicates) of tractor's offset distances based on furrow slice detection test

Gear [Speed (km/hr)]		Offset (m)			
		1.5		3.0	
		AOD (°)		AOD (°)	
		15	20	15	20
L2 [2.0]	Max	16.20	30.70	32.40	35.40
	RMS	5.99±0.52	10.29±0.87	14.11±1.05	17.71±1.13
L3 [2.8]	Max	15.80	34.60	41.40	27.20
	RMS	4.94±0.46	13.00±0.87	20.86±1.34	14.12±0.92
H1 [5.5]	Max	17.20	27.80	35.80	30.80
	RMS	4.55±0.46	14.87±0.73	20.24±1.03	17.08±1.04

AOD = angle of depression; Max = maximum all three replicates, the tractor traveled in a relatively straight path while the actual offset distance was maintained between 135 cm and 160 cm. The absolute maximum and RMS errors calculated from the differences between the actual and desired offset distances from all the test conditions are summarized in Table 2. Considering all the test conditions, the ranges of the maximum and RMS errors were 15.80–41.40 cm and 4.55 and 20.86 cm, respectively. Comparing the RMS errors with those reported by other authors (Table 3), the errors in the current study were in a similar range. When the SLR was installed at an AOD of 15°, the errors at the 3.0 m offset were greater than those at the 1.5 m offset. On the other hand, at an AOD of 20°, the errors occurring at both offset distances ranged between 27 m and 35 m. As the speed of the tractor increased, the errors did not seem to substantially increase. Although the errors could be influenced by uncontrollable factors, such as the uniformity of the land surface, the consistency of the driver or the shape and size of the furrow slice, these results indicated that with further refinement, the driver assistance system developed in the current study could potentially be used in practice.

Sugarcane row detection results

When travelling between sugarcane rows, the driver assistance system displayed a GUI window similar to that shown in Fig. 8. On both sides of the tractor, the sugarcane rows could be detected and were represented on the display by solid blue lines. The dotted blue line indicated the middle path which the driver used to keep the middle of the tractor aligned by steering to the right. Fig. 9 shows the measured offset distances along the sugarcane rows for the L3-gear test condition. The absolute maximum and RMS errors from all the test conditions are listed in Table 4. The maximum and RMS errors were 15.05–22.32 cm and 4.32–10.20 cm, respectively, which were still within a satisfactory range and similar to those in the furrow slice detection results. Referring to the study by Subramanian (2006) and the obstacles detection by Thanpattranon et al. (2015, 2016), the sugarcane row detection and driver assistance system in the current study provided comparable results.

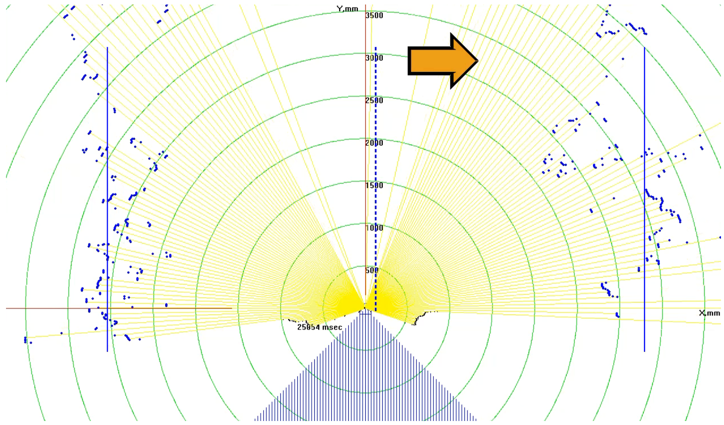

Fig. 8 Example of GUI window of driver assistance system while traveling between rows of sugarcanes, where origin (X = 0, Y = 0) is location of scanning-laser rangefinder, blue dots are coordinates of detected sugarcane plants, solid blue lines are reference landmark lines, dotted blue line is middle path, Y-axis is actual forward direction of tractor and orange left arrow indicates suggested steering direction

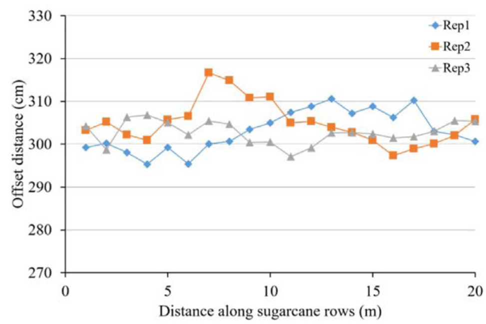

Fig. 9 Example of measured offset distances from the sugarcane row detection test when gear = L2

Table 4 Absolute maximum and root-mean-square (RMS) errors (mean ± SE [cm] based on three replicates) of tractor's offset distances based on sugarcane row detection test

Gear [Speed (km/hr)]		Offset (m)
		3.0
		AOD (°)
		0
L2 [2.0]	Max	16.68
	RMS	4.32±0.46
L3 [2.8]	Max	15.05
	RMS	6.11±0.57
H1 [5.5]	Max	22.32
	RMS	10.20±1.01

AOD = angle of depression; Max = maximum

Table 3 Root-mean-square (RMS) errors for tractor guidance systems from other studies

Reference	System	RMS error
Han et al. (2021)	In-field path planner for autonomous tractor	14.9–21.8 cm at tractor speed of 3 km/hr
Yun et al. (2021)	Ridge-furrow detection and tracking using a stereovision camera	2.78–8.67 cm at tractor speed of 0.9 km/hr
Lee et al. (2022)	Electrohydraulic steering system for autonomous tractor	12 cm at tractor speeds of 2 and 5 km/hr
Ma et al. (2022)	Satellite and visual integrated navigation for a crawler tractor	5.5 cm at the tractor speed of 3.6–4.3 km/hr

Conclusion

A low-cost driver assistance system for a tractor was developed and tested. The cost of such systems at the commercial level may vary widely depending on factors such as software and after sale service. However, as a reference, the cost of the SLR sensor used in this study ranged between USD 4,000 and USD 5,000 (Acroname, 2022). With further refinement, for example, detection algorithm adjustment, integrating extra SLRs or other sensors and performance testing in other conditions, the driver-assistance system could potentially be used in practice.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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