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Development of a Path Generation and Tracking Algorithm for a Korean Auto-guidance Tillage Tractor

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Abstract

Purpose: Path planning and tracking algorithms applicable to various agricultural operations, such as tillage, planting, and spraying, are needed to generate steering angles for auto-guidance tractors to track a point ahead on the path. An optimal coverage path algorithm can enable a vehicle to effectively travel across a field by following a sequence of parallel paths with fixed spacing. This study proposes a path generation and tracking algorithm for an auto-guided Korean tractor with a tillage implement that generates a path with C-type turns and follows the generated path in a paddy field. A mathematical model was developed to generate a waypoint path for a tractor in a field. This waypoint path generation model was based on minimum tractor turning radius, waypoint intervals and LBOs (Limit of Boundary Offsets). At each location, the steering angle was calculated by comparing the waypoint angle and heading angle of the tractor. A path following program was developed with Labview-CVI to automatically read the waypoints and generate steering angles for the tractor to proceed to the next waypoint. A feasibility test of the developed program for real-time path tracking was performed with a mobile platform traveling on flat ground. The test results showed that the developed algorithm generated the desired path and steering angles with acceptable accuracy.

Keywords: Auto-guided steering, Minimum turning radius, Paddy field, Path planning, Path tracking, Turning pattern

Introduction

Agricultural productivity has significantly increased in recent years through mechanization and automation. The application of automation to agriculture has lowered production costs, reduced reliance on manual labor, and raised the quality of products (Edan et al., 2009). These advances have been achieved with sensors and controllers. Sensors and mechanical actuators are used in many agricultural machines such as automated navigators in agricultural vehicles. Automatic guidance has been an active area of study in agricultural machinery automation.

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Automated guidance of agricultural vehicles (e.g., tractors, combines, sprayers, and spreaders) has been motivated by a number of factors—the most important factor is to reduce the need for operators to continuously adjust vehicle steering while operating various implements for agricultural operations (Groover and Grisso, 2009).

A typical auto-guidance system consists of hardware and software. A position sensor, such as an RTK-GPS (Real Time Kinematic - Global Positioning System), a steering angle sensor, and a steering actuator comprise the hardware components, while a path planning and steering algorithm and an operation program for controlling the system constitute the software components.

Much research on automatic navigation of agricultural vehicles has been reported in recent years. Stoll and

Kutzbach (2000) tested a self-propelled forage harvester equipped with an automatic steering system and a path planning algorithm that generated paths based on position information from an RTK-GPS system. Noguchi et al. (2001) used an RTK-GPS, a FOG (Fiber Optic Gyroscope), and an IMU (Inertial Measurement Unit) as guidance sensors and a sensor fusion algorithm to identify FOG bias and compensate for location errors in real time. Zhang and Qiu (2004) developed a dynamic path search algorithm to guide an agricultural tractor on a desired path and make effective turns at the ends of a field. Massey (2006) developed a waypoint following algorithm that drove a truck on a course defined by GPS waypoints at speeds as high as 80 km/hr. A simulator was also developed, based on a three-degree-of-freedom model of vehicle dynamics. Recently, Gomel-Gil et al. (2011) proposed a simple method to improve tractor positioning by applying a low-cost GPS receiver and kinematic laws of tractor movement.

Path planning algorithms compute target points for a vehicle based on the coverage area in a field, the vehicle's minimum turning radius, and other constraints. In principle, the path planner provides the position of the desired vehicle, and the desired position is then compared with the position measured with a position sensor such as RTK-GPS. The steering angle is calculated from the difference between the desired and the measured way-points, and a command signal is then sent to a controller to activate the steering actuator.

The objectives of this research were: 1) to generate a waypoint path model with C-type turning for a tractor traveling in a paddy field, 2) to develop a waypoint driving program that generates steering angles by measuring and comparing the waypoint and tractor heading angles at each location, and 3) to evaluate the developed algorithm through a feasibility test using a moving platform traveling on flat ground for real-time path tracking.

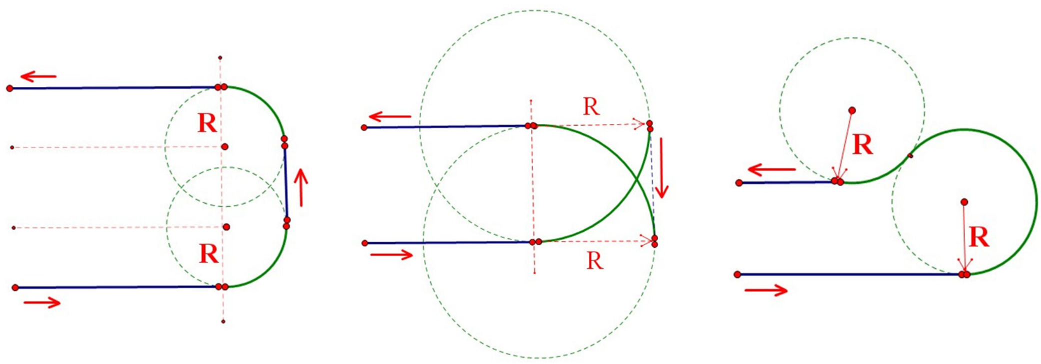
Materials and Methods

Research platform

In this study, a Novatel ProPak RTK-GPS was used to measure the absolute position of the vehicle. The RTK-GPS transmitted data at 10 Hz with a baud rate of 115,200 bps and received '$GPGGA' frames, extracted latitudes and longitudes, and then sent data to the navigator. The path generation and tracking navigator was a Samsung laptop computer running a waypoint driving program, designed with Labview (ver.2011, National Instruments, USA) software, that calculated steering angles based on data from the RTK-GPS.

Turning patterns for tillage operation

Based on previous results reported by Seo (2010), there are mainly three types of turning patterns used in Korean tillage operations: C-type, X-type, and R-type, as shown in Figure 1. The C-type turning pattern is defined by the turning radius, R, and a turning angle of 90°. This C-type pattern features continuous forward motion and avoids reverse movement. When the tractor reaches a location where it will make a 90° turn, the PTO power is shut off, the tillage implement is raised, and the tractor turns. The tractor then moves forward to another point and makes another 90° turn, forming a C-shaped curve. The X-type turning pattern consists of a combination of a



(a) C-type turning (b) X-type turning (c) R-type turning

Figure 1. Turning patterns for Korean tillage operations in paddy fields (Seo, 2010).

straight line and two 90° turns. The tractor stops at the first turning point, moves backward, and turns again to begin a new swath parallel to the master line. Similar to the C type pattern, the R-type turning pattern involves only forward motion. The tractor makes a left turn and then a right turn, and continues moving forward on an adjacent line.

Waypoint path model

A waypoint is an absolute location on the earth's surface defined by its latitude and longitude coordinates. A series of waypoints is generated to direct a tractor to move at an appropriate speed based on constant waypoint intervals and LBO values. In this study, a waypoint driving model for tractor tillage was developed by generating paths and applying the C-type turning pattern to guide the tractor at ends of paths. Waypoint data were created in a Route Data Definition File (RDDF) that includes a waypoint index, waypoints based on latitude and longitude coordinates, an LBO value, a travel velocity, and event information such as PTO ON/OFF.

Path planning is the generation of a sequence of 2-D positions or a trajectory for a vehicle. In this study, a sequence of positions, i.e., waypoints, were generated from tractor kinematics, such as the minimum turning radius and other constraints. A visual map was designed to allow an operator to select an appropriate starting position, P_1, and a reference position, P_2, as shown in Figure 2. Based on the flow chart of the path generation algorithm shown in Figure 2, the desired tillage path was calculated automatically using the starting point, $P_1 = (x_1,y_1,\varphi_1)$, and the reference point, $P_2=(x_2,y_2,\varphi_2)$. A path point frame, $P_n=(x_n,y_n,\varphi_n)$, represents a vehicle position of (x_n,y_n) and a heading angle of φ_n (Hofner and Shchmidt, 1995).

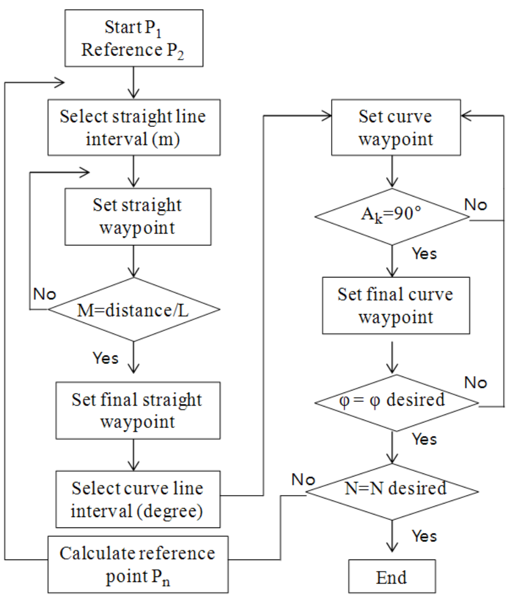


Figure 2. Flowchart of a C-type turning algorithm.

Path tracking

In a typical waypoint driving scenario, an operator guides a tractor along a path that is described by a series of waypoints. The tractor navigates between consecutive waypoints that are generated and sent to an RDDF in the tractor's controller. In this study, a computer was used as a controller to direct the tractor at a given speed along the desired heading and path within a given margin of error. A tractor reaches a waypoint when it passes near the waypoint, within the offset distance defined by the LBO. In this study, the waypoint following algorithm was developed with steering angle calculations based on GPS information, including the heading and the offset values (Moon, 2008).

Steering angle algorithm

The steering angle was defined by subtracting the heading angle (the vehicle direction vector) from the waypoint angle for that vehicle facing north (the desired vector). A schematic diagram of the steering angle calculation is shown in Figure 3 (Woo et al., 2009). A flowchart for calculating the steering angle is shown in Figure 4. Steering angles were determined using the following equations:

$$\text{Waypoint } \theta_1 = \tan^{-1}\frac{(\text{Latitude wp} - \text{Latitude current})}{(\text{Longitude wp} - \text{Longitude current})}$$

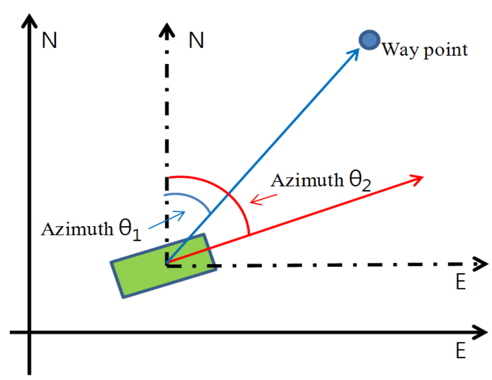


Figure 3. Schematic of the steering angle calculation (Woo et al., 2009).

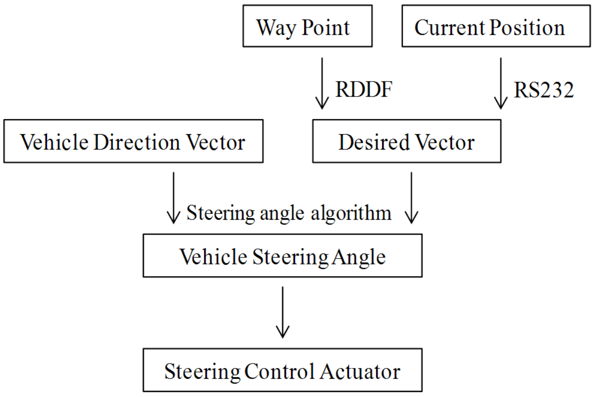


Figure 4. Flowchart for calculating a steering angle.

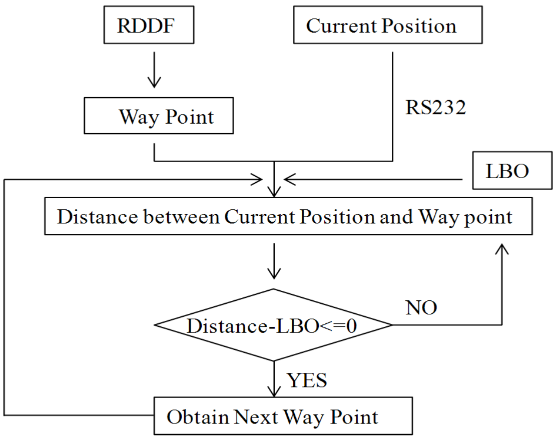


Figure 5. Flowchart for updating waypoints.

$$\text{Heading angle } \theta_2 = \tan^{-1}\frac{(\text{Latitude current} - \text{Latitude prior})}{(\text{Longitude current} - \text{Longitude prior})}$$

$$\text{Steering angle } \theta = \text{Waypoint } \theta_1 \text{ - Heading } \theta_2$$

Waypoint update algorithm

Because the size of the LBO affects waypoint recognition, the error was defined as the distance from the waypoint to the center of the LBO, which forms a circle. When the vehicle passes within the LBO of the previous waypoint, the next waypoint is read. A flowchart for loading a waypoint is shown in Figure 5.

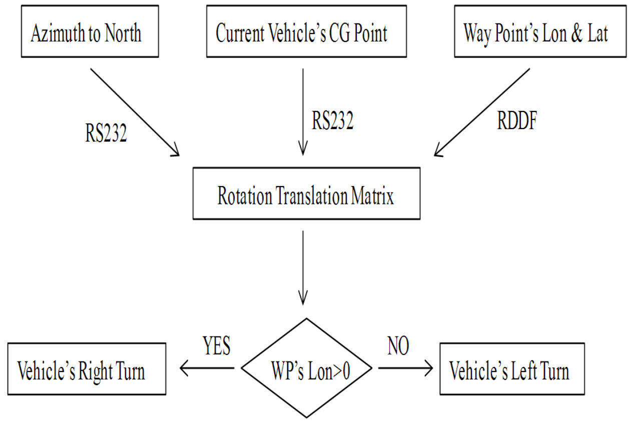


Figure 6. Flowchart for determining the change in vehicle direction.

Steering direction algorithm

After the steering angle is calculated, an algorithm determines whether to turn the steering wheel to the left or the right. A flowchart for determining the steering direction is shown in Figure 6.

Feasibility test of the path following algorithm

A feasibility test of the waypoint driving program for real-time path tracking was performed with a mobile platform traveling on flat ground. The tracking program was installed on a laptop computer equipped with an RTK-GPS rover (Figure 7a). The platform was moved by hand almost at constant velocity while GPS signals were collected at a sampling rate of 10 Hz. A path was

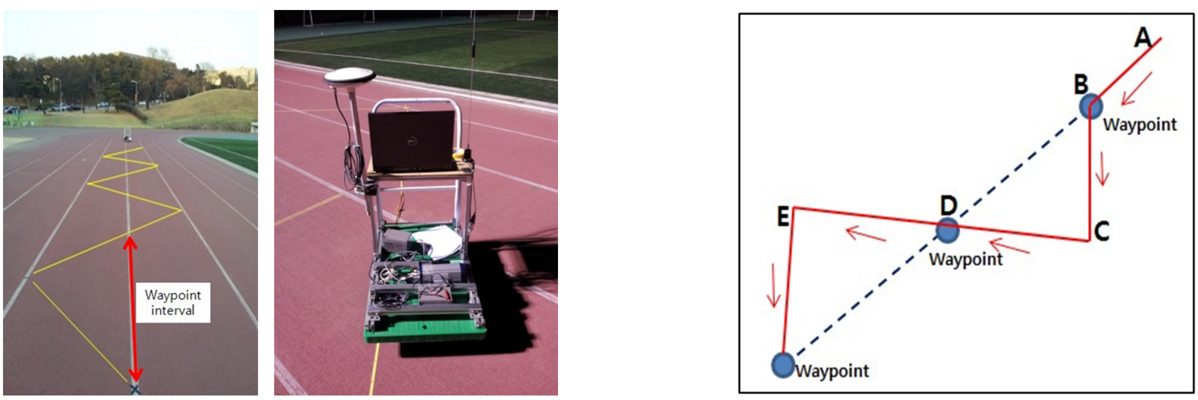


Figure 7. (a) The path with three waypoints and waypoint intervals (b) Tracking route through the three waypoints

generated with three waypoints, which consisted of latitude and longitude coordinates (Figure 7b). A waypoint LBO test was performed to determine the minimum LBO range for waypoint intervals on the path. Steering angles for the platform were calculated using the Labview program and information obtained with the GPS rover. As shown in Figure 7(a), a straight yellow line passing through the three waypoints with arbitrary angles was marked on the ground. To observe the calculation of variable steering angles at each location, the mobile platform followed the yellow path (Figure 7(b)), moving forward from point A to point B, turning left and moving from B to C, turning right and moving from C to E through D, and finishing at the third waypoint.

Results and Discussion

Waypoint path generation with c-type turning

As shown in Figure 8, a pattern consisting of a straight line and a circular arc was repeated to generate parallel paths with fixed spacing. As previously mentioned, this C-type turning pattern was one of three models for tillage operations reported by Seo et al. (2010). In this study, a waypoint technique including waypoint intervals and an LBO was used, and GPS waypoints were generated in the form of an RDDF.

The starting waypoint, XS_1,YS_1, and the reference waypoint, XC_1,YC_1, were based on the tillage implement

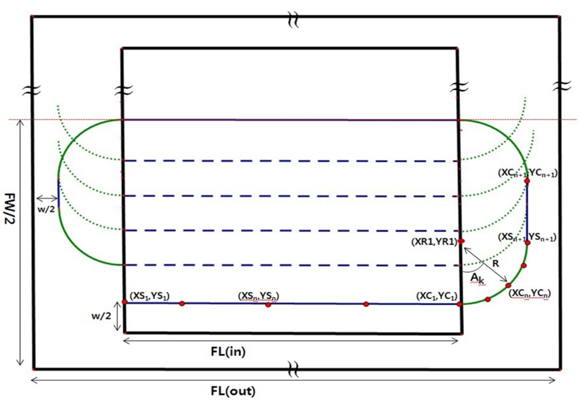


Figure 8. Diagram of a path consisting of straight lines and circular arcs.

width and defined as follows:

$$\begin{cases} XS_1 = R + \frac{w}{2} \\ YS_1 = R + w \end{cases} \tag{1}$$

$$\begin{cases} XC_1 = FL_{(out)} - (R + \frac{w}{2}) \\ YC_1 = YS_1 \end{cases} \tag{2}$$

where R is the turning radius; w is the width of tillage implement and FL(out) is the length of paddy field.

The rotation coordinates, XR_1, YR_1, and the next waypoint, XS_{n+1}, YS_{n+1}, on turn were defined as follows:

$$\begin{cases} XR_1 = XC_1 \\ YR_1 = YC_1 + R \end{cases} \tag{3}$$

$$\begin{cases} XS_{n+1} = XR_1 + R \\ YS_{n+1} = YR_1 \end{cases} \tag{4}$$

To track the straight line more precisely, several waypoints, XS_n ,YS_n, , were generated as follows:

$$\begin{cases} XS_n = XS_1 + k(XC_1 - XS_1)/D_{(interval)} \\ YS_n = YS_1 \end{cases} \tag{5}$$

where $D_{(interval)}$ is the distance between two waypoints and k is a whole number (0, 1, 2, …).

On headland turns, all waypoints, XC_n ,YC_n, were calculated to generate the next straight line more precisely as follows:

$$\begin{cases} XC_n = XR_1 + R \times \cos(A_k) \\ YC_n' = YR_1 + R \times \sin(A_k) \end{cases} \tag{6}$$

$$\begin{cases} \theta_1 = \tan^{-1}(YR_1 - YC_1)/(XR_1 - XC_1) \\ \theta_2 = \tan^{-1}(YR_1 - YS_{n+1})/(XR_1 - XS_{n+1}) \\ A_k = \theta_1 + k(\theta_2 - \theta_1)/N_{(interval)} \end{cases} \tag{7}$$

where A_k is the angle between two waypoints and $N_{(interval)}$ is the number of waypoints.

RDDF Regeneration

The latitude and longitude in the RDDF were converted to a TM coordinate format (Table 1) to more easily calculate the steering angle in the waypoint driving

Table 1. Original RDDF data based on a straight line consisting of two points

No.	Latitude (m)	Longitude (m)	LBO (m)	Width (m)	Curve	Velocity (m/s)
1	540648.8371	195572.4481	0.6	6	1	1
2	540594.9221	195534.3801	0.6	6	1	1

Table 2. RDDF data regenerated by the Labview program

Waypoint index	Latitude (m)	Longitude (m)	LBO (m)	Width (m)	Curve	Velocity (m/s)
1	540648.8371	195572.4481	0.6	6	1	1
2	540594.9221	195534.3801	0.6	6	1	1
….	….	….	….	….	….	….
311	540631.7984	195606.9821	0.6	6	1	1

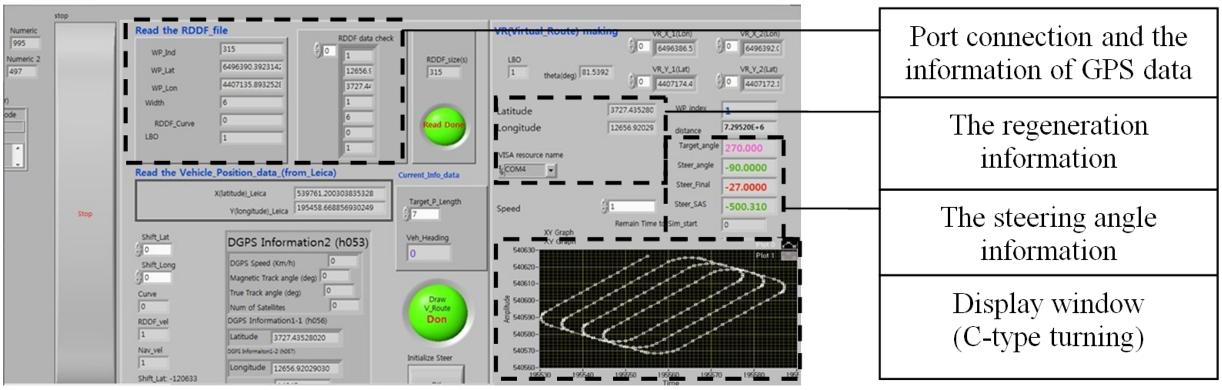


Figure 9. Path following program developed in this study.

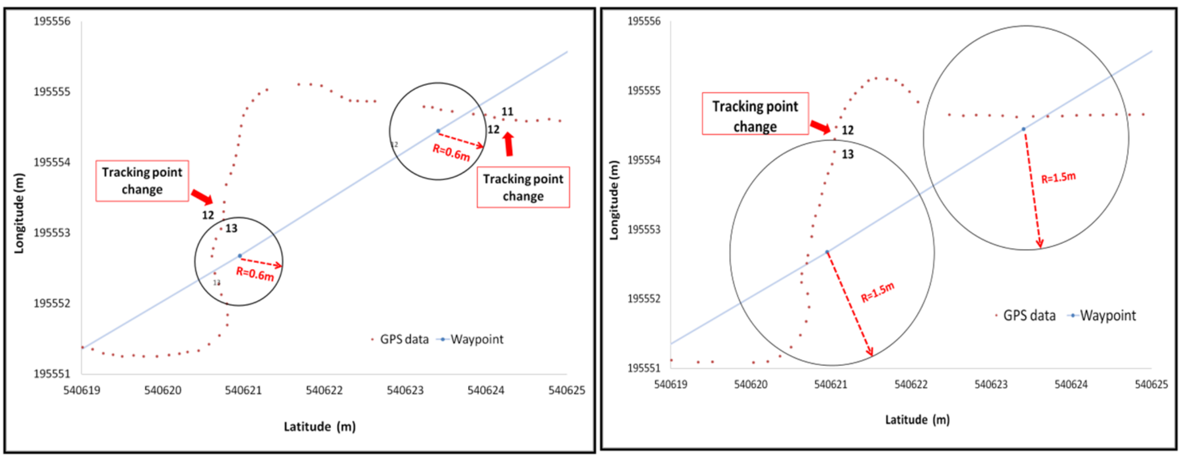


Figure 10. Waypoint LBO tests (0.6 m and 1.5 m).

program.

The Labview program was used to regenerate RDDF data from two points. For example, assuming a 6 m radius, an angle of 15° on a curved line and an interval of 3 m on a straight line were used. These results are presented in Table 2.

Development of a GUI program

A GUI program for waypoint driving was developed using Labview (Figure 9) All regenerated waypoints can be shown when the GUI program reads an RDDF file that contains a start point and a reference point. Tractor conditions at each waypoint and the GPS connection status are confirmed by an operator, and GPS data and steering angle information are provided. Regenerated waypoint and GPS data are displayed in the window of the GUI program during waypoint driving. The new program successfully generated guidance paths based on C-type turning.

Waypoint LBO Test

Figure 10 shows the test results for the minimum LBO. The LBO sizes were set to 1.5 and 0.6 m. There were no overlaps between waypoints for these two LBOs.

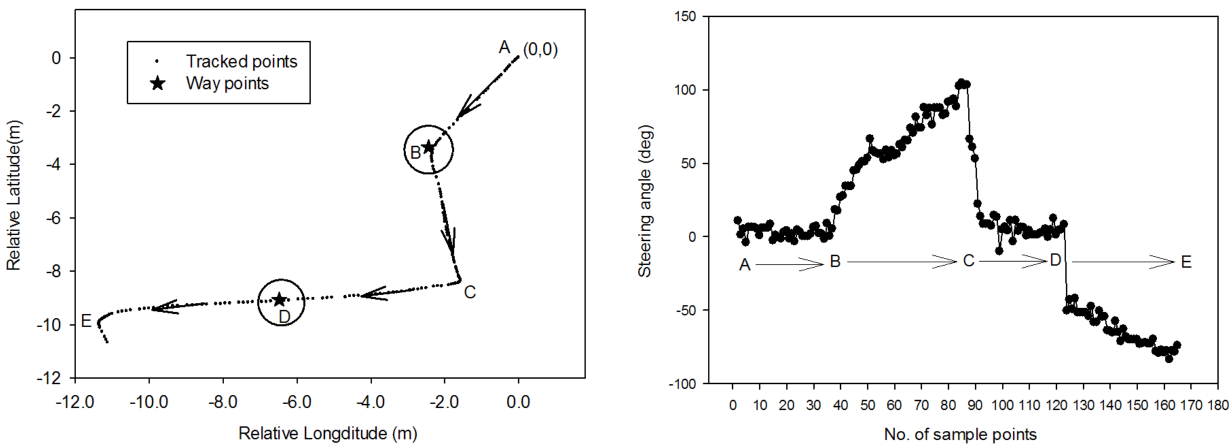


Figure 11. (a) Tracking route used in the study and (b) steering angle changes generated along the tracking route.

Therefore, the vehicle tracked the path without losing its ability to recognize a specific waypoint. In addition, new waypoints were updated when the vehicle approached a waypoint within its LBO. Waypoint tracking was more accurate when the LBO was smaller. Consequently, the optimum LBO size was 0.6 m.

Feasibility test of the path following algorithm

Figure 11 shows the trajectories of the moving platform on the ground (a) and the steering angles generated using the developed waypoint driving program along the tracking route (b). As the platform traveled from point A to point B, the steering angles were almost zero because the waypoints were maintained at B. However, steering angles constantly increased when the platform moved from point B to point C because the platform rotated clockwise toward waypoint D. There were almost no steering angle changes along the straight path to waypoint D. These driving test results showed that the waypoint driving program generated steering angles with acceptable accuracy as the moving platform equipped with an RTK-GPS traveled on flat ground.

Conclusions

In this paper, we have proposed an efficient algorithm to integrate path generation and tracking for tractors used for tillage. A C type-based path generation algorithm, consisting of straight lines and circular arcs, was developed based on a waypoint technique that includes waypoint intervals and LBO values. This waypoint generation algorithm can provide input commands for a path following program. Tractor steering angles were calculated by comparing waypoint and heading angles measured at each location with an RTK-GPS. In a feasibility test, the algorithm for real-time path tracking generated steering angles with acceptable accuracy. In future work, this waypoint driving program will be integrated with a tractor steering control system for tillage operation.

Conflict of Interest

No potential conflicts of interest relevant to this article were reported.

Acknowledgements

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References

Edan, Y., Han, S. and Kondo, N. 2009. Automation in Agriculture, In: Nof, S.Y. (Ed.), Springer Handbook of Automation. Springer Berlin Heidelberg, pp. 1095-1128.

Gomez-Gil, J., S. Alonso-Garcia, F. J. Gomez-Gil, and T. Stombaugh. 2011. A simple method to improve autonomous GPS positioning for tractors. Sensors 11:

5630-5644.

Groover, G. and R. Grisso. 2009. Investing in GPS guidance systems? Virginia Cooperative Extension, Virginia Polytechnic Institute and State University, Publication 448-076.

Hofner, C. and G. Shchmidt. 1995. Path planning and guidance techniques for an autonomous mobile cleaning robot. Robotics and Autonomous Systems 14(2): 199-212.

Massey, J. P. 2006. Control and waypoint navigation of an autonomous ground vehicle. Unpublished MS thesis. Texas A&M University, Dept. of Mechanical Engineering.

Moon, H.C. 2008. Design of distributed control system and development of autonomous driving algorithm for unmanned ground vehicle. Unpublished PhD diss. Seoul: Kookmin University, Department of Automotive Engineering.

Noguchi, N., J. F. Reid, Q. Zhang, J. D. Will, and K. Ishii. 2001. Development of robot tractor based on RTK-GPS and gyroscope. ASAE Paper No. 01-1195. St. Joseph, Mich: ASAE

Seo, I. H. 2010. Working path formation system for autonomous traveling tractor. Unpublished PhD diss. Daejeon: Chungnam National University, Department of Agricultural Machinery Engineering.

Seo, I. H., D. H. Seo and K. D. Kim. 2010. Development of working path formation program for autonomous tractor system. Journal of Agricultural Science 37(1): 113-121.

Stoll, A. and H. D. Kutzbach. 2000. Guidance of a forage harvester with GPS. Precision Agriculture 2:281-291.

Woo, H. J., B. J. Yoon, B. G. Cho and J.H. Kim. 2009. Research into navigation algorithm for unmanned ground vehicle using real time kinematic (RTK)-GPS. ICROS-SICE International Joint Conference.

Zhang, Q. and H. Qiu. 2004. A dynamic path search algorithm for tractor automatic navigation. Transactions of the ASAE 47(2):639-646.