Development of angular correction algorithm for movement of agricultural mobile robots in a straight line

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Abstract: This paper proposes the angular correction algorithm for the autonomous navigation of the agricultural mobile robots, which are driven in a straight line, with simple hardware based on the data of the digital compass and the GPS receiver. The motion of the mobile robot was accomplished by the differential drive mechanism with four driving wheels in which the overall velocity is split between left and right wheels. The two-channel DC motor controller was used to drive motors. The digital compass was used to calculate the position angle of the mobile robot with respect to the target point. A Kalman filter was used to fuse the information from GPS and digital compass. In the proposed algorithm, the mobile robot is driven in a straight line along a predefined path by calculating in real time the deviation angle difference with respect to the target point. When the robot encounters an unexpected external force varying the desired path, it achieves a smooth and stabilized straight line movement by correcting the deviation angle difference. The performance of the mobile robot was evaluated based on a total of 18 straight lines in a farmland. Standard errors of cross track error (XTE) values of straight lines for each target point were analyzed. The mean of arithmetic means was found to be 4.14 cm. The mean of R-square was 0.990. This value shows that the proposed angular correction algorithm is useful in driving the mobile robot in a straight line.

Keywords: agricultural mobile robots, angular correction algorithm, cross track error, Kalman filter, straight line movement.

1. INTRODUCTION

In the age of Industry 4.0, mobile robots are one of the main components that enable the digitization of agricultural processes and automation of manual processes. In the past decades, a significant amount of research has focused on the autonomous operation of mobile robots in open agricultural landscape. Traveling in straight lines, curved path following, trajectory tracking, and headland turning are considered the fundamental problems and are some of the common studied problem in agricultural robots for field operations (Luo et al., 2018). On the other hand, agricultural mobile robots work under the disruptive effect of many different environmental parameters along a desired trajectory in open agricultural landscape. Although some of these effects are related to the design of mobile robots (Rubio et al., 2019), most of them are related to the spatial conditions of the farmland such as slope, rough terrain, and elevation difference (Moysiadis et al., 2020). Motion control of mobile robots is an algorithmic plan of action by which the robot moves from one position to another, requiring techniques in perception, state estimation, path planning, motion planning, and the implementation of this plan of action. (Xiao et al., 2022). In this action plan, any deviation or orientation error of the robot from the desired path is undesirable, since both lead to lose the path. Therefore, an improved plan of action with a correction algorithm becomes necessary for a stable and an efficient navigation performance.

Motion and navigation in uneven and difficult terrains is an essential problem for agricultural mobile robots. In order to provide completely autonomous steering in hard farmlands, the robot would need to be able to travel in straight line, turn in the headland, enter the next operating row, and follow the parallel tracks in the field (Huang et al., 2020). In order to achieve all these tasks optimally, it is necessary to equip the mobile robot with navigation sensors and algorithms incorporating ground-based absolute and relative measurements (Han et al., 2022). In this context, Global Positioning System (GPS) is a satellite navigation system used for determination of time, position and velocity in the guidance and control of a mobile robot. Also, the Real-Time Kinematic GPS (RTK GPS) with precision of a few centimeters is capable of precisely measuring the vehicle position in real time for outdoor navigation. (Dong et al., 2011). But when it comes to navigating outdoors and addressing more complex and environmentally challenging tasks, GPS alone is insufficient for the guidance of the mobile robots. Inertial Navigation Systems (INS), digital compasses, machine vision, accelerometers, gyroscopes, radars are other devices that support accuracy and efficiency in the navigation of mobile robots (Gomez-Gil et al., 2011).

It is difficult to determine the actual location of the mobile robot in outdoor conditions using only the GPS receiver. Digital compass and fiber-optic gyroscope have been widely used for localization and navigation of the mobile robots. Digital compass, which plays an important role in the navigation area, measures the azimuth by use of the earth's magnetic field and determines the heading angle of the mobile robot. The absolute heading angle of mobile robots can be measured using the digital compass for an orientation angle errors caused by wheel slip, and these errors can be minimize using sensor fusion of digital compass with GPS (Lee and Jung, 2008). The most accurate and reliable technique is the use of a digital compass to eliminate wheel slips by continuous correction of the orientation of the mobile robot in autonomous mobile robot navigation (Neto et al., 2009). An electronic compass does not depend on GPS signals for measuring heading angle. In case wherein a mobile robot autonomously moves to a target point and loses the correct GPS signal, the compass continues to point toward the correct direction (Han et al., 2019). On the other hand, accuracy of the digital compass can be easily affected by magnetic interference. Particularly if the mobile robot passes through stray magnetic fields as part of its course of navigation, large errors will occur in the heading angle of the mobile robot (Zhou and He, 2014).

Positioning the mobile robot to advance in a straight line requires a suitable and efficient correction algorithm, so that the mobile robot accurately reaches the target point. Real time position correction algorithm is a helpful method to the local and global path planning in the known environment for the path planning of the mobile robots. For this reason, it is very important to study the multi-sensor fusion technology for location the mobile robot accurately (Xu, 2019). The objective of this study is to develop an angular correction algorithm using sensor fusion of GPS and digital compass for the movement of the agricultural mobile robots in a straight line. In order to improve the accuracy of the mobile robot localization, an approach including a calibration method of the digital compass and an angular correction algorithm is presented. The proposed fusion of GPS and electronic compass in this paper can correct the orientation error in real time to improve the accuracy of the mobile robot localization in straight line movement.

2. MATERIALS and METHODS

2.1 Four wheel differential drive agricultural mobile robot

The four wheel differential drive (4WD) mobile robot with nonholonomic constraints structure was used as the prototype in this study (Fig. 1).

The robot was equipped with two 24 V – 500 kW – 1440 rpm brushed DC motors which were coupled to the wheels through a gear mechanism, whose gear ratio is i = ωM/ωL = 20. The left front and rear wheels were powered with the first motor and wheels on the other side was powered with the second motor to provide differential steering. The external dimensions of the mobile robot were 1920 mm (length) x 1610 (width). One 300 W DC/AC inverter was used to convert the DC output power to AC power for powering the industrial computer, electronic compass, and the GPS receiver.

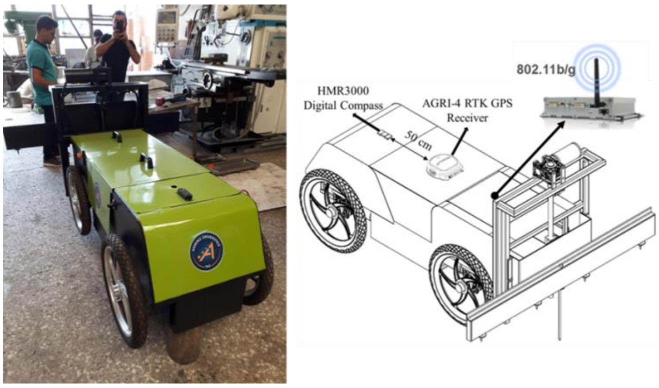

Fig. 1. Autonomous driving 4WD agricultural mobile robot.

The RoboteQ’s FDC3260 (RoboteQ Inc., Arizona, USA) three-channel motor controller was used to drive DC motors through its H-bridge configuration. The left front and back wheels were driven by the first channel of the motor controller, and the right pair was driven by the second channel. The Honeywell HMR3000 digital compass (Honeywell Inc., North Carolina, USA) was used to determine the heading angle of the mobile robot and was thus the most important sensor on system. The AGRI-4 RTK GPS (Topcon Positioning Systems Inc., Livermore, CA, USA) receiver was used to collect the mobile robot’s longitude and latitude data.

The nonholonomic 4WD agricultural mobile robot is shown on a two dimensional Cartesian workspace in Fig. 2. A global coordinate (X1, Y1) and a local coordinate (x1, y1) is attached to the robot with the origin at point O. x1 indicate the driving direction, y1 is the robot lateral direction, and θO is the heading angle of the mobile robot .The mobile robot’s kinematics is defined as:

$$\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\theta}\end{bmatrix} = \begin{bmatrix}\mathrm{Cos}\theta o & 0\\ \mathrm{Sin}\theta o & 0\\ 0 & 1\end{bmatrix} * \begin{bmatrix}v\\ \omega\end{bmatrix} \tag{1}$$

$$P = \begin{bmatrix}v\\ \omega\end{bmatrix} = \begin{bmatrix}\frac{r}{2} & \frac{r}{2}\\ \frac{r}{L} & -\frac{r}{L}\end{bmatrix} * \begin{bmatrix}v_R\\ v_L\end{bmatrix} \tag{2}$$

Where v is the linear velocity, ω is the angular velocity, v_L indicates the velocity of the left driving wheel, v_R indicates the velocity of the right driving wheel, L indicates the width between the left and right wheels. According to the specified equation, the equation for the turning radius and the kinematic equation of the nonholonomic mobile robot are defined as:

$$\rho = \frac{v}{\omega} = \frac{L*(v_L + v_R)}{2*(v_L - v_R)} \tag{3}$$

$$P = \begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\theta}\end{bmatrix} = \begin{bmatrix}\frac{r}{2}*\mathrm{Cos}\theta & \frac{r}{2}*\mathrm{Cos}\theta\\ \frac{r}{2}*\mathrm{Sin}\theta & \frac{r}{2}*\mathrm{Sin}\theta\\ \frac{r}{L} & \frac{-r}{L}\end{bmatrix} * \begin{bmatrix}v_R\\ v_L\end{bmatrix} \tag{4}$$

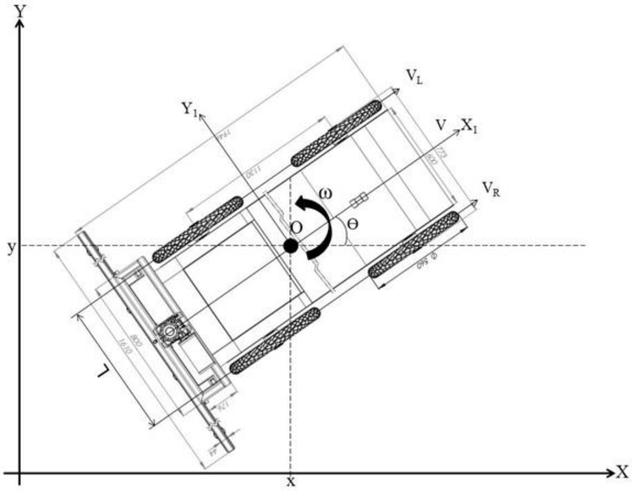

Fig. 2. Model of a nonholonomic 4WD agricultural mobile robot.

2.2 Kalman filter for GPS receiver and digital compass data fusion

In order to drive the mobile robot in a straight line, a Topcon AGI-4 RTK GPS (Topcon Positioning Systems, Inc., Livermore, CA, USA) receiver was combined with a Honeywell HMR3000 (Honeywell International Inc., Charlotte, North Carolina, USA) digital compass to precisely provide the mobile robot with its position data and also heading angle data. The update rate of the GPS receiver was 10 Hz, and the correction signals were received from the Corse-TR (Continuously Operating Reference Stations-Turkey). The digital compass was suitable for integration with GPS receiver for providing heading angle data, it technically provided 0.5 degrees nominal accuracy, 0.1 resolutions, ±180 degree roll, ±45 degree tilt, and electronically gimbaled tilt compensation. The maximum update rate of the digital compass was 20 Hz, but it was used as10 Hz to provide synchronization with the GPS receiver.

A Kalman filter is an efficient recursive filter that combines a GPS receiver and a digital compass, and compensate for sensor errors to determine an optimal estimate for positioning and heading data of the mobile robot (Fig. 3). The main advantage of the Kalman filter usage for GPS receiver and digital compass integration is that the digital compass does not need any specific configuration to be installed in the mobile robot. The one important disadvantage of this integration is that digital compass is affected by the strong magnetic fields or highly magnetic material especially batteries, electric motors and electric currents on the mobile robot. For this reason, it is recommended that the digital compass should be mounted as far away as practical from these items and performs a compensation of their effects. The sequences of operations for Kalman filtering to estimation, update and gain matrix were shown in Fig. 4.

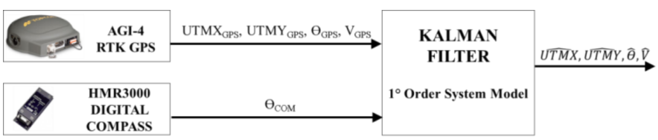

Fig. 3. Block diagram for the described implementation.

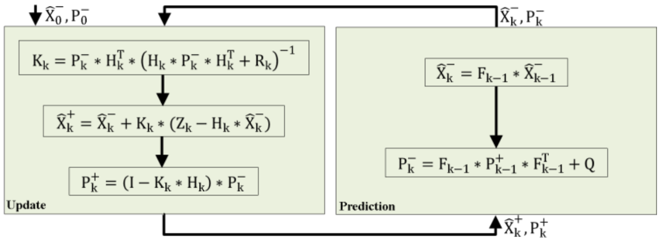

Fig. 4. Sequences of operations for Kalman filtering.

In this study, the Kalman filter was used to reduce the effects of digital compass and GPS noises caused by the disruptive effect of many different environmental parameters and produce an accurate state update. In Fig. 4, $\hat{X}_k$ is the updated estimate value, $\hat{X}_k^-$ is the priori estimate values, and $\hat{X}_k^+$ is the a posteriori estimate values. And also, K_k is the Kalman gain, P_k is the updated error covariance matrix, P_k^- is the initial error covariance matrix, P_k^+ is the posteriori error covariance matrix, Q is the process noise covariance matrix, I is the identity matrix, R_k is the covariance matrix for the measurement noise vector, T is the update period of the Kalman filter, F_k is the state transition matrix, and H_k is the measurement connection matrix.

2.3 The calibration procedure for the digital compass

The digital compass is a basic navigation sensor for mobile robots. On the other hand, the problem of compass deviation due to the ferrous materials or mobile robot's other devices that generate magnetic fields is the most important problem. The digital compass should be calibrated to get the real heading angle and proper tracking. In this study, it was offered to a special simplified calibration method to correct the heading angle and minimize the errors for mobile robots depending on the measured heading angle and the calculated azimuth angle of the target point. In this calibration method, the readings of the digital compass were recorded, azimuth angle of the target point and correction degrees calculated, and then added to the readings of the digital compass.

In proposed method first the mobile robot was placed in the middle of a circle with a diameter of 10 m (Fig. 5).

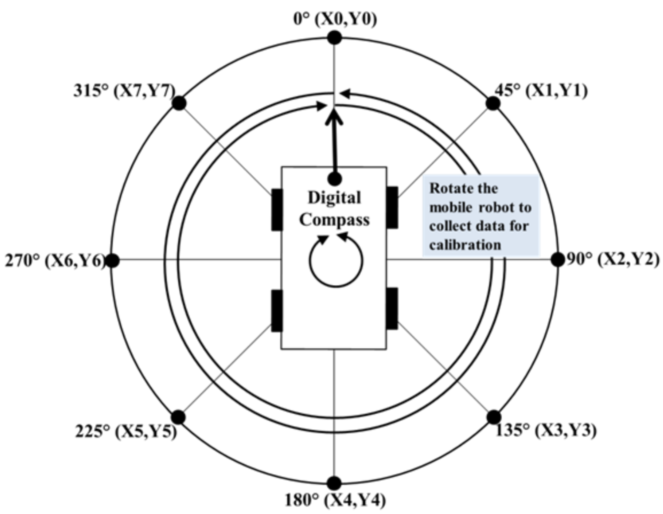

Fig. 5. Digital compass calibrations.

The latitude and longitude data of the calibration points (X0, Y0…X7, Y7) was recorded in database. The mobile robot was rotated to the calibration points both counterclockwise and clockwise in 45-degree steps. When the mobile robot's heading and the calibration point are collinear, the rotating was stopped, heading angle was read, distance and azimuth angle was calculated (Eq.5-6), and the angle difference was determined (Eq.7).

$$\text{Distance} = \sqrt{(X_R - X_{CP})^2 + (Y_R - Y_{CP})^2} \qquad (5)$$

$$\text{Azimuth} = \text{Atan2}\left((Y_{CP} - Y_R); (X_{CP} - X_R)\right) * 180/\pi \qquad (6)$$

$$\text{Angle Difference} = \text{Heading Angle from Digital Compass} - \text{Azimuth} \qquad (7)$$

In Eq.5 and 6; X_R and Y_R were the longitude and the latitude points of the mobile robot. X_{CP} and Y_{CP} were the longitude and the latitude points of the calibration points. The each angle difference was calculated for a total of 16 points and computed the arithmetic mean of all differences. To find the true heading angle, if the arithmetic mean of all differences was negative, this value was added to the heading angle or if the arithmetic mean of all differences was positive, this value was subtracted from the heading angle. This value was added or subtracted to the heading angle measured from the digital compass for use in the correction algorithm.

2.4 Data Collection

Field experiments were performed on a 20 ha wheat field after harvest located approximately 20 km from Antalya between the coordinates of 30.84 E and 36.94 N. The mobile robot was autonomously driven both with and without angle correction algorithm along the south-north direction in straight line. In the study, the coordinates of the start and target points of the mobile robot were stored to the database for desired trajectory tracking. These data were used to create the attribute table for plotting the straight lines (connection lines) in ArcGIS 10.5. All data were stored in a database with a 100 ms interval. The mobile robot was driven on parallel transects approximately 70 cm apart over the field. The average velocity of the mobile robot was 1.08 m/s. A total of 18 straight lines were recorded in the field.

2.4 Data Analysis

In precision agriculture applications using autonomous mobile robots, ideal mobile robot trajectories for most processes should be made of parallel lines separated by a uniform W distance. The accuracy of the mobile robot position can be evaluated according to the situation of the distance W. The desired situation is that the distance W would be close to the true line. In statistical navigational analysis of the mobile robots, Cross Track Error (XTE) is useful navigational data that measures how far the straight-line distance of the mobile robot from the true line (Fig. 6).

In this study, connection lines between two points were created to compute the XTE values using the ArcMap application of the ArcGIS 10.5. The connection lines were used as the reference lines of the mobile robot. These two points were defined the start and target points of the mobile robot for the movement in a straight line. In ArcMap, it is possible to generate a set of lines from waypoints collected from the GPS receiver using the XY To Line tool (Fig. 7).

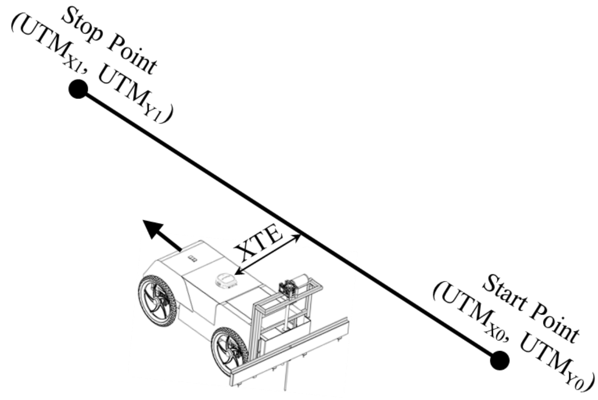

Fig. 6. Cross Track Error (XTE).

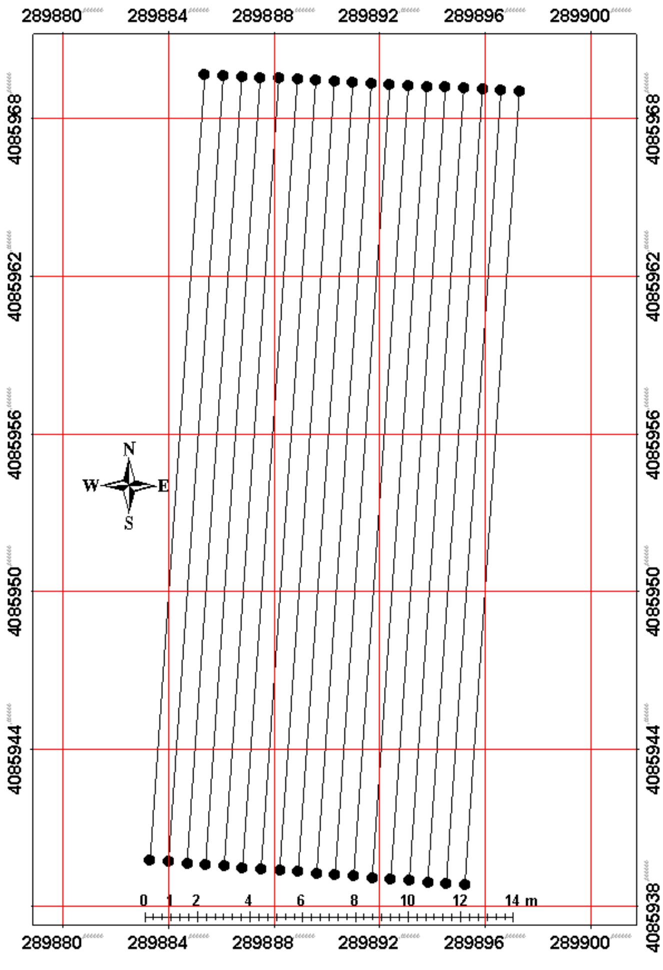

Fig. 7. Connection lines for the movement in a straight line.

To create the connection lines in ArcMap, the attribute table should be contained the latitude and longitude of the start and end point features.

The distance between a point and a line (XTE) is defined to be the shortest distance from a given point to any point on an infinite straight line. If the line passes through two points P1 = (UTM_{X0}, UTM_{Y0}) and P2 = (UTM_{X1}, UTM_{Y1}) then the distance of (UTM_{XR}, UTM_{YR}) from the line is:

$$\mathrm{XTE} = \frac{|(\mathrm{UTM}_{X1} - \mathrm{UTM}_{X0})(\mathrm{UTM}_{Y0} - \mathrm{UTM}_{YR}) - (\mathrm{UTM}_{X0} - \mathrm{UTM}_{XR})(\mathrm{UTM}_{Y1} - \mathrm{UTM}_{Y0})|}{\sqrt{(\mathrm{UTM}_{X1} - \mathrm{UTM}_{X0})^2 + (\mathrm{UTM}_{Y1} - \mathrm{UTM}_{Y0})^2}} \quad (8)$$

Linear regression analysis was used to determine the relationship between the connection line and the XTE values. Standard deviations and standard errors of the XTE values were determined for each experiment.

2.5 Angular correction algorithm

The proposed angular correction algorithm for the movement of mobile robot in a straight line and its flowchart which is the combination of Kalman Filter, digital compass and RTK GPS were described in this section (Fig. 8). An RTK GPS was used to collect high accuracy latitude and longitude coordinates of the mobile robot at the cm level. And also, it was used to store the latitude and longitude coordinates of the target points in SQL Server database. RTK GPS contains error due to many factors such as field conditions, inadequate number of satellite signals, signal jamming, etc. And also, there are several factors that can greatly influence the digital compass such as the time-varying magnetic fields, tilt measurement errors, magnetic inclination, field conditions, sudden starts and stops of the mobile robot. In order to improve accuracy, these errors should be filtered and reduced so that the GPS receiver and the digital compass can be used in navigation applications. For this reason, the Kalman filter was used to minimize the errors of whole system.

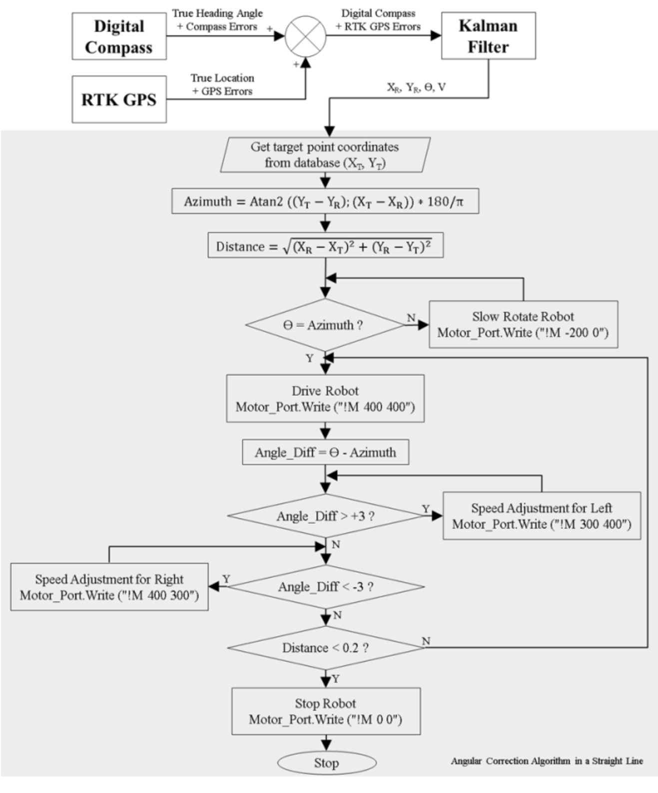

Fig. 8. Flowchart of the angular correction algorithm.

The mobile robot was driven by two high power DC motors via the worm gearbox. In order to ensure straight guidance of the mobile robot to the target point, it was driven by creating a speed difference between the right and left wheels, depending on the difference between the heading and azimuth angles. It should be required to modify the motor speeds often to guarantee that the robot travels in a straight line. To achieve this angular correction, the measured heading angle and the computed azimuth angle should be constantly checked and the difference between them should be computed.

In this algorithm, the mobile robot rotates in place until it is facing the target point, and then starts moving in a straight line towards the target point. The important thing here is that the difference between the heading and the azimuth angles remains within acceptable limits. As the robot moves towards the target point, it corrects its heading by changing the motor speeds. When the difference between the heading and azimuth angles was in the range of -3 to +3 degrees, the robot was driven no speed difference between the wheels. When the angle difference was greater than +3 degrees, the speed of the left wheels was reduced by 10%, allowing the angle difference to keep it between -3 and +3 degrees. Likewise when the angle difference was less than -3 degrees, the speed of the right wheels was reduced by 10%, allowing the angle difference to keep it between -3 and +3 degrees. In this algorithm, DC motor controller sends PWM signals to the mobile robot that allow it to change the path, through the differentiation of the speed sent to the wheels on each side, which allows the mobile robot to make the motion curves. This correction algorithm is repeated until the true position of the mobile robot lies within a certain distance of the target point (20 cm by default). Because the robot only uses angular control, the desired heading is typically not reached because of the rough terrain, but the mobile robot moves close enough to the straight line within desired limits. In this way, it is compensated that the robot’s heading deviates too far from the desired heading.

3. RESULTS AND DISCUSSION

The mobile robot's straight motion in the test field was divided into two parts: calibration of the digital compass and evaluation of the movements of the mobile robot on the straight line. In the process of calibration test in real time, the mobile robot was placed in the middle of a circle with a diameter of 10 m and rotated to total eight calibration points both counterclockwise and clockwise in 45-degree steps. During the calibration test, the heading angle was measured and the azimuth angle was computed for each calibration point. A total of 16 heading and azimuth angles were collected to determine the heading angle error of the mobile robot to the target point (Table 1).

In the course of calibration test, it was observed that the angle differences in the north-south directions increased compared to the east-west directions. In the evaluation of the movements of the mobile robot on the straight line, the mobile robot was autonomously driven along approximately in the north- south direction by the help of proposed algorithm. It was added 9.21 degrees to the digital compass measurements to eliminate the heading angle error.

Table 1. Calibration data to compensate the heading angle error.

Angle	Rotate	Heading	Azimuth	Difference	Mean
0	Clockwise	9.20	0.01	9.19	9.21
0	Counterclockwise	9.23	0.01	9.22	
45	Clockwise	52.77	45.05	7.72	7.72
45	Counterclockwise	52.76	45.05	7.71	
90	Clockwise	94.12	90.01	4.11	4.11
90	Counterclockwise	94.12	90.01	4.11	
135	Clockwise	141.70	135.03	5.67	5.68
135	Counterclockwise	141.71	135.03	5.68	
180	Clockwise	189.17	180.01	9.16	9.17
180	Counterclockwise	189.19	180.01	9.18	
225	Clockwise	232.67	225.01	7.66	7.65
225	Counterclockwise	232.65	225.01	7.64	
270	Clockwise	274.09	270.01	4.08	4.08
270	Counterclockwise	274.08	270.01	4.07	
315	Clockwise	320.47	315.02	5.45	5.42
315	Counterclockwise	320.45	315.02	5.43	

The field test was implemented in a small field to test the algorithm of angular correction of the mobile robot localization in straight line movement and the control performance. A total of 2081 GPS positions were collected on 18 straight lines approximately 70 cm apart over the field. The lengths of the straight lines were approximately 30 m. The mobile robot's location data in straight lines were shown in Fig. 9. There were no missing data due to loss of differential correction signal. After the field test, the mobile robot's location data for each straight line were mapped by the ARCGIS 10.5 mapping software.

A XTE is a distance between the true course a mobile robot should follow and the actual course it does follow whenever an angular error exists in the digital compass. The purpose of the proposed algorithm in this paper is to minimize the XTE errors of the mobile robot moving in a straight line, depending on the heading angle. On the other hand, while correcting the XTE errors, the heading angle of the mobile robot should not deviate too much from the target point. Because, corrections on XTE and differences between headings angle of the mobile robot and the azimuth angle tend to counteract one another. As the mobile robot moves closer to the true route, XTE shrinks, and the heading angle of the mobile robot dominates more. For this reason, if the difference exceeds ±3 degrees between heading angle of the mobile robot and azimuth angle, the angular correction is activated. Otherwise, the robot moves straight forward. If this limit value, which determines the straight forward movement of the mobile robot, rises above or falls below 3 degrees, oscillation problems start in mobile robot movements.

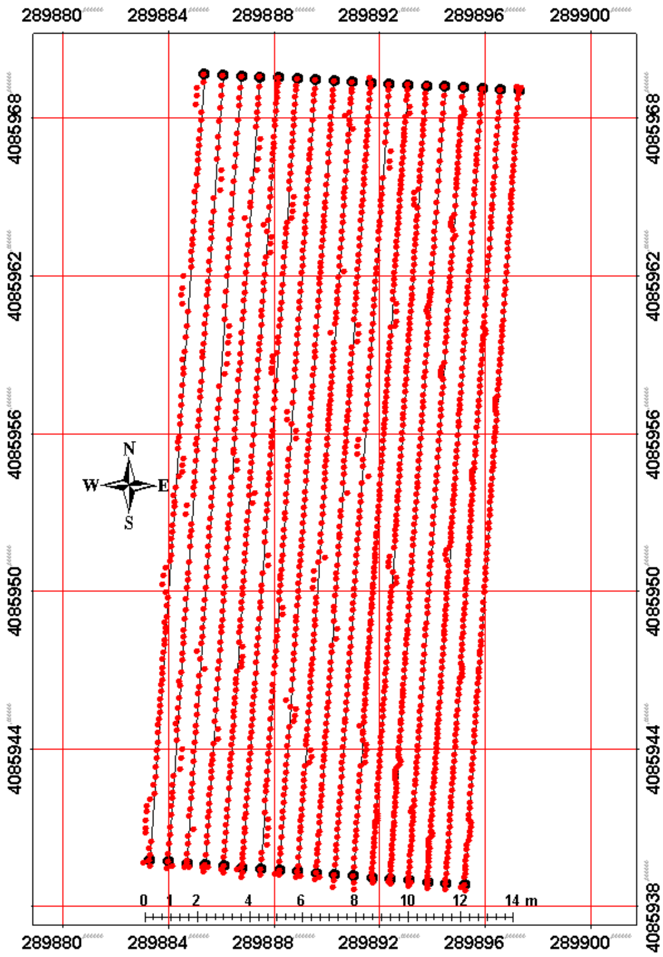

Fig. 9. Mobile robot's location data in straight lines.

The arithmetic mean, standard deviation, standard error and R-square values calculated for 18 straight lines under these conditions are given in Table 2.

Table 2. Field test results.

Line No	Max. XTE (cm)	Min. XTE (cm)	Mean (cm)	SD (cm)	SE (cm)	R^2
1	32,30	2,80	5,69	3,95	4,01	0,9812
2	24,75	3,18	5,12	3,78	3,85	0,9875
3	33,12	2,25	4,56	3,66	3,79	0,9926
4	19,50	1,64	4,18	3,59	3,71	0,9932
5	19,25	1,82	4,65	3,45	3,68	0,9918
6	18,70	2,32	4,88	3,46	3,68	0,9895
7	20,05	1,85	4,28	3,54	3,70	0,9902
8	20,26	1,15	4,37	3,39	3,58	0,9965
9	22,20	1,35	4,46	3,41	3,58	0,9882
10	19,34	1,25	4,35	3,35	3,55	0,9911
11	18,62	1,28	4,66	3,45	3,62	0,9890
12	17,33	1,20	3,65	3,15	3,42	0,9901

13	17,35	1,42	3,77	3,21	3,44	0,9897
14	12,85	1,10	3,15	3,08	3,31	0,9923
15	11,71	1,28	3,12	3,05	3,28	0,9925
16	15,80	1,75	3,21	3,06	3,28	0,9945
17	10,15	1,41	3,18	3,06	3,28	0,9962
18	9,89	1,32	3,27	3,09	3,28	0,9965

When Table 1 is examined, it can be seen that the maximum XTE errors vary between 9.89 cm and 32.30 cm. The minimum XTE errors vary between 1.10 cm. and 3.18 cm. It is seen that the XTE errors decrease from line no 1 to line no 18. This is because the test field was rugged terrain up to line no 9 and smoother on other lines. The mean of arithmetic means was found to be 4.14 cm. It was observed that the standard deviation of the XTE errors was varied between 3.05 and 3.95. And also, the standard error of the XTE errors was varied between 3.28 and 4.01. It was seen that the standard deviations were approximately similar to the standard errors for all 18 line. The results of the regression analysis show that the collected GPS points were close to the connection lines (min: 0.9812 max: 0.9965). The mean of R-square was 0.990.

From the results map, it shows that the mobile robot strays off true route, and then is trying to track the true route (Fig.10). It takes a short time for the mobile robot to catch up the connection line and maneuver towards the true path smoothly. This is show that the proposed correction algorithm has very smooth and quick tracking response. Path tracking for autonomous mobile robots is a critical task for driving the robot on a straight line such that the XTE error converges to zero. Mobile robots in general don't move with perfect precision in outdoor conditions. Their trajectory can be affected by the non-flat surfaces, and slight misalignments in its mechanics. In Fig. 10, it can be seen that the mobile robot quickly compensates for the XTE error.

Han et al. (2002) developed a Kalman filter method that improves the DGPS position estimates for parallel tracking applications. Researchers have reported that the RMS XTE positioning errors in the straight travel were 1.35 m for the mean filter and 0.26 m for the Kalman filter. And also, It was reported that he Kalman filter reduced the root-mean-squared XTE from 0.58 m to 0.56 m. Rounsaville et al. (2016) presented four different XTE calculation methods using the procedures in the ASABE/ISO standard 12188-2. These methods were Nearest Point (NP) Method, Linear Path Interpolation (LPI) Method, Cubic Path Interpolation (CPI) Method, and Perpendicular Component (PC) Method. Researchers have reported that the PC method was simpler to implement in code than the other methods and suggested that this method should be used when calculating XTE. The results of the study indicated that the mean XTE value was 9.81 cm for vehicle speed at 1.25 m/s and 12.33 cm for vehicle speed at 0.5 m/s speed. Jingwei et al. (2021) presented a robust path tracking algorithm to guarantee the performance of path tracking for automated vehicles. In this study, it was used a modified Kalman filter is employed to adapt to a more complex scenario with variable position error. Researchers reported that the proposed method can decrease the tracking error to less than 0.3 m. If our results are compared with values stated in the literature, it is seen that the XTE values are lower. It demonstrates that the proposed angular correction algorithm can increase the efficiency of the path tracking of the mobile robots.

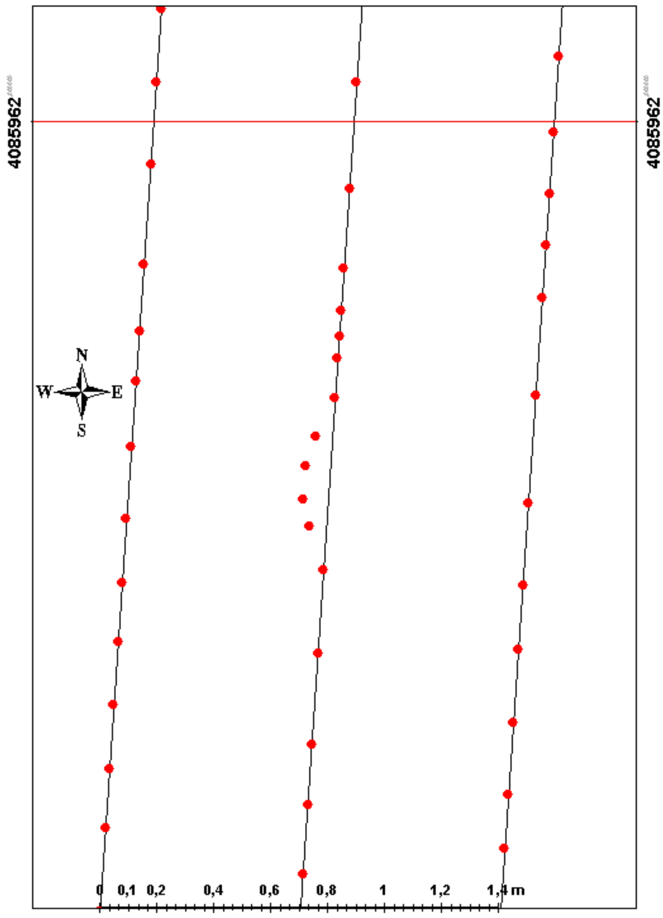

Fig. 10. Tracking a straight connection line.

Precise calibration has a crucial effect on the heading accuracy of the mobile robots integrated with digital compasses. It is very important to filter the Earth's magnetic fields from the digital compass measurements for measuring the heading angles of the mobile robots. To improve the accuracy of the heading angle measurement, the digital compass should be calibrated again before every study. Because, different magnetic field transitions, such as high voltage transmission lines, can be found in different working areas and conditions. Many researchers have proposed several angular correction algorithms for calibrating and compensating the digital compass errors, such as Kalman filtering, rule-based techniques, Bayesian theory, fuzzy logic, or neural networks (Mohamed et al., 2018). The algorithm proposed in this study reveals a different approach to both correcting the heading angle and compensating for XTE errors. The calibration and angular correction processes are simple, and no external auxiliary equipment is needed. The convergence speed is faster, the convergence accuracy is higher, and the stability is better. This algorithm not only solves the problem that digital compass calibration accuracy is low but also obviously improves the convergence rate of the heading angle of digital compass data fusion. Compared with other methods, this method is more precise, and the compensation process is simpler.

4. CONCLUSIONS

An angular correction algorithm using sensor fusion of GPS and digital compass for the movement of the agricultural mobile robots in a straight line was developed in this study. It was evaluated the mobile robot ability to accurately and repeatedly maintain established straight line transects under agricultural field conditions, where XTE was measured. Across the field conditions, where straight line XTE was measured, mean XTE did not exceed 5.69 cm. In agricultural practices, it is critical to drive in a straight line from one point to another without deviating for a mobile robot. This deviation is considered to be suitable for the spatial accuracy needed for parallel tracking applications of agricultural mobile robot. The system stability and the convergence of XTE errors to zero have been proven using this algorithm. This proposed algorithm mainly offers a software solution for the movement of the agricultural mobile robots in a straight line. Therefore, it can be easily applied to mobile robots with differential drive system. The future work is toward reducing the cross-track error and integrates in the curved path tracking applications.

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