Development of autonomous navigation system for rice transplanter

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Abstract: Rice transplanting requires the operator to manipulate the rice transplanter in straight trajectories. Various markers are proposed to help experienced drivers in keeping straightforward and parallel to the previous path, which are extremely boring in terms of large-scale fields. The objective of this research was to develop an autonomous navigation system that automatically guided a rice transplanter working along predetermined paths in the field. The rice transplanter used in this research was commercially available and originally manually-operated. An automatic manipulating system was developed instead of manual functions including steering, stop, going forward and reverse. A sensor fusion algorithm was adopted to integrate measurements of the Real-Time Kinematic Global Navigation Satellite System (RTK-GNSS) and Inertial Measurement Unit (IMU), and calculate the absolute moving direction under the UTM coordinate system. A headland turning control method was proposed to ensure a robust turning process considering that the rice transplanter featured a small turning radius and a relatively large slip rate at extreme steering angles. Experiments were designed and conducted to verify the performance of the newly developed autonomous navigation system. Results showed that both lateral and heading errors were less than 8 cm and 3 degrees, respectively, in terms of following straight paths. And headland turns were robustly executed according to the required pattern.

Keywords: autonomous navigation, rice transplanter, sensor fusion, headland turning
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1 Introduction

With applications of autonomous navigation technologies in agriculture, more and more off-road vehicles including tractors, combine harvesters and orchard mobile machines are automatically guided along a desired direction or a predetermined path while performing production tasks[1-5]. Of those research topics, some focused on utilization of absolute localization techniques like Real-time Kinematic Global Positioning System (RTK-GPS), Inertial Measurement Unit (IMU) and compass. And others utilized local positioning methods by using sensors including laser range finders and RGB or depth cameras under structured or semi-structured environments.

For agricultural autonomous navigation, an appropriate positioning method needs to be determined according to the specific requirements of an operation task conducted in the agricultural circle. An autonomous navigation system based on absolute positioning is suitable for seasons like tillage and seeding when global spatial information of the operation area is acquired and there are no objects to be detected or referenced in the field[6-9]. Meanwhile, a relative positioning based navigation system is preferred when agricultural mobile machines perform plant-related operations like intertillage, canopy spraying and crop harvesting, during which crop plants, as the operated targets, are taken as references perceived by navigation sensors like laser scanners and 3D cameras for local positioning of off-road vehicles[10-16]. This study aimed to explore the potential in autonomous navigation for rice transplanters considering the insufficiency of working labors with adequate experience and skilled manipulation of transplanting machines in paddy fields. The newly developed autonomous navigation system in this study was based on absolute positioning by using a Real-Time Kinematic Global Navigation Satellite System (RTK-GNSS) receiver and an IMU as navigation sensors to guide the rice transplanter in traversing along straight paths. This would reduce demands in labors, ensure planting linearity and improve working efficiency compared with manual operation. With regards to absolute positioning, position, heading and speed under the global coordinate system are fundamental parameters to describe the rice transplanter status in kinematics. Position information represented by coordinates under the UTM coordinate system could be obtained through conversion from latitude and longitude measurements of the RTK-GPS rover. And the running speed could be simply derived from two successive UTM coordinates and the elapsed time between them. Besides, various algorithms were used to integrate a serial of sensor measurements in order to obtaining the running speed in a more accurate and stable way[17,18]. To acquire the absolute heading direction, a sensor fusion algorithm was used to estimate the initial deviation and time drifting error of the IMU and compensate its yaw angles that were relative measurements in the vehicle heading direction[1-2].

Headland turning has been remaining as an inspiring research subject involving many researchers during the past decades. The purpose of planning the headland turning process is to minimize the

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number of turnings and the time spent in headlands with implements like seed drillers and fertilizer idle and hitched-up. Martin et al.[19] and Wei et al.[20] depicted different turning patterns including swallowtail, omega and lane-skipping in trajectory shape, which was chosen according to the on-site conditions in a specific field. Zhou et al.[21] analyzed four turn types in terms of required turning space, time consumption, turning smoothness and exit-entry distance by using theoretical simulation and field experiments. Due to the time-consuming and costly maneouvers required by narrow width equipment in sugarcane production, Mark et al.[22] took economic and energy factors into account to observe the impact of headland turning on costs besides operational and spatial factors during four main field operations. And the impacts of turning patterns were obtained as references to minimize time and space for headland treatment. Operating graphs were created by Bochtis and Vougioukas[23] to illustrate different combinations of operating width, turning radius and working route sequence, and non-working travelled distance was analyzed, calculated and optimized as a binary integer programming problem.

The objective of this research was to develop an autonomous navigation system that guided a rice transplanter working along predetermined paths in the field. Such a rice transplanter was able to automatically traverse along parallel straight paths and turn in headlands. This made it possible that a single operator could manage two or more rice transplanters simultaneously to improve working efficiency and alleviate effects of labour shortage on agricultural production. Besides its applicability in rice transplanters, the newly developed autonomous navigation system was also suitable for other agricultural wheeled machines because it was modularized as the automatic steering system, speed control system, sensor fusion and navigation control system based on the CAN-bus communication network.

2 Materials and methods

The rice transplanter platform in this research was a commercial product of SPV-6C ride-on type by Kubota Agricultural Machinery as shown in Figure 1. It features integrated power steering, hydrostatic transmission (HST) and a six-row transplanting implement. A RTK positioning system was established by using two Trimble R8 GNSS receivers as the base station on the ground and the rover station on the rice transplanter, respectively. An IMU LPMS-USBAL by LP-Research was fixed on the platform to provided attitude measurements. A vehicle PC with multiple serial and USB ports was used to collect data from the RTK-GPS rover and the IMU, and implement the sensor fusion algorithm and the autonomous navigation program during field working.

Figure 1 Rice transplanter and main components

2.1 Automatic steering

For compactness in mechanical structure and convenience in installation, an electric assist steering mechanism, composed mainly of steering wheel, upper steering shaft, motor and reducer assembly and U-joint assembly, was utilized to replace the original steering wheel and upper shaft. The image on the left in Figure 2 shows the power steering mechanism in the rice transplanter. Steering torque by the driver is conveyed through the steering shaft to the hydraulic unit that considerably augments the manual effort by controlling hydraulic energy. Therefore, a relatively small torque is needed to steer the rice transplanter while it works in the field. Figure 2 also describes the layout of the newly developed automatic steering mechanism. Motor and reducer assembly provides adequate steering torque that is conveyed to the hydraulic unit through U-joint assembly and splined shaft. The potentiometer detects the rotatory angle of the splined shaft by transmission of pulley assembly, which feeds back the actual steering angle since there exists a nearly linear relationship in rotation between the splined shaft and the front wheel.

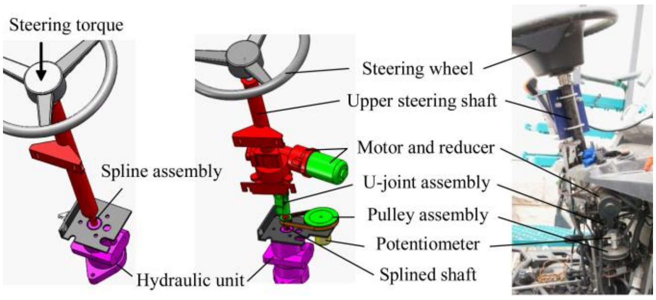


Figure 2 Layout and installation of principal components of the automatic steering mechanism

Figure 3 depicts operational principle of the automatic steering system. The potentiometer is a 5 kΩ type powered by 5VDC. For automatic steering, PID controller keeps reading errors from the comparator unit that implements subtraction between the desired steering angle φ_d and the actual one φ_a. And then it calculates an appropriate voltage V_C, according to which DC motor driver output V_D to control both rotatory direction and speed of the motor.

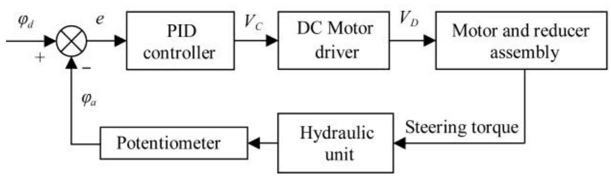


Figure 3 Operational principle of the automatic steering system

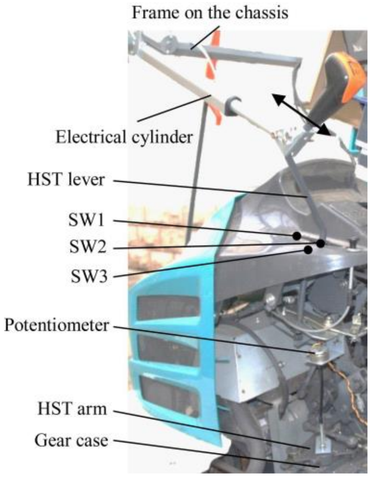
Table 1 shows details about variables mentioned above. With V_D varying from –12 V to 0 the motor rotates from a maximum speed to stop in one direction, while it rotates from stop to a maximum speed in opposite direction with V_D changing from 0 to +12 V. The newly developed automatic steering system was calibrated in terms of its resolution and control accuracy in the laboratory and finally evaluated by autonomous navigation in terms of lateral errors described in section 3.1.

Table 1 Variables for automatic steering

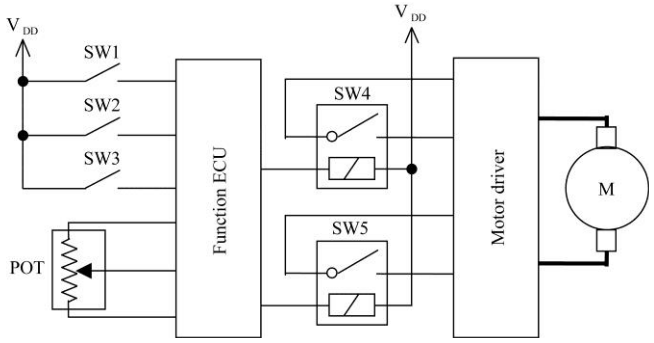
Item	Range/V	Description
φ_d	(0, +5)	Desired steering angle
φ_a	(0, +5)	Actual steering angle
e	(–5, +5)	Angle error, $e=\varphi_d-\varphi_a$
V_C	(–5, +5)	Speed command
V_D	(–12, +12)	Controlling voltage

2.2 Speed control

The rice transplanter in this research features clutchless movements based on the HST that continuously changes running speed and direction (forward/reverse) with the HST lever controlling the HST arm position. For retention of manual operations, the HST lever was retained and an electrical linear cylinder was utilized to provide operational force with its two ends hinged to the HST lever and the chassis, respectively, as shown in Figure 4a.



a. Installation of the electrical linear cylinder



b. Schematic diagram of HST arm position control

Figure 4 Speed control system

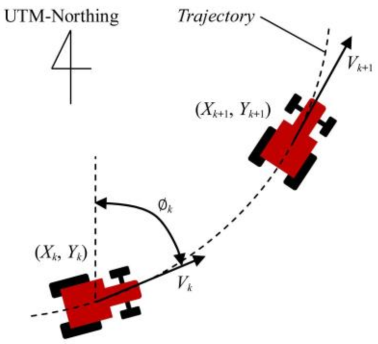
Switches are represented in Figure 4b, of which SW1, SW2 and SW3 as limit switches are installed at the front end, neutral position and the reverse end of the HST lever travel, respectively. And SW4 and SW5 are relays controlled by the function ECU for forward and reverse motion of the electric cylinder, respectively. The potentiometer connects to the HST arm of the gear case and feeds back the arm position. During automatic operation, the function ECU controls motion of the electric cylinder, reads signals from SW1, SW2 and SW3, and records potentiometer values S_F, S_N and S_R corresponding to the switch-on state of these three switches. Then the calibration for speed and directional control is finished. Since the potentiometer works almost linearly with the HST arm rotating, running speed V_a of the transplanter could be represented by Equation (1):

$$V_a = \begin{cases} K_1(S_F - S_N) \\ K_2(S_N - S_R) \end{cases} \tag{1}$$

where, K_1 and K_2 are scalar coefficients in transformation from potentiometer values to actual speeds measured by the RTK-GNSS rover during operation.

2.3 Calculation of absolute heading

The IMU has intrinsic characteristics including time drifting and relative measurement change in yaw, which makes it necessary to calculate absolute heading to eliminate the initial offset and accurately estimate the amount of drifting in yaw measurements of the IMU. In this research, a sensor fusion method was adopted to integrate positioning information from the RTK-GNSS receiver shown in Figure 1 and the yaw measurements from the IMU based on the Least Square Method (LSM) algorithm.



Note: X_k – UTM-Easting, Y_k – UTM-Northing, $\emptyset_k$ – the deviation of heading direction from the UTM-Northing.

Figure 5 Vehicle model along a non-linear trajectory

As shown in Figure 5, (X_k, Y_k) and (X_{k+1}, Y_{k+1}) are vehicle positions at t_k and t_{k+1}, respectively, under the UTM coordinate system. $\emptyset_k$ and V_k are the vehicle's heading direction and instantaneous speed at t_k, respectively, of which, V_k is measured by the RTK-GNSS. The kinematic equation of the vehicle model from t_k to t_{k+1} could be obtained as Equations (2) and (3):

$$X_{k+1} = X_k + \int_{t_1}^{t_2} V(t)\sin\emptyset(t)dt \tag{2}$$

$$X_{k+1} = Y_k + \int_{t_1}^{t_2} V(t)\cos\emptyset(t)dt \tag{3}$$

where,

$$\emptyset(t) = \emptyset_t^{IMU} + D_t \tag{4}$$

Here, $\emptyset_t^{IMU}$ is the relative change measurement in yaw by the IMU and D_t is the correction value used to compensate the IMU drifting over a period of time. Therefore, it is feasible to obtain absolute heading when the value of D_t is known.

The trajectory vectors T_k^{GPS} and T_k^{IMU} measured by the RTK-GPS and IMU from the sampling step k to k+1 could be represented by Equations (5) and (6), respectively:

$$T_k^{GPS} = \begin{bmatrix} X_{k+1} - X_k \\ Y_{k+1} - Y_k \end{bmatrix} \tag{5}$$

$$T_k^{IMU} = \frac{V_k \Delta t}{2} \begin{bmatrix} \sin\emptyset_k + \sin\emptyset_{k+1} \\ \cos\emptyset_k + \cos\emptyset_{k+1} \end{bmatrix} \tag{6}$$

Equation (5) could be discretized on the time base. And according to Equations (5) and (6), the vector error function E_k for N steps could be defined using Equation (7):

$$E_k = \sum_{i=k-N}^{k} \| T_k^{GPS} - T_k^{IMU} \|^2 \tag{7}$$

Since the function E_k is the error sum of N steps, a proper deviation D_k at step k can be determined when E_k convergences to a minimization value according to the LMS algorithm as Equation (8) shows:

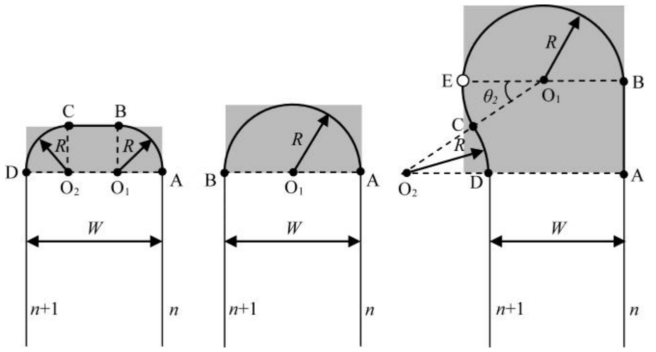
$$\frac{dE_k}{dD_k} = 0 \tag{8}$$

Then, the value of D_k can be calculated by solving Equation (8).

In this research, the running speed V_i (i=k–N, …, k) was measured by the RTK-GNSS. Therefore, information needed for calculating the heading direction included the UTM coordinates and the running speed measured by the RTK-GNSS and the relative change in yaw measured by the IMU. Besides, measurements in pitch and roll denoting the transplanter attitude were used to correct RTK-GNSS measured positions because of deviations of the GPS antenna attachment relative to the center of gravity of the rice transplanter.

2.4 Headland turning

For most agricultural vehicles, the turning process at the field headland is taken into comprehensive consideration in reducing non-operating time and improving working efficiency since the minimum turning radius *R* always has different relationship with the working width *W* of different implements as depicted in Figure 6. And there are many other control methods of headland turning as described by Zhou et al.[21]. It is noticed that a larger area of headland is needed for a larger value of *R* when *W* remains the same.



a. $2R<W$ b. $2R=W$ c. $2R>W$

Figure 6 Procedures for headland turning from path *n* to path *n*+1: (a) Turning left from A to B by a quarter of the turning circle O_1, forward straight to C by a distance of $W–2R$ and then turning left to D by a quarter of the turning circle O_2; (b) Turning left from A to B by a half turning circle O_1; (c) Forward straight from A to B by a distance calculated by Equation (9), turning left from B to C along the circle O_1, turning right from C to D along the circle O_2

For the rice transplanter in this research, it features six transplanting units in 300 mm spacing and a minimum turning radius of 1500 mm. And in consideration that the slip rate is considerably large in paddy fields, the procedure depicted by Figure 6c was used in this research. The distance *d* from A to B and the turning radius *R* could not be fixed for each headland turning procedure because the slip rate was an uncertain factor for different areas even in the same field. During in-field navigation at the headland, *d* would be given a value 1.0 m larger than that calculated by using Equation (9). And the rice transplanter kept straight forward until arriving at point B according to positioning information from the RTK-GNSS receiver. At point B, the yaw angle γ by IMU and the absolute coordinate (E_0, N_0) under the UTM coordinate system was temporarily recorded in the memory. Point E was a key point in step B-C, at which γ had experienced an angular change θ_1 equal to 180° and the position (E_1, N_1) was recorded. The distance from E to B was considered as the turning diameter, according to which the angular change θ_2 in yaw from E to C was determined by using Equation (10). Step C-D required the rice transplanter to keep a right turn by the same angular change as step E-C. The whole procedure in headland turning is illustrated in Figure 7. Step A-B was controlled according to positioning information by the RTK-GNSS receiver while steps B-C and C-D were implemented according to relative angular measurements by the IMU.

$$d=\sqrt{4R^2-W^2} \tag{9}$$

$$\theta_2=\cos^{-1}(W/2R) \tag{10}$$

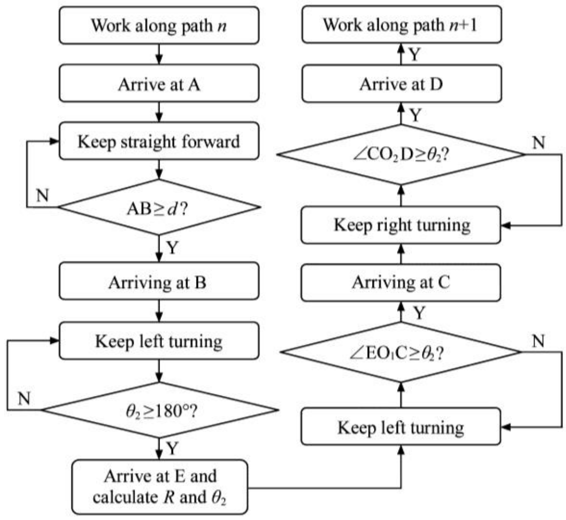
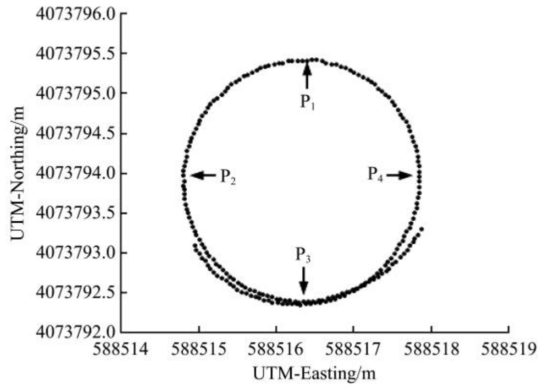


Figure 7 Flow chart for headland turning

3 Results and discussion

A serial of experiments was designed and conducted in a paddy field, Zibo, China on June 25, 2018 to evaluate accuracy in automatic steering control, performance in path tracking and robustness in headland turning. The RTK-GNSS receiver was attached at the center of the beam approximately 2 m above the front tread as show in Figure 8a, which made it more sensitive to localize the rice transplanter compared with its attachment above the rear tread. The rice transplanter was manually operated by its maximum steering angle and the clear turning radius was roughly 1500 mm according to measurements by the RTK-GNSS rover as illustrated in Figure 8b.

a. Experiments in paddy field



b. Trajectory recorded by the RTK-GNSS receiver

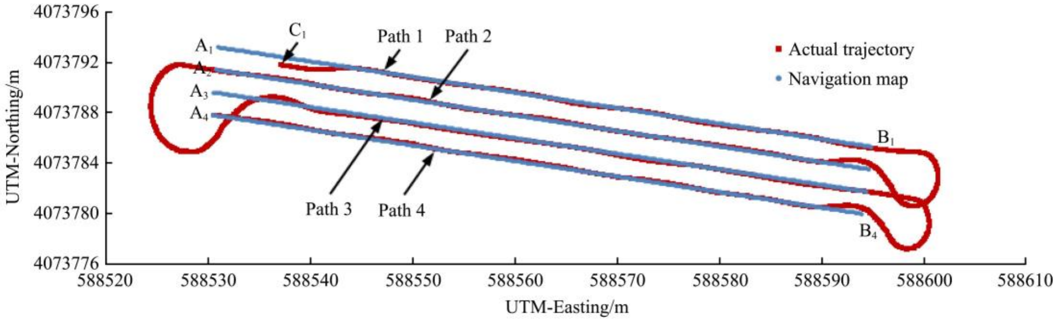
Note: P_1 (588516.463, 4073795.407), P_2 (588514.818, 4073794.028), P_3 (588516.321, 4073792.347) and P_4 (588517.856, 4073793.822).

Figure 8 Measurements for the clear turning radius

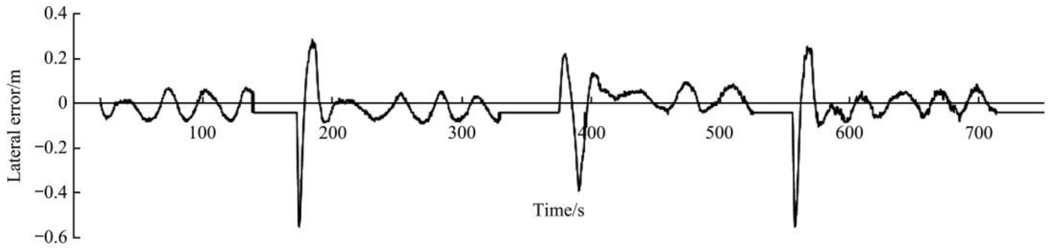
3.1 Evaluation of straight navigation

In most practical applications, the rice transplanter is required to operate in straight trajectories. For experiments in this research, a navigation map consisting of four paths parallel to each other was created by using A_1 (588531.087, 4073793.144) and B_1 (588594.842, 4073785.264) together with the working width of 1800 mm under the UTM coordinate system as shown in Figure 9a. The distance between A_1 and B_1 was about 64 m. And the operation order was set as Path 1, Path 2, Path 3, and Path 4. During autonomous navigation, the rice transplanter was arbitrarily placed at a certain point C_1 (588531.087, 4073793.144) about 0.6 m on the right side of Path 1. From that point, it started to move, finished initialization and then executed autonomous navigation procedures for covering the navigation map. At B_1, the rice transplanter prepared for headland turning with transplanting units idle.

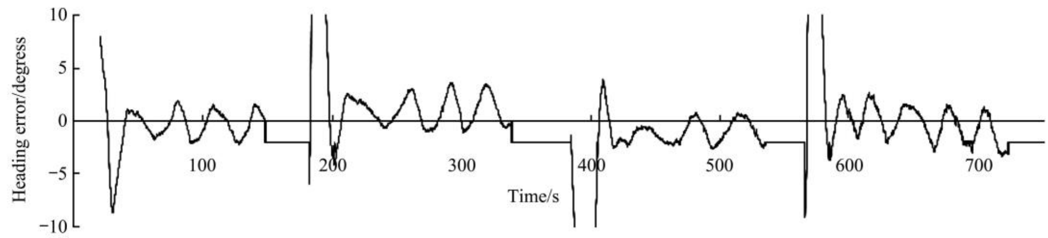
During straight path tracking, the newly developed autonomous navigation system determined the desired steering angle in real-time and sent steering commands to the automatic steering system. Lateral errors were positive values if the RTK-GNSS rover was on the right side of the desired path and heading errors were positive if the actual heading direction was on the right of the desired one. Figures 9b and 9c show both lateral errors and heading errors during autonomous navigation. Results showed that the rice transplanter could follow the path with lateral error and heading error no more than 8 cm and 3 degrees, respectively, after finishing headland turns and converging to a relatively steady state in following straight paths.



a. Navigation map and actual trajectory



b. Lateral error



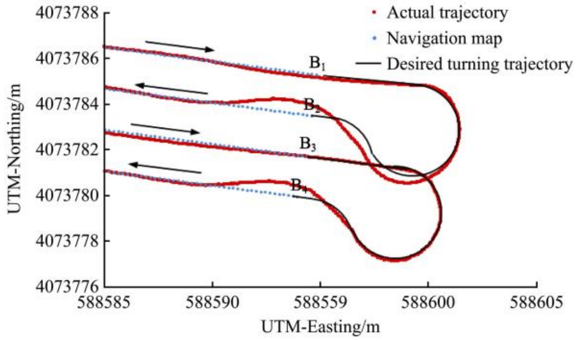
c. Heading error

Figure 9 Autonomous navigation along straight paths

As seen in Figures 9b and 9c, both lateral and heading errors fluctuate around 0 by maximum values of 8 cm and 3 degrees, respectively, in terms of straight navigation, which could meet the requirements in planting linearity for most agricultural applications, especially in paddy fields. Lateral RMS errors were 0.03 m, 0.02 m, 0.02 m and 0.02 m for following path 1, path 2, path 3 and path 4, respectively. And heading RMS errors were 1.9, 1.7, 1.0, and 1.7 in degrees, respectively. It is indicated that the automatic steering system worked in high accuracy and adequate robustness in following straight paths.

3.2 Evaluation of headland turning

The turning radius was set to 1800 mm for headland turning during experiments considering the errors in realizing extreme steering angles. The actual turning radius was calculated and self-learned by the autonomous navigation system for each turn according to RTK-GNSS measurements at predetermined positions as depicted in Figures 6 and 7. And that radius value would be recorded and used for the next turning procedure. As shown in Figure 10, the rice transplanter prepares for headland turning procedures when arriving at ending points such as B_1, A_2 and B_3 in predetermined four paths.



Note: 1st turn is from B_1 to B_2 and 3nd turn is from B_3 to B_4.

Figure 10 Evaluation for headland turning

From actual trajectory for two headland turns in Figure 10, it could be observed that the actual minimum turning radius is a little larger than that in manual mode because the realization of the desired steering angle requires some time and there exists a great slip rate when the rice transplanter turns at its extreme steering angle. It is also noticed that the rice transplanter locates on the right of the desired path when finishing turning procedures, which is not executed exactly as depicted in Figure 6c because of limitation of the steering mechanism in turning left. Since headland turning is not controlled and navigated throughout the whole turning process, it is unavoidable that deviation from the desired turning trajectory is relatively large.

4 Conclusions

In this research, an autonomous navigation system was developed for a rice transplanter that could traverse along straight paths through the target field with a navigation map predetermined according to the field spatial information. The rice transplanter commercially available was utilized and modified into an automatically manipulated one by integrating an automatic steering system and a speed control system. A sensor fusion algorithm was used to estimate the absolute heading error that was a necessary parameter in determining appropriate steering angles. Headland turning was designed in consideration of kinematic characteristics in paddy fields. Experiments were conducted to verify its performances both in following straight paths and executing turns at headlands.

Results showed robust straight tracking with RMS errors no more than 8.0 cm and 3 degrees for lateral offset and heading direction, respectively. And headland turning was automatically performed according to required procedures. It could be concluded that the newly developed steering system worked reliably, the proposed sensor fusion algorithm gave accurate calculation of absolute heading and the newly fabricated navigation program fully automated implementation of algorithms, data processing and management. For general purposes, the newly developed autonomous navigation system could easily be transplanted to other wheeled off-road vehicles like tractors and combines based on its modularization concept. Future work will be focused on the further validation of the newly developed autonomous navigation system for rice transplanting and the finding of countermeasures to longitudinal trackslip and lateral skid during operations in paddy fields.

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