

Article

Design and Field Experiment of an ROS-Based Navigation System for a Wheeled Orchard Mower

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Abstract

To improve autonomous path execution of a wheeled mower in standardized orchards, an ROS-based navigation control system integrating dual-antenna RTK-GNSS positioning and heading, an industrial computer, CAN-based drive control, and wireless manual takeover was developed. Parameterized reference paths consisting of straight sections and U-shaped turns were generated for inter-row operation, and an adaptive Pure Pursuit controller was implemented within the ROS framework. Three repeated field trials were conducted on a U-shaped path at a nominal speed of 0.8 m/s, with conventional Pure Pursuit using a fixed 2.0 m look-ahead distance as a reference. The mower completed the planned path under both controller settings. For the adaptive controller, the mean absolute lateral errors in the curved, straight, and overall sections were 0.124, 0.035, and 0.047 m, respectively. The corresponding overall error for PP-2m was 0.115 m. These results support the feasibility of the developed system for RTK-GNSS-guided closed-loop path tracking under the tested standardized-orchard conditions.

Keywords: orchard wheeled mower; navigation control system; ROS

1. Introduction

With the development of orchard production toward standardization, mechanization, and intelligent management, higher requirements have been placed on the autonomy, operational efficiency, and stability of orchard weeding and mowing equipment. Compared with conventional manual or remote-controlled mowing methods, autonomous mowing systems can reduce labor intensity. They can also improve operation continuity and provide stable technical support for orchard ground management. Recent studies on agricultural mowing and orchard weeding equipment have shown the application potential of autonomous mowing. However, specialized systems for long-term stable operation, inter-plant obstacle avoidance, automatic row switching, and closed-canopy orchard environments are still being developed [1–4]. Therefore, the development of a reliable navigation control platform for unmanned wheeled orchard mowers has clear engineering significance.

Autonomous navigation is a fundamental prerequisite for unmanned orchard operations. Agricultural machinery navigation systems generally include high-precision positioning, environmental perception, path planning, path-tracking control, and drive actuation modules [5,6]. In standardized orchards, operation paths are usually characterized by narrow inter-row spaces, repeated straight-line travel, frequent headland row changes, and high trajectory repeatability. Stable position and heading information should therefore



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be provided by the navigation system. The system should also be readily integrated with reference-path generation and chassis control.

RTK-GNSS, RTK-BDS/INS integrated navigation, dual-antenna RTK-based information fusion, and other GNSS-based navigation systems have been extensively investigated for agricultural machinery. Single-antenna RTK-GNSS provides high-precision absolute positioning within a common coordinate frame. However, vehicle heading is generally estimated from consecutive position measurements or the direction of motion. Consequently, heading availability may decrease when the vehicle is stationary or operating at a very low speed. RTK-GNSS/INS integrated navigation can improve the continuity of vehicle-state estimation but requires additional inertial sensors, sensor calibration, and data-fusion processing. Dual-antenna RTK-GNSS, by contrast, can determine vehicle heading directly from the baseline between the two antennas without relying on vehicle motion. It is therefore well suited to low-speed agricultural platforms that frequently start, stop, and turn. Nevertheless, its positioning and heading performance may still be affected by the availability of differential corrections and the accuracy of antenna installation [7–11]. These navigation configurations present different trade-offs among positioning accuracy, heading availability at low speeds, navigation continuity, and system complexity. Given the low operating speed of the wheeled orchard mower and the repeated U-shaped turns required during operation, a dual-antenna RTK-GNSS system was adopted to provide both absolute position and vehicle heading information. This configuration also supports boundary mapping, target-point guidance, path recording, and repeatable path execution in structured orchard environments.

In addition to satellite-based positioning, vision-, LiDAR-, and SLAM-based methods have been applied to crop-row detection, local navigation, and obstacle perception in orchards and other agricultural environments [12–15]. Rich environmental information can be provided by these perception methods. They are also useful for tree-row extraction and local obstacle response. However, field performance is often affected by illumination variation, canopy occlusion, point-cloud processing complexity, sensor configuration, and onboard computational resources. In standardized orchard mowing, predefined inter-row paths are usually executed repeatedly. Therefore, an RTK-GNSS-based navigation backbone can provide a practical balance between navigation accuracy and engineering implementability when it is combined with structured path generation and a lightweight path-tracking module.

Path planning is another key component of the navigation control chain. Existing studies on agricultural ground robots and orchard mowers have focused on full-coverage path planning, reduction in redundant travel, and coordination of headland turns [16–18]. For orchard mowing, row spacing, cutting width, non-mowing safety margins, and smooth transitions between adjacent operation rows should be considered in reference-path generation. After a feasible reference path is generated, path information and vehicle state are converted into actuator commands by the path-tracking module. Pure Pursuit and its improved forms have been widely used in agricultural vehicle navigation. They have simple geometric structures, low computational costs, and good compatibility with vehicle kinematic models [19–21]. Other control methods, such as sliding mode control, model predictive control, and learning-based control, have also been applied to agricultural vehicle path tracking [22–25]. However, for low-speed wheeled orchard mowers, the control module should remain compatible with limited onboard computing resources, differential-drive actuation, and long-duration field operation. Therefore, the path-tracking function was treated in this study as one module of the navigation control system. It was not treated as an isolated algorithmic objective.

This study developed an ROS-based autonomous navigation platform for an unmanned wheeled orchard mower. The system integrated a dual-antenna RTK-GNSS positioning and heading module, an industrial computer, a drive actuation unit, a wireless remote-control module, and an ROS-based software framework. To meet the requirements of inter-row operation in standardized orchards, a parameterized reference-path generation method was implemented. Straight operation segments, U-shaped turning segments, and transition segments were generated according to the orchard boundary, row spacing, cutting width, non-mowing margin, and headland geometry. The generated paths were then discretized, and curvature information was calculated to support path execution. The main contribution of this study is the orchard-oriented integration of dual-antenna RTK-GNSS positioning and heading, parameterized reference-path generation, adaptive path tracking, and CAN-based differential-drive actuation within an ROS-based closed-loop framework. This integration supports heading acquisition during low-speed operation and enables modular execution of predefined orchard paths. Field experiments on a U-shaped path were conducted to evaluate the closed-loop operation and path-tracking performance of the developed navigation control system. During the tests, the positioning and heading, reference-path management, path-tracking control, and CAN-based actuation modules operated cooperatively within the ROS framework. The results provide a system-level reference for the development and field application of autonomous navigation platforms for wheeled orchard mowers.

The remainder of this paper is organized as follows. Section 2 describes the hardware and software architecture of the navigation control system, the Pure Pursuit path-tracking method, the adaptive path-tracking module, the parameterized reference-path generation method, and the field experimental procedures. Section 3 presents and analyzes the results of the U-shaped path-tracking experiments. Section 4 discusses system performance, the factors affecting tracking errors, the applicability of the developed system, and its current limitations. Finally, Section 5 summarizes the main conclusions and identifies directions for future work.

2. Materials and Methods

2.1. Design of the Navigation Control System

To achieve high-precision positioning, stable heading estimation, and autonomous path tracking in standardized orchard inter-row environments, a navigation control system was developed for the unmanned wheeled orchard mower. The system consisted of a positioning and heading module, a main control module, a drive actuation module, a wireless remote-control module, and an ROS-based software system. The operating principle was as follows. First, real-time position and heading information of the mower were acquired by the dual-antenna RTK-GNSS system. Then, the positioning data were parsed by the industrial computer. Coordinate transformation was performed, the reference path was loaded, and path-tracking control commands were calculated. Finally, the control commands were transmitted to the low-level drive controller through CAN communication. In this way, stable travel along the target path was achieved.

The positioning and heading module used an NC504 GNSS receiver (Beijing BDStar Navigation Co., Ltd., Beijing, China) and two GPS500 tri-constellation seven-frequency GNSS antennas (Harxon Corporation, Shenzhen, China). A dual-antenna RTK-GNSS positioning and heading system was constructed. As shown in Figure 1, centimeter-level positioning and vehicle heading information could be provided directly by the dual-antenna RTK-GNSS system. Compared with a single-antenna system, this configuration was more suitable for low-speed mobile platforms.

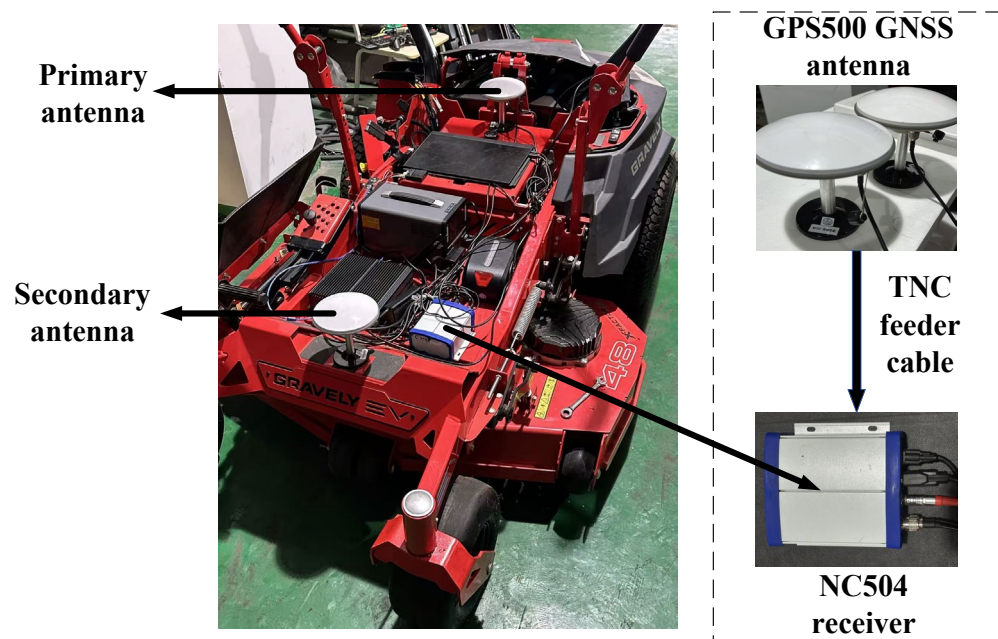


Figure 1. Dual-antenna RTK-GNSS positioning and heading system.

For receiver selection, the NC504 receiver equipped with the UM982 high-precision positioning and heading module (Unicore Communications, Inc., Beijing, China) was used. The NC504 receiver was compact and lightweight. It supported a 9–36 V DC input voltage range and could be integrated into the onboard platform of the wheeled mower. Two RS232 serial ports were provided by its communication interface. Thus, a stable data transmission link with the industrial computer was established. For antenna configuration, two Huaxin GPS500 survey-grade antennas were selected. Multi-constellation and multi-frequency signal reception were supported, including GPS, BDS, and GLONASS. A stable phase center and high gain were also provided. Therefore, the multi-frequency solution capability of the UM982 module was fully used. The hardware connections of the navigation control system are shown in Figure 2.

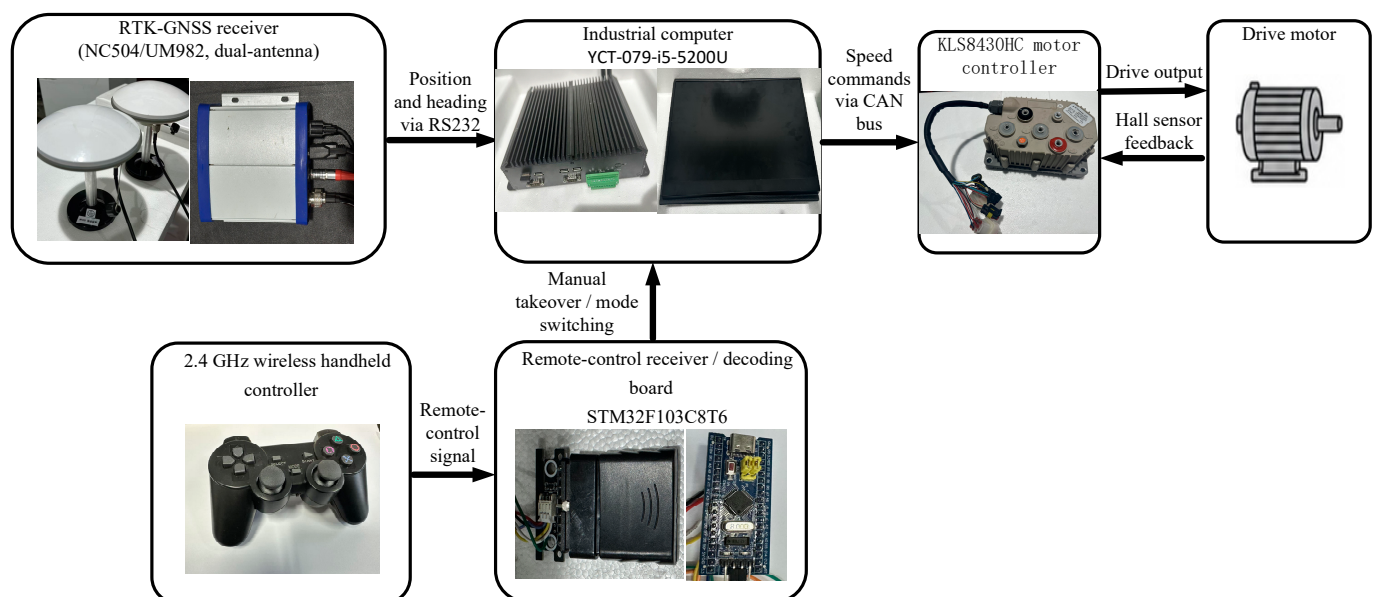


Figure 2. Hardware connection diagram of the navigation control system.

The mower adopted a rear-wheel differential-drive configuration. The two rear wheels were independently driven by two 5 kW brushless DC motors, each equipped with a KLS8430HC motor controller (Kelly Controls, Hefei, China), while the front wheels were passive caster wheels. The drive-wheel radius, rear-wheel track width, wheelbase, and total vehicle mass were 0.27 m, 0.92 m, 1.43 m, and 572 kg, respectively. The field path-tracking experiments were conducted at a nominal commanded longitudinal speed of 0.8 m/s. The absolute value of each drive-wheel speed command was limited to 1.2 m/s, and its rate of change was limited to 0.5 m/s². Independent speed control was implemented for the left and right drive wheels. The path-tracking controller converted the commanded longitudinal and angular velocities into left- and right-wheel target velocities according to the differential-drive kinematic model. The actual speeds of the two motors were acquired separately and used as feedback for two independent PID control loops. The resulting left- and right-drive commands were transmitted independently through the CAN bus to the corresponding KLS8430HC controllers, thereby enabling independent control of the two rear drive wheels.

The main controller was a YCT-079-i5-5200U industrial computer (Shenzhen Yancheng-tuo Technology Co., Ltd., Shenzhen, China). Sufficient computing performance, multiple industrial communication interfaces, and strong environmental robustness were provided by the industrial computer. The control requirements of the unmanned orchard mower under outdoor conditions were met. These conditions included vibration, temperature variation, and long-duration operation. The system software was run on the ROS platform. The main controller was responsible for GNSS data parsing, vehicle-state acquisition, reference-path management, path-tracking algorithm computation, and low-level command transmission. Vehicle position and heading information were output by the RTK-GNSS receiver through the RS232 interface. Control commands were calculated by the industrial computer according to the path-tracking algorithm. The commands were then sent to the KLS8430HC motor controller through the CAN communication module. Thus, a closed-loop process from positioning perception and control decision-making to drive actuation was formed.

To support autonomous operation and safe manual takeover, a 2.4 GHz wireless spread-spectrum handheld controller was used as the remote-control terminal. Compared with mobile-terminal control methods based on Wi-Fi or Bluetooth, this remote-control method provided stronger anti-interference capability. More direct operational feedback was also provided. Therefore, the requirements for manual remote control within line-of-sight range were met. In addition, an embedded decoding board based on the STM32F103C8T6 (STMicroelectronics, Geneva, Switzerland) was designed. Remote-control signals were parsed by this board and connected to the low-level control network. A CAN bus transceiver circuit based on a TJA1050 high-speed CAN transceiver (NXP Semiconductors N.V., Eindhoven, The Netherlands) was integrated into the decoding board. Communication with the vehicle drive network was implemented through this circuit. Thus, effective switching between autonomous control and manual takeover was ensured.

The system software was developed using ROS Kinetic Kame on Ubuntu 16.04 LTS and organized within a Catkin workspace, as shown in Figure 3. The core functional package, `path_tracking`, mainly comprised the navigation, coverage_planner, purepursuit, and control nodes. The navigation node received GGA position data and TRA dual-antenna heading data from the RTK-GNSS receiver via the RS232 interface. It published the WGS-84 position on the `gnss_pos` topic using the `sensor_msgs/NavSatFix` message type, the transformed local ENU position on the `enu_pos` topic using the custom `path_tracking/enu_pos` message type, and the vehicle heading on the `gnss_yaw` topic using the `std_msgs/Float32` message type. These data were updated at 10 Hz. Both the vehicle position and the reference path were expressed in the same local ENU map frame.

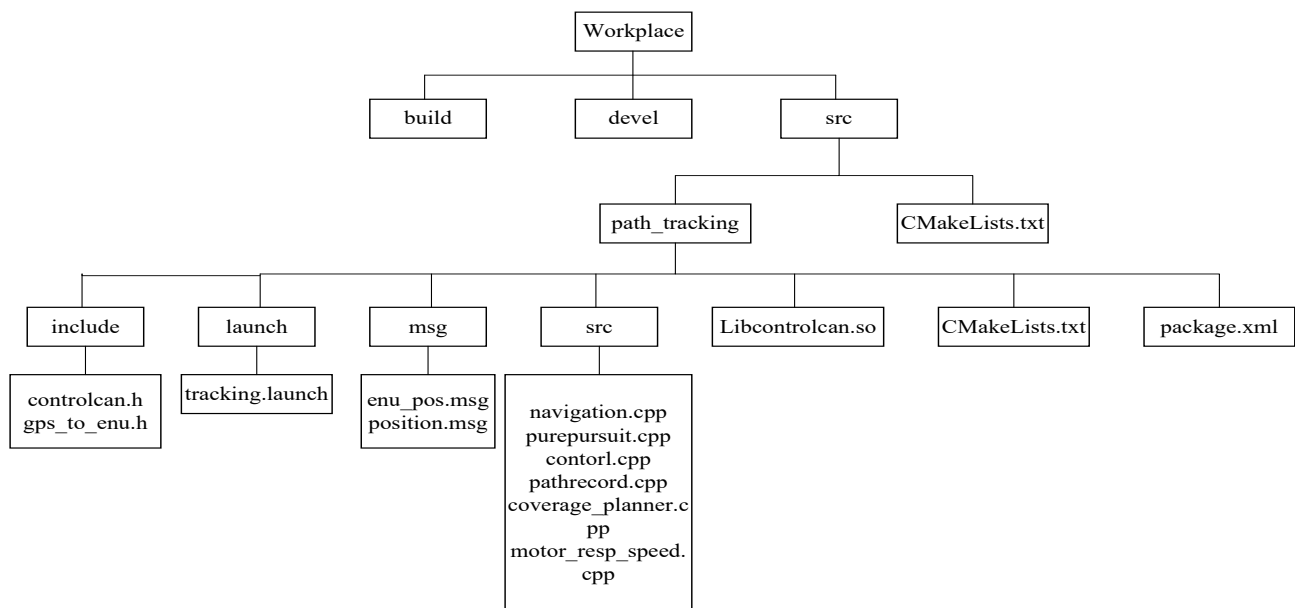


Figure 3. ROS project workspace.

The coverage_planner node generated and managed the discretized reference path and published it on the reference_path topic as a nav_msgs/Path message. The purepursuit node subscribed to the ENU position, vehicle heading, and reference path, calculated the linear and angular velocity commands at 10 Hz, and published them on the cmd_vel topic as a geometry_msgs/Twist message. The control node converted these commands into target speeds for the left and right drive wheels, applied separate PID regulation using the corresponding motor-speed feedback, and transmitted the resulting drive commands to the two motor controllers via a CANalyst-II USB-CAN interface (Zhuhai Chuangxin Technology Co., Ltd., Zhuhai, China) interface at 20 ms intervals.

2.2. Pure Pursuit Path-Tracking Method

The Pure Pursuit algorithm is a typical geometric look-ahead path-tracking method. Its basic principle is to select a look-ahead point on the reference path at a specified look-ahead distance from the current vehicle position. The control command is then calculated from the geometric relationship between the current vehicle pose and the look-ahead point. The vehicle is thereby guided to converge to the target path. This method has an intuitive principle, low computational cost, and simple engineering implementation. Therefore, it has been widely used for path-tracking control of mobile robots and autonomous vehicles. In this study, a low-speed differential-drive orchard mower was used as the research object. Real-time performance and stability were required during operation. Therefore, the Pure Pursuit algorithm was selected as the basis for path-tracking control.

The geometric relationship of the Pure Pursuit algorithm is shown in Figure 4. In the navigation coordinate system xOy , the current vehicle position is denoted as point A. The vehicle heading angle is denoted as θ . The look-ahead point on the reference path is denoted as point C, with coordinates (X_C, Y_C) . The Euclidean distance between the current vehicle position and the look-ahead point is defined as the look-ahead distance L_d . The angle between the direction from the vehicle to the look-ahead point and the vehicle heading is defined as the look-ahead deviation angle α . The desired angular velocity of the vehicle is calculated by the controller according to L_d and α . It is then converted into left- and right-wheel velocity commands. Thus, reference-path tracking is achieved.

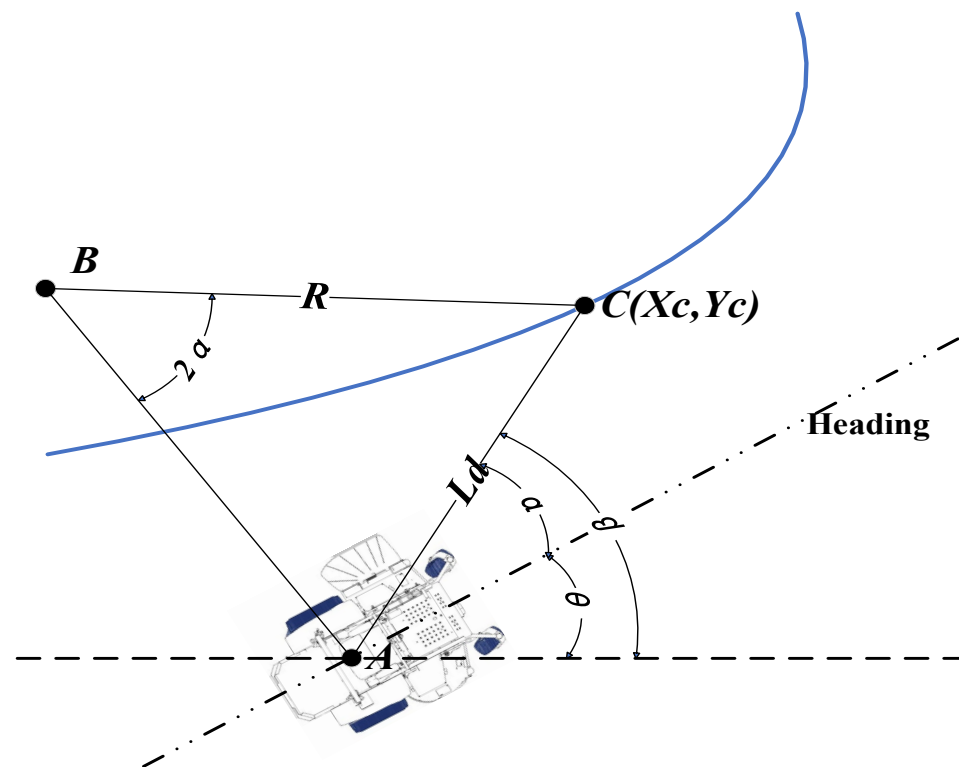


Figure 4. Pure Pursuit model. The blue curve denotes the reference path.

The main control relationships used for path-tracking control in this study are as follows:

$$\omega = \frac{2v\sin\alpha}{L_d} \quad (1)$$

$$v_r = v + \frac{b\omega}{2}, v_l = v - \frac{b\omega}{2} \quad (2)$$

In Equation (2), the rear-wheel track width, (b), was set to 0.92 m. The field path-tracking experiments were conducted at a nominal commanded longitudinal speed of 0.8 m/s, with the speed command gradually increased from 0 to 0.8 m/s during startup. The magnitude of each drive-wheel speed command was limited to 1.2 m/s, and its rate of change was limited to 0.5 m/s². During turning, if either wheel-speed command exceeded this limit, both commands were scaled by the same factor. This ensured that the wheel-speed commands remained within the allowable range while preserving their ratio and the commanded path curvature.

Here, ω is the desired angular velocity of the vehicle; v is the longitudinal vehicle velocity; L_d is the look-ahead distance; α is the look-ahead deviation angle; b is the vehicle track width; and v_r and v_l are the linear velocities of the right and left wheels, respectively. As indicated by Equations (1) and (2), the look-ahead distance L_d is a key parameter affecting the control performance of the Pure Pursuit algorithm. When L_d is large, the control process becomes smoother. However, steering lag may occur on curved sections and in straight-to-curved transition regions. When L_d is small, the vehicle responds more sensitively to path changes. However, control oscillations may be induced. Therefore, the look-ahead distance should be adjusted according to the geometric characteristics of the path. This adjustment is important for improving the tracking performance of the Pure Pursuit algorithm under composite path conditions in orchards.

2.3. Implementation of the Adaptive Path-Tracking Module

To improve path-execution stability along composite orchard paths, an adaptive Pure Pursuit path-tracking module was integrated into the navigation control system. The conventional geometric structure and low computational cost of the Pure Pursuit method were retained, with the look-ahead distance L_d , serving as the only variable adjusted online.

During operation, the path-tracking node received the current vehicle position, heading, and ordered reference-path sequence through the ROS framework. For each candidate look-ahead distance, the vehicle position and heading at the next control step were predicted using the differential-drive kinematic model. The look-ahead distance was then selected by minimizing the following objective function:

$$L_d^* = \underset{L_d \in [L_{d,\min}(\kappa), L_{d,\max}(\kappa)]}{\operatorname{argmin}} (a_1 e_1^2 + a_2 e_2^2), a_1 + a_2 = 1, \quad (3)$$

where e_1 is the normalized distance error between the predicted vehicle position and the target point and therefore incorporates the lateral-error component, whereas e_2 is the normalized heading error relative to the tangent direction of the reference path at the target point. These two error terms were jointly used to evaluate each candidate look-ahead distance rather than serving as separate switching thresholds. The allowable search interval for the look-ahead distance was continuously adjusted according to the local path curvature k , as follows:

$$L_{d\min}(k) = \max\left(0.5L - 0.1L \cdot \min\left(\frac{k}{k_{\max}}, 1\right), 0.4L\right),$$

$$L_{d\max}(k) = \begin{cases} 1.7L + 0.7L \cdot \exp\left(-\frac{k}{k_0}\right) & (k > 0) \\ 2.7L & (k = 0) \end{cases} \quad (4)$$

where $L = 1.43$ m is the mower wheelbase, $k_{\max}$ is the maximum curvature of the reference path, and $k_0 = 0.1\text{m}^{-1}$ is the curvature-decay coefficient. No discrete curvature-switching threshold was applied. Instead, the allowable search interval narrowed continuously as the local curvature increased. This maintained a relatively broad search range along straight segments while preventing the selection of excessively large look-ahead distances in turning segments.

The bounded online search defined in Equation (3) was performed at 10 Hz. The resulting optimal look-ahead distance, L_d^* , was provided to the Pure Pursuit controller to calculate the desired angular velocity and the target velocities of the left and right drive wheels. The adaptive module was implemented in the ROS package `path_tracking` and operated in coordination with the GNSS data-parsing, reference-path management, wheel-speed control, and CAN communication modules, thereby forming a complete closed-loop navigation control process.

2.4. Path Planning Method

To facilitate the practical implementation of path planning, a parameterized method was used to describe inter-row operation paths in standardized orchards, as illustrated in Figure 5. The boundary points $P_1(x_1, y_1)$, $P_2(x_2, y_2)$, $P_3(x_3, y_3)$, and $P_4(x_4, y_4)$ were connected sequentially to form the closed outer boundary of the planned operating area. The start point $A_0(x_{A0}, y_{A0})$ and end point $B_0(x_{B0}, y_{B0})$ defined the position and direction of the first straight operation path. The areas between the endpoints of the straight paths and the corresponding outer boundaries were designated as headlands. Within each headland, the areas available for connecting adjacent straight paths were defined as feasible turning regions. Additional input parameters included the single-row operation length L , row spacing W_d , number of operation rows N , cutting width B , half-width of the non-mowing strip w , and path-sampling resolution Δs . The path-sampling resolution was set to 0.1 m.

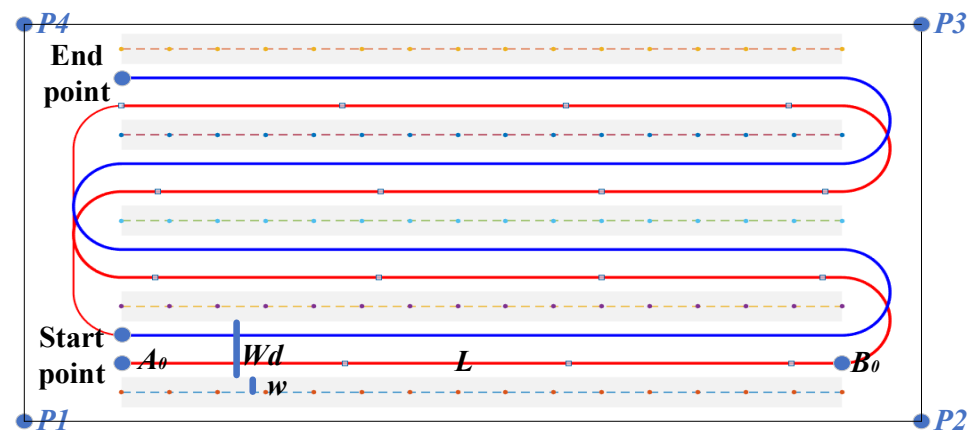


Figure 5. Schematic diagram of the path planning method. The red and blue solid curves denote the first and second coverage passes, respectively. The shaded bands represent the non-mowing strips. Within the shaded bands, the dashed lines denote the tree-row centerlines, and the small dots indicate individual trees. The labeled blue points indicate the boundary points and the start and end points of the reference path.

Since both path planning and positioning were performed in the global coordinate system, the reference path-point sequence was generated directly in the global coordinate system. To describe the translation relationship along the tree-row direction, the operation-direction unit vector e_x and its normal unit vector e_y were constructed from the reference line A_0B_0 :

$$e_x = \frac{B_0 - A_0}{\|B_0 - A_0\|} \quad (5)$$

$$e_y = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} e_x \quad (6)$$

where e_x denotes the direction along the operation rows, and e_y denotes the cross-row direction. All straight operation segments were generated parallel to e_x . The first coverage pass in the first channel was selected as the reference, with $A_{1,1} = A_0$. The endpoint $A_{k,m}$ of the m -th coverage pass in the k -th channel was obtained by translating A_0 along e_y . Accordingly, each straight operation path was expressed as follows:

$$A_{k,m} = A_0 + [(k-1)W_d + (m-1)B]e_y, p_{k,m}(s) = A_{k,m} + se_x, s \in [0, L] \quad (7)$$

where $k = 1, \dots, N$ denotes the channel index, $m = 1, \dots, M_k$ denotes the coverage-pass index within the k -th channel, and M_k is the number of coverage passes in that channel. The term $(k-1)W_d$ represents the lateral offset between adjacent channels, whereas $(m-1)B$ represents the lateral offset between successive coverage passes within the same channel. Here, $A_{k,m}$ denotes the endpoint of the corresponding straight segment on the A_0 side.

To account for tree trunks, drooping branches, and operational safety margins, non-mowing strips with a half-width of w were defined on both sides of each tree-row centerline. The available operating width between two adjacent tree rows was therefore calculated as follows:

$$W_n = W_d - 2w \quad (8)$$

where W_d is the center-to-center spacing between adjacent tree rows, and W_n is the available operating width after excluding the non-mowing strips on both sides. When the available width of a channel exceeded the cutting width, multiple coverage passes were required to

ensure complete coverage. In this study, the number of coverage passes in each channel was determined from the cutting width B as follows:

$$M = \left\lceil \frac{W_n}{B} \right\rceil \quad (9)$$

Based on Equation (9), the operation centerlines were initially generated at intervals equal to the cutting width B . When the residual width after the preceding passes was smaller than B , the final centerline was repositioned $B/2$ inward from the opposite boundary of the available operating strip. Consequently, the outer edge of the final cutting swath coincided with the safe boundary, while its overlap with the preceding swath ensured complete coverage without entering the non-mowing strip.

To reduce the non-working travel distance during row switching, a reciprocating traversal sequence was adopted. A discrete state variable D_k was defined to represent the operation direction of the k -th channel. When $k = 2q$, namely for even-numbered channels, $D_k = +1$. The straight segment was then traversed along the e_x direction. When $k = 2q + 1$, namely for odd-numbered channels, $D_k = -1$. The straight segment was then traversed along the $-e_x$ direction. This strategy enabled the robot to switch between adjacent channels with the shortest travel distance. A continuous serpentine coverage pattern was thereby formed.

In standardized orchards, the available headland space is limited. Although an in-place turn can reverse the mower direction, it may produce a discontinuous connection between successive path segments and increase disturbance to the headland soil and vegetation. Therefore, a U-shaped turning path was designed to connect adjacent channels, provided that the required turning radius was not smaller than the minimum allowable turning radius. The connection between the m -th pass in the k -th channel and the corresponding m -th pass in the $(k + 1)$ -th channel was considered as an example. Let S and E denote the turning start and end points in the global ENU coordinate system, respectively. Depending on the serpentine travel direction, S was located at the terminal point of the current straight segment, whereas E was located at the corresponding terminal point of the adjacent straight segment. The two straight-path centerlines were parallel, traversed in opposite directions, and separated laterally by the row spacing W_d . This separation defined the diameter of the semicircular turn. Accordingly, the turning radius R and circle center C were determined as follows:

$$R = \frac{W_d}{2}, C = \frac{S + E}{2} \quad (10)$$

A local arc coordinate system was established with its origin at C , its x -axis oriented along $D_k e_x$, and its y -axis oriented along e_y . The local semicircular arc was parameterized as follows:

$$\begin{cases} x(\varphi) = R \cos \varphi \\ y(\varphi) = R \sin \varphi \end{cases}, \varphi \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right] \quad (11)$$

where $-\pi/2$ and $\pi/2$ denote the initial and final angular parameters, respectively. The corresponding semicircular path in the global ENU coordinate system was expressed as follows:

$$P_U(\varphi) = C + R(D_k \cos \varphi e_x + \sin \varphi e_y) \quad (12)$$

Here, $D_k = +1$ and $D_k = -1$ correspond to counterclockwise and clockwise turns, respectively.

When multiple coverage passes were required within a channel ($M > 1$), the robot needed to return to the next centerline of the first channel after completing the first serpentine coverage pass. This centerline served as the starting straight line for the next pass. To avoid repeated compaction caused by crossing the interior of the operation area, a transition

segment was constructed outside the operation area along the outer edge of the headland. This arrangement also reduced repeated wheel traffic within the treated area, thereby limiting unnecessary disturbance to soil physical conditions during repeated mechanized operations [26]. The robot was thereby moved smoothly from the current endpoint to the starting point of the next pass. In the engineering implementation, a combined transition consisting of an arc, a straight segment, and another arc was adopted. This design satisfied the non-holonomic constraints and trajectory-continuity requirements. It also ensured that the transition segment did not affect inter-row coverage.

To facilitate real-time path tracking, the continuous geometric path was converted into a discrete path-point sequence containing attribute information. With the path sampling resolution set to Δs , which was 0.1 m in this system, the generated continuous path was interpolated and sampled. An ordered set of path points was then obtained:

$$P = \{P_1, P_2, \dots, P_{N_p}\} \quad (13)$$

To support stable path execution in different path sections, the geometric curvature k_i of each path point was calculated in advance. For straight path segments, $k \approx 0$. For U-shaped turning segments, $k = 1/R = 2/W$. This curvature information was provided to the path-tracking module as geometric reference information. The controller could then adjust the look-ahead behavior according to the path section while maintaining stable vehicle motion.

2.5. Experimental Method

To evaluate the closed-loop operation of the developed navigation control system under composite-path conditions, a U-shaped path-tracking experiment was conducted based on the reciprocating row-switching pattern commonly used in orchard mowing. The experiment was performed at Anyuan Farm in Zhenjiang, Jiangsu Province, China, and the test site is shown in Figure 6. The path starting point was located at 32.11437301° N and 119.66885661° E. A local ENU navigation frame was established by transforming the WGS-84 coordinates. The orchard row spacing and available headland width were 4.0 and 4.3 m, respectively. The U-shaped reference path comprised a 23.5 m entry straight segment, a semicircular turning segment with a radius of 2.0 m, and a 23.5 m exit straight segment. The mower dimensions were 210.8 cm $\times$ 127 cm $\times$ 87 cm in length, width, and height, respectively, with a wheelbase of 1.43 m and a rear-wheel track width of 0.92 m. The inter-row terrain was generally level, with no evident longitudinal or lateral slope. The soil surface was relatively dry and firm and consisted primarily of exposed soil with scattered pruned branches and dry plant residues. Sparse, low-growing weeds were present, whereas no evident waterlogging, muddy areas, or dense ground vegetation was observed. These conditions represented a standardized orchard with fixed row spacing and headland geometry and were used to assess the complete closed-loop operation of the navigation system during a typical U-shaped row-switching maneuver.

After the boundary information of the operating area, reference-line points, and other planning parameters were specified, the path planner generated the complete reference path. A representative U-shaped path unit was then extracted from the planning result and used for the path-tracking experiment. The path was discretized into an ordered sequence of points at a fixed spatial resolution of 0.1 m. The adaptive Pure Pursuit module integrated into the ROS-based framework was used for path-tracking control. Conventional Pure Pursuit with a fixed look-ahead distance of 2.0 m, denoted as PP-2m, was also tested as a fixed-look-ahead reference under the same path, commanded speed, initial conditions, and control settings.



Figure 6. Field experiment site.

The nominal commanded longitudinal speed was set to 0.8 m/s. The GNSS receiver provided position and heading data at 10 Hz, and the path-tracking controller updated the target linear and angular velocities at the same frequency. CAN commands were transmitted at 50 Hz, and the PC-side wheel-speed PID controllers also operated at 50 Hz, corresponding to a control cycle of 20 ms. Trajectory-related variables were logged at 10 Hz.

During the experiment, the vehicle position and heading (x , y , ψ), reference-point index, lateral error, heading error, and other variables were recorded through the ROS-based data-logging module. The experiment was repeated three times, and statistical indicators were calculated. The initial vehicle heading was set to $\psi_0 = 0^\circ$. Starting from the initial point, the vehicle completed the full U-shaped trajectory along the reference path. The trajectory consisted of an entry straight, a turning arc, and an exit straight. Across the three repeated trials, approximately 299, 87, and 303 valid trajectory points were recorded on average in these sections for the adaptive controller, whereas the corresponding values for PP-2m were approximately 301, 92, and 309, respectively. Curved sections were defined as arc segments with $|k| > 0$, whereas straight sections were defined as intervals with $k = 0$. The mean lateral error, standard deviation of lateral error, and maximum lateral error were calculated for each section.

For each recorded vehicle position (x , y), the Euclidean distances to all discrete reference-path points were calculated. The reference point with the minimum distance was selected as the nearest point, $P_i = (x_i, y_i)$. The local reference heading was then calculated from P_i and the subsequent reference point P_{i+1} as follows:

$$\psi_i = \text{atan2}(y_{i+1} - y_i, x_{i+1} - x_i)$$

The lateral error was defined as the signed perpendicular distance from the vehicle position to the local tangent of the reference path:

$$e_y = (x - x_i) \sin \psi_i - (y - y_i) \cos \psi_i.$$

Under this sign convention, a positive lateral error indicated that the vehicle was located on the right side of the reference-path direction, whereas a negative value indicated that it was located on the left side. The heading error was calculated as $e_\psi = \psi - \psi_i$ and normalized to the interval $(-\pi, \pi]$.

3. Results and Discussion

3.1. Experimental Preparation

To ensure the reliability of the path-tracking experiment, the positioning, path planning, drive communication, and safety protection functions were checked before the formal test. First, the dual-antenna RTK-GNSS module was installed. The two antennas were connected to the NC504 receiver through TNC feeder cables. The receiver was connected to the industrial computer through the RS232 serial port. The system was then connected to an RTK correction service provided by Qianxun Spatial Intelligence Inc. (Shanghai, China) via a 4G network. The serial data output, positioning solution status, number of satellites, HDOP, and coordinate stability were checked. These checks were used to confirm that RTK positioning and dual-antenna heading estimation operated normally.

After the positioning status became stable, the boundary-point coordinates, start point, row spacing, number of rows, operation width, and turning radius were entered according to the experimental site. A straight path or U-shaped composite path was then generated and discretized into a reference point set. This set could be called by the path-tracking program. Meanwhile, the consistency between the heading angle and the actual vehicle orientation was checked under stationary and low-speed straight-line conditions. Small-angle steering was then performed. The test was used to verify that the heading change direction was consistent with the vehicle turning direction. Thus, errors in the coordinate system or heading sign were avoided.

Finally, CAN communication and the responses of the left and right drive motors were tested under low-speed conditions. The speed commands, braking commands, and feedback data were checked. The emergency stop button and communication-fault protection function were also verified. Thus, prompt braking under abnormal conditions was ensured. After these checks and a short-distance preliminary run had been completed, the path-tracking experiment was conducted.

3.2. Field Test Results and Analysis

Figure 7 shows a representative trajectory obtained during the U-shaped field experiment. The trajectory from the second adaptive Pure Pursuit trial was selected because its overall mean absolute lateral error was closest to the three-trial average. The measured trajectory generally followed the reference path. Tracking was relatively stable along the straight sections, whereas larger deviations occurred primarily in the turning section and the adjacent transition regions.

During the field experiments, the CAN bus baud rate was set to 500 kbps. Both the drive-command and motor-speed-feedback update periods were 20 ms, and the maximum recorded command interval was 30 ms. No communication interruption affecting mower operation was observed, and the emergency-stop function operated normally. These observations confirmed that CAN communication remained stable throughout the path-tracking experiments.

The instantaneous lateral error e_y was defined as the signed perpendicular distance from the vehicle position to the local tangent of the reference path. In this section, the reported mean lateral error refers to the mean absolute value of e_y , and the maximum lateral error was calculated from the absolute value of e_y . As shown in Table 1, the mean absolute lateral errors obtained with the adaptive Pure Pursuit controller were 0.124, 0.035, and 0.047 m for the curved section, straight sections, and overall path, respectively. The relatively small mean error in the straight sections indicated stable path execution during inter-row travel.

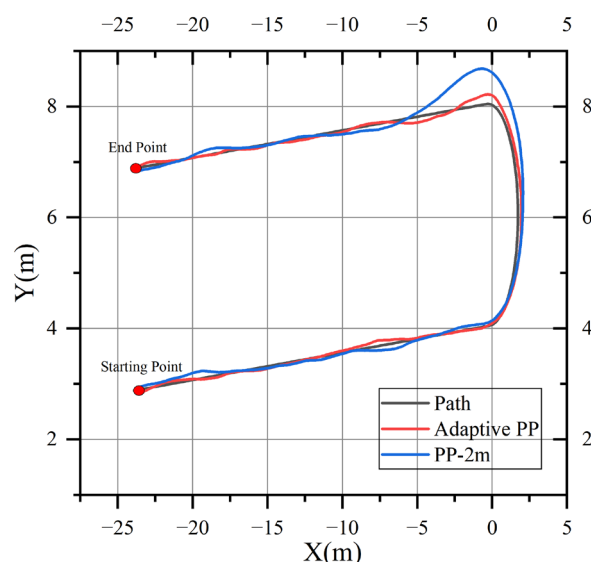


Figure 7. Representative trajectory obtained in the U-shaped path-tracking experiment.

Table 1. Lateral-error statistics of the adaptive Pure Pursuit controller.

Path Section	Mean Absolute Lateral Error (m)	Standard Deviation of Lateral Error (m)	Maximum Absolute Lateral Error (m)
Curved	0.124 ± 0.011	0.075 ± 0.018	0.219 ± 0.028
Straight	0.035 ± 0.002	0.045 ± 0.003	0.157 ± 0.038
Overall	0.047 ± 0.002	0.063 ± 0.006	0.219 ± 0.028

Values are presented as the mean $\pm$ standard deviation of the corresponding trial-level metrics from three repeated trials.

The larger mean error in the curved section was mainly associated with the operating characteristics of the U-shaped turn. Turning required a higher angular velocity and a larger speed difference between the left and right drive wheels, making deviations in differential-drive response more evident. Changes in curvature at the straight-to-arc connections also produced transient tracking responses. Conventional Pure Pursuit with a fixed look-ahead distance of 2.0 m, denoted as PP-2m, was additionally evaluated under the same reference path, commanded speed, initial conditions, control frequency, and low-level control parameters. As shown in Table 2, its mean absolute lateral errors were 0.305, 0.085, and 0.115 m for the curved section, straight sections, and overall path, respectively.

Table 2. Lateral-error statistics of PP-2m.

Path Section	Mean Absolute Lateral Error (m)	Standard Deviation of Lateral Error (m)	Maximum Absolute Lateral Error (m)
Curved	0.305 ± 0.014	0.261 ± 0.030	0.698 ± 0.061
Straight	0.085 ± 0.001	0.162 ± 0.009	0.742 ± 0.048
Overall	0.115 ± 0.003	0.195 ± 0.006	0.742 ± 0.048

Values are presented as the mean $\pm$ standard deviation of the corresponding trial-level metrics from three repeated trials.

For both controller settings, the mean absolute lateral error varied among path sections and was higher in the curved section than in the straight sections. This pattern was consistent with the geometric characteristics and turning-control requirements of the U-shaped path. The lower error level obtained with the adaptive configuration supported the use of online look-ahead-distance adjustment in the navigation system. More importantly, the mower completed the entire reference path under both look-ahead configurations.

This result indicated that the developed navigation control system maintained continuous closed-loop path execution and supported the feasibility of its overall architecture and hardware–software integration under the tested orchard conditions.

4. Discussion

From a system-level perspective, the field results demonstrated that dual-antenna RTK-GNSS positioning and heading, parameterized reference-path generation, adaptive path tracking, and CAN-based differential-drive actuation could be integrated within the ROS framework to support low-speed execution of a U-shaped path. The error results supported the use of curvature-dependent look-ahead-distance adjustment. Moreover, successful completion of the reference path under both look-ahead configurations indicated that the overall navigation architecture maintained continuous closed-loop operation under the tested conditions.

The field results reflected the combined effects of path geometry, differential-drive response, and orchard surface conditions. The larger mean error in the curved section was mainly associated with the higher angular velocity and greater speed difference between the left and right drive wheels required during the U-shaped turn. Changes in curvature at the straight-to-arc connections also produced transient tracking responses. In addition, ground unevenness, vegetation resistance, and wheel–soil interactions may have influenced the actual wheel responses. Similar disturbances arising from soil–machine interactions have been reported for other agricultural machinery, highlighting the importance of directional stability in limiting deviations from planned paths [27].

Wang et al. [21] developed an autonomous navigation system for a high-clearance sprayer that integrated dual-antenna RTK-GNSS positioning, a Linux-based control framework using Ubuntu and ROS 2, CAN communication, and Pure Pursuit control with a self-adjusting look-ahead distance. Their field experiments used a U-shaped path comprising two straight sections and a semicircular turning section. Of the reported operating conditions, the test conducted at 1.0 m/s was considered because its speed was closest to the 0.8 m/s used in the present study. Wang et al. reported a mean lateral error of 0.143 m in the curved section. In the present study, the mean absolute lateral errors in the curved section, straight sections, and complete U-shaped path were 0.124, 0.035, and 0.047m, respectively. Both systems incorporated dual-antenna RTK-GNSS, an ROS-based control framework, CAN communication, a 10 Hz navigation update rate, and a U-shaped reference path, which provided limited comparability in terms of system configuration and experimental design. However, the two studies differed in chassis configuration, steering mechanism, turning radius, operating speed, and field conditions. Accordingly, the reported results should be regarded as a cross-platform reference rather than a direct performance ranking.

The present experiments evaluated RTK-GNSS-guided tracking of a U-shaped path under the specified orchard conditions. Obstacle perception and avoidance, degraded GNSS reception, substantially different terrain and canopy conditions, and long-duration operation were not included in the current evaluation. Further field experiments under these conditions, together with the integration of local perception sensors, are required to assess system performance in more complex orchard environments.

Overall, the developed ROS-based navigation control system provided an integrated framework for position and heading acquisition, reference-path generation, path-tracking control, CAN-based drive actuation, and autonomous path execution. The field experiments demonstrated its closed-loop path-execution capability under the tested conditions and provided a basis for the further development of autonomous orchard mowing platforms.

5. Conclusions

(1) An ROS-based navigation control system was developed for a low-speed differential-drive orchard mower. The system integrated dual-antenna RTK-GNSS positioning and heading, an industrial computer, independently controlled rear-wheel drive units, CAN communication, wireless manual takeover, and ROS-based software modules to form a closed-loop navigation control architecture.

(2) A parameterized reference-path generation method was implemented for standardized orchard operations. Straight operation segments, U-shaped headland turns, and transition segments were generated according to the operating-area geometry, row spacing, cutting width, non-mowing margin, and path-sampling resolution. An adaptive Pure Pursuit controller with curvature-dependent look-ahead-distance adjustment was integrated into the navigation system to support the execution of composite paths.

(3) Field experiments were conducted along a U-shaped path at a nominal commanded speed of 0.8 m/s. With the adaptive controller, the mean absolute lateral errors in the curved section, straight sections, and complete path were 0.124, 0.035, and 0.047 m, respectively. The mower completed the tested path under both the adaptive and PP-2m settings, while the tracking results supported the curvature-dependent look-ahead-distance adjustment used in the system. These results demonstrated the RTK-GNSS-guided closed-loop path-tracking capability of the developed navigation control system under the tested orchard conditions.

The present results do not establish reliable autonomous navigation in the presence of obstacles, degraded GNSS reception, substantially different terrain or canopy conditions, or prolonged operation. Further field validation under these conditions, together with the integration of local obstacle-perception and avoidance functions, is required before the system can be applied in more complex orchard environments.

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