Design of an intelligent Navigation System for Unmanned Rice Transplanters Based on the Beidou Satellite Navigation System

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Abstract. Agricultural mechanization is a vital indicator of agricultural modernization. Historical developments in China and abroad demonstrate that agricultural machinery has fundamentally transformed production methods. With the advancement of agricultural mechanization, improving production efficiency is crucial for ensuring food security. Rice, as one of China’s primary food crops, relies heavily on transplanting—a critical stage in rice cultivation. High-efficiency transplanting technology forms the foundation of rice production. However, traditional transplanters in China still suffer from low automation, slow operation, and inefficiency. Autonomous navigation technology, a core element of modern agricultural intelligence, can significantly enhance rice planting efficiency. This paper analyzes the feasibility of unmanned intelligent transplanter navigation technology based on an overview of traditional transplanter technologies and their limitations. A BeiDou Navigation Satellite System (BDS)-based autonomous navigation system for unmanned rice transplanters is proposed, integrating multi-sensor fusion. Subsequent optimization enables path planning for the transplanter. Finally, prospects for multi-machine collaboration in future smart agriculture are discussed.

1 Introduction

Rice is one of China’s major food crops, with diverse varieties and cultivation practices that integrate varying levels of planting technologies [1]. Rice transplanters, as the primary machinery for rice cultivation, have seen increasing adoption in recent years [2]. Enhancing rice production efficiency is a critical task in China’s agricultural development. Full mechanization is a key pathway to achieving this goal, while improving the intelligence of agricultural machinery is essential for high-level mechanized production. Thus, upgrading current rice transplanting machinery by integrating intelligent technologies holds significant importance for advancing agricultural modernization.

Automatic navigation technology of agricultural machinery is an agricultural automation technology.It utilizes sensors to perceive surroundings, acquire precise

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positioning and attitude data, and perform intelligent path planning and navigation control to autonomously complete agricultural tasks. Its widespread application alleviates labor shortages and enables precision agriculture [3]. In rice cultivation, autonomous navigation can improve transplanter operation quality and efficiency.

The BeiDou Navigation Satellite System (BDS), a national space infrastructure independently developed by China, provides global users with all-weather, high-precision positioning services [4].

Navigation systems have been extensively researched and applied in agriculture. For instance, Ding et al. designed a BeiDou-based positioning controller using three low-precision modules to obtain central positioning data [5]. Mid-tech in the U.S. developed the Field Pilot system integrating navigation, autonomous driving, and variable fertilization [6]. However, despite existing autonomous navigation products, challenges such as insufficient navigation accuracy persist in China's transplanter-navigation systems. Further improvements are needed to meet practical demands.

This paper proposes an intelligent navigation system for unmanned rice transplanters based on BDS, integrating satellite positioning, sensors, and control systems to achieve autonomous navigation and positioning in field operations. The design includes high-precision BeiDou positioning, environmental perception, obstacle avoidance, path planning, control systems, actuators, and monitoring modules. Future applications in multi-machine collaborative networks for planting, sowing, and harvesting are also envisioned.

2 Analysis and disadvantages of traditional rice transplanter technology

Rice constitutes a primary food crop in China, and its cultivation techniques can be categorised into two systems: direct sowing and transplanting. The latter has distinct advantages over the former, including the production of new seedlings, more effective weed control, and superior agronomic benefits. Nevertheless, the process of transplanting entails a substantially higher labour intensity. The high labour intensity and inefficiency of manual insertion of rice seedlings necessitates the promotion of scientific research on agricultural machinery. Since the inception of the People's Republic of China, the state has proactively promoted independent research and development and technology introduction to establish a rice transplantation machinery system with Chinese characteristics. Through these stages of independent research and development and technology introduction, a rice transplanting machinery system with Chinese characteristics has gradually been established. In this stage, rice transplanting machines can be divided into two types according to the operation mode: handheld type and high-speed ride-on type [7]. The handheld rice transplanter is categorised as semi-automatic equipment, necessitating manual assistance from the operator for propulsion. The power system predominantly utilises a single-cylinder gasoline engine, which lead to its modest power output and suboptimal operating efficiency. Consequently, its application is constrained to small-scale, decentralised planting areas. Moreover, it is still associated with high intensity labour. Conversely, the high-speed ride-on rice transplanter utilises a multi-cylinder diesel engine and a hydraulic continuously variable transmission system, a configuration that significantly enhances operational efficiency. This enhancement in efficiency is especially salient in large-scale transplanting operations, as it ensures optimal performance of the rice transplanter. However, it must be noted that the machine's complex operation and the presence of multiple joysticks and gauges require employee significant training time to achieve proficiency. The machine's high initial cost and maintenance requirements are also factors that limit its popularity on small farms.

3 Realisability of navigation technology for unmanned intelligent rice transplanter

3.1 Intelligent navigation key technology

At this stage, there are 3 main intelligent navigation technologies: Global Navigation Satellite System (GNSS), Inertial Navigation System (INS) and Machine Vision Technology (MVT).

3.1.1 Global navigation satellite system and application

GNSS is a multi-nationally operated satellite system that provides high-precision positioning, navigation and time synchronisation services to users worldwide. The Chinese BeiDou Navigation Satellite System (BDS) is the latest addition to GNSS. Following the completion of 55 satellites in June 2020, the BeiDou satellite system formally provides services to the globe. The centimetre-level accuracy of the system greatly improves navigation technology and promotes progress in the field of unmanned intelligent agricultural machinery. The tractor path tracking control system was optimised by Wang and others with the HG-GOYH7151 BeiDou positioning device [8]. which was developed independently by China. This development is of great significance in the field of unmanned intelligent agricultural machinery. The BeiDou satellite navigation system has the capacity to provide high-precision absolute position and heading information on a continuous basis, regardless of weather conditions. However, in extreme weather or strong occlusion environments, the system is susceptible to missing satellite signals or multipath effects, which can result in a decline in positioning reliability.

3.1.2 Inertial navigation technology

Inertial navigation technology is an autonomous navigation technology based on an inertial measurement unit (IMU) [9]. The core principle of the IMU is to measure the angular velocity and linear acceleration of the carrier's movement in real time through accelerometers and gyroscopes. These measurements are then integrated to deduce the position, velocity and attitude information of the carrier. The following inertial navigation technologies are of particular significance:

（1）Gyroscope

The operation of gyroscopes is predicated on the conservation of angular momentum or optical effects by sensing changes in physical quantities caused by the rotation of the carrier to output angular velocity signals and to decipher the attitude and heading.

Gyroscopes are not reliant on external signals and thus possess the advantages of strong environmental adaptability, high dynamic response and short-time high accuracy, which renders them suitable for continuous navigation in complex sheltered environments or electromagnetic interference scenarios. Nevertheless, the error of inertial navigation can accumulate significantly over time, thereby limiting long-term accuracy.

(2) Magnetometer

Magnetometers work on the principle of measuring the direction of the carrier relative to the geomagnetic field, and are capable of determining the magnetic heading angle by detecting the projection of the geomagnetic vector in the carrier's coordinate system. The core component typically employs the magneto-resistive or Hall effect principle and integrates three-axis magnetic sensitive elements to achieve three-dimensional magnetic field measurement.

(3) accelerometer

The accelerometer is a device that detects linear acceleration based on the principle of inertia. It consists of a core consisting of a mass block, which is an elastic structure, and a sensing element. The acceleration forces the mass block to overcome damping, resulting in a displacement. This displacement is then converted into an electrical signal. Accelerometers are widely used in navigation due to their cost-effectiveness, reliability and durability.

3.1.3 Visual navigation techniques

Visual navigation technology is predicated on computer vision and artificial intelligence in order to facilitate environment perception and path planning [10]. The fundamental principle underpinning this technology is the collection of environmental images through sensors such as LiDAR and depth cameras. Using algorithms such as feature extraction, target recognition, simultaneous positioning and map construction, the technology analyses the spatial position, motion status and surrounding obstacle information of carriers in real time. The objective is to plan a safe path and achieve autonomous movement. Y. Zhou and others have employed visual navigation technology to assist intelligent agricultural machines in field operations in route planning [11], with the aim of improving the accuracy and reliability of agricultural machine navigation. The schematic diagram of visual navigation technology is shown in Fig. 1.

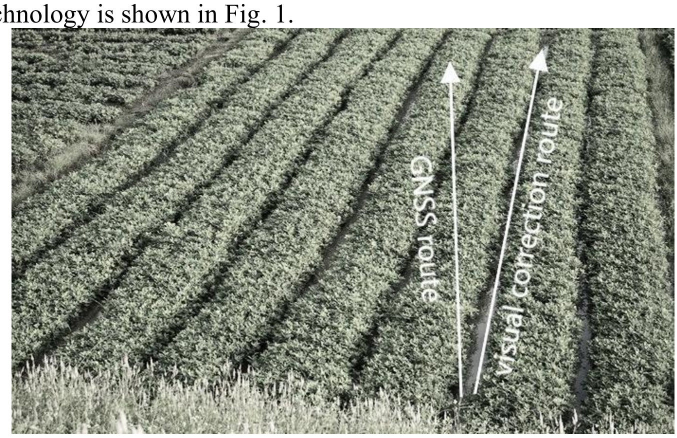

Fig. 1. Schematic of visual navigation

3.2 Feasibility of unmanned intelligent rice transplanter

The primary challenge in developing an autonomous rice transplanter lies in achieving high-precision navigation and adaptability to the dynamic environment of a farm, a goal that has been partially realised through the advancement of existing navigation technologies. The centimetre-level positioning technology based on the BeiDou system ensures the absolute coordinate positioning of the rice transplanter in the field, and the combination of inertial navigation and vision SLAM technology achieves precise control of the row spacing of the seedlings and the plant spacing. The fusion perception system of the LIDAR and multi-spectral sensors can detect the surface undulation of the paddy field in real time, the concentration of the mud and other variables. Through the reinforcement learning algorithm, it dynamically adjusts the speed of the travelling speed and the depth of transplanting, so as to avoid the stuck car or the missed insertion. The system's capacity for real-time adjustment of its operational parameters, namely the velocity and the depth of transplantation, is enabled by the implementation of reinforcement learning algorithms. These algorithms facilitate the avoidance of trapping and the successful execution of transplant operations, even in instances where precise timing and depth control are paramount.

4 System design

The design of the system mainly includes the overall design of the machine, the overall design of navigation system, data acquisition module, control module and monitoring module.

4.1 Overall design of rice transplanting machine

For accurate transplanting operations, in addition to advanced transplanting equipment, multi-sensors combined with agricultural machinery automatic navigation technology are also needed to ensure the accuracy of high-speed sowing.

This paper takes the classic Kubota rice transplanter as the research platform, and combines the advanced technology of Beidou satellite with the self-developed navigation system to improve work efficiency.

4.2 Overall design of the navigation system

The navigation system consists of a data acquisition module, multi-source sensors, a Beidou receiver, a cloud-based monitoring platform, and mobile terminals. It integrates positioning data from the Beidou satellite system with pre-imported field boundary and obstacle coordinates to enable environmental perception and path planning. Multi-sensor fusion, used to detect the mechanical running speed, while improving the positioning accuracy in a complex environment.Real-time operational data collected from agricultural machinery is transmitted to the cloud via Beidou short message communication, allowing users to monitor equipment status and remotely coordinate tasks through mobile terminals.

4.3 Data acquisition module design

4.3.1 The Beidou high-precision positioning module

In the monitoring link of the operation scope, the Beidou positioning technology is used to accurately locate the man-machine within the operation scope.Because the Beidou navigation satellite system has high positioning accuracy and coverage,So it can provide precise location information for people or objects on the ground and in near-Earth space.Real-time matching of location data and map information [12].

4.3.2 Perception module

Accurate and fast environment perception is the prerequisite for the reliable work of the navigation system [13].The sensing module detects the surrounding environment in real time through multi-sensor fusion, including lidar, which can obtain the distance, speed and other information of the target with high precision and high accuracy or achieve the target imaging [14-16],In the process of the transplanter, it can scan the front range of five meters to identify the stone ridge and other obstacles around the transplanter;it also includes ultrasonic sensor,the system designed in this paper uses the reflection characteristics of ultrasonic wave to transmit and receive obstacle signals to avoid the collision .

4.3.3 Data acquisition module

In the data acquisition module, the unique short message function of the Beidou navigation satellite system is used to send the data to the satellite, and then forward it from the satellite to the receiving end. The received data is decoded and stored in the cloud database to facilitate the subsequent analysis and application.

4.4 Control module

In order to realize the seeding effect, the Beidou satellite positioning technology is used for the real-time positioning and path planning of the transplanter.Path planning is a key step for the autonomous navigation of agricultural machinery.transplanter automatic navigation path planning technology research purpose is to make the transplanter to automatic positioning and automatic walking, in the process of operation according to the navigation positioning system to make accurate judgment, and then the transplanter steering and speed integrated control and input plot parameters, eventually make the transplanter can drive according to the planning path [17].

This transplanter model uses the simplified two-wheeler kinematics model proposed by A.J.Kelly [18], Consider the movement of the transplanter in the field as a pure rolling in the two-dimensional plane, ignoring the impact of turbulence from the uneven ground, without considering the lateral sliding of the transplanter machine and the ground.

A kinematic model was built under the Gaussian projection plane coordinate system of WGS-84 [19]. As shown in Fig. 2.

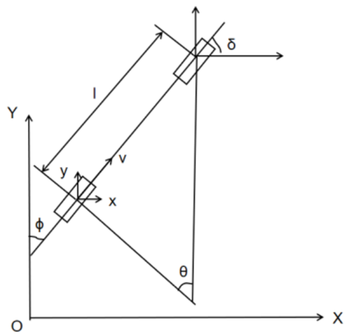

Fig. 2. Simplified two-wheeler model

Analysis of the model provides the following formula:

$$\begin{cases} x'(t) = v\cos\phi(t) \\ y'(t) = v\sin\phi(t) \\ \phi'(t) = \frac{v\tan(\theta)}{l} \end{cases} \tag{1}$$

Where v is the driving speed of the transplanter and l is the front and rear wheelbase of the transplanter.

The automatic navigation control algorithm of agricultural machinery mainly includes PID (proportion, integral, differential) control algorithm, optimal control algorithm, pure tracking control algorithm and neural network control algorithm, etc[20].This design uses PID control algorithm, which has the advantages of simple, reliable, robustness, wide adaptation surface and easy to implement [20, 21].

The most commonly used controller in the analog control system is the PID controller. The principle of the conventional PID control system is shown in Figure 3.

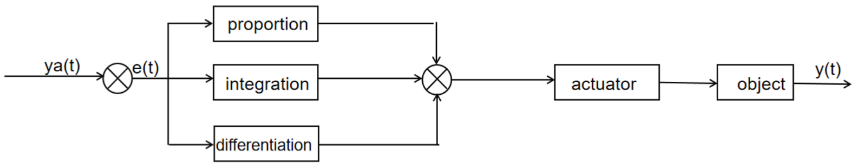

Fig. 3. Schematic diagram of the conventional PID control system

Fig. 3 shows ya (t) is a given value, and y (t) is the output value, which together constitute the control deviation e of the system, e (t), e (t) =ya (t) -y (t), proportion, integral and differential calculation, get the linear combination of the control amount u (t), to control the controlled object. In a continuous time domain, the expression of the PID control algorithm is:

$$Nu(t) = Kp[e(t) + \frac{1}{Ti}\int_0^t e(t)dt + T_d \frac{de(t)}{dt})] \quad (2)$$

Kp is the scaling factor, Ti is the integral time constant, andT_d is the differential time constant. The system output response is related to the size of the above 3 parameters [22].

4.5 Monitoring Module

4.5.1 Core Functions

The monitoring module, core of unmanned rice transplanter navigation, handles real-time data exchange, operational visualization, and anomaly management. The Android interface displays key parameters (speed, engine status, planting depth, seedling levels) with dynamic data updates via charts for quality analysis [23].

Combining BeiDou positioning with e-maps, it visualizes real-time locations, work trajectories, and completed zones through scalable maps. Planting quality appears as color-coded heatmaps to aid farming decisions.

It triggers SMS alerts or pop-ups for detected anomalies (mechanical faults, boundary breaches, low seedlings), while initiating automatic shutdown/path correction commands to ensure safety.

4.5.2 System Architecture

The vehicle-mounted information collection system integrates multi-source sensors via the CAN bus to acquire real-time data such as the transplanter’s steering angle, planting depth, and speed, ensuring low-latency and reliable transmission (Fig. 4). A central server acts as a data hub, receiving and storing operational data while synchronizing it to an Android client, and supports remote command issuance. MySQL-based historical data storage enables operational backtracking and quality evaluation. Bidirectional communication is achieved using the Socket protocol (TCP/IP ensures stable transmission), and short message communication eliminates monitoring blind spots in areas with weak BeiDou signals [24].

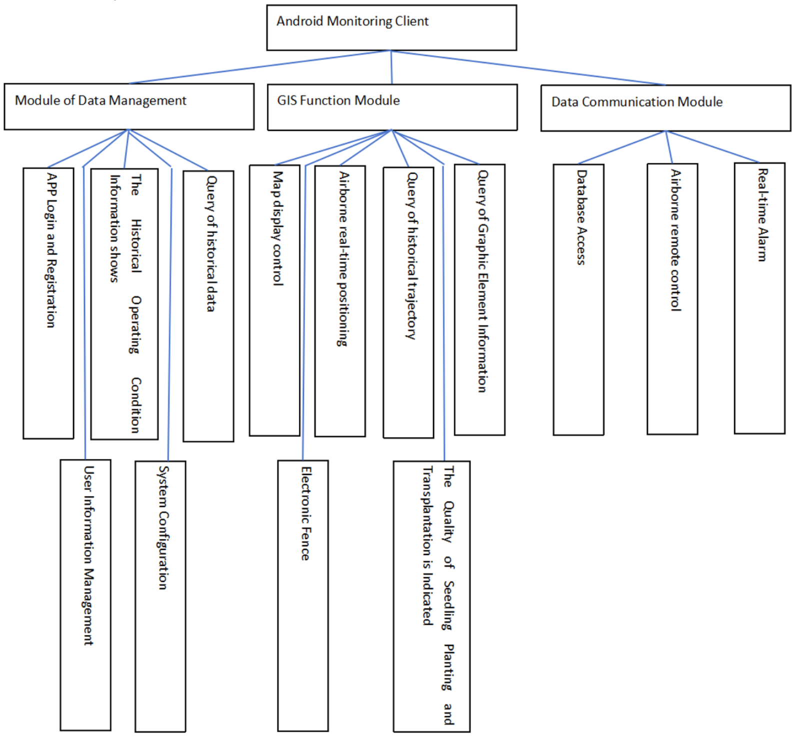

Fig. 4. The monitoring module employs a layered architectural design

4.5.3 Key Technologies

LoRa wireless communication protocol connects field sensor nodes to reduce wiring complexity, while the MQTT protocol enables lightweight data publish/subscribe mechanisms to accommodate low-bandwidth farmland environments. The client, developed using Android Studio, supports touchscreen operations and multi-window split-screen displays for human-machine interaction.

A hybrid diagnostic method combining rule engines and machine learning performs real-time analysis of sensor data. This approach distinguishes mechanical faults from environmental interference, reducing the false alarm rate to below 5%.

4.6 Integration and Optimization

4.6.1 Control-Monitoring Linkage

The control module generates steering commands based on BeiDou positioning data and PID algorithms, driving the electric steering wheel while feeding execution results back to the monitoring module. If the actual path deviates from the planned path by more than a threshold (±5 cm), the monitoring module triggers path replanning, forming a "perception-decision-execution-feedback" closed loop [25].

The monitoring module receives real-time transplanter location data via WebSocket, overlaying planned paths and actual trajectories on GIS maps. Color gradients mark deviation levels (green: ≤3 cm; red: ≥8 cm), helping users quickly locate anomalies.

4.6.2 BeiDou Communication Optimization

To address the single-message capacity limit of BeiDou short messages, hexadecimal compression encoding reduces environmental data (temperature, humidity, light) to 40% of their original size, with CRC-16 checksums ensuring data integrity [24].The transmitter dynamically adjusts retransmission frequency based on success rates, while the receiver adopts a cumulative acknowledgment strategy to reduce confirmation messages. Experiments show this mechanism achieves a 99.2% data transmission success rate under fluctuating signal conditions (60%–95% success rate).

4.6.3 Multi-Machine Collaboration Optimization

An improved ant colony algorithm dynamically allocates field zones by considering agricultural machinery positions, remaining workloads, and energy consumption, reducing idle travel distance by 37% in simulations.
When path conflicts arise in headland turning areas, priority scheduling combined with virtual potential field methods enables collision-free path adjustments with sub-200ms response times, minimizing accident risks.

5 Conclusion

This paper presents a systematic analysis of the intelligent design of an unmanned rice transplanter, with a focus on the technical framework, as it pertains to the BeiDou satellite navigation system. The design scheme is predicated on BeiDou centimetre-level positioning technology, which serves as its core. In addition, it combines multi-sensor fusion to achieve environmental sensing and dynamic obstacle avoidance, and it completes path planning and navigation optimisation based on the two-wheeled vehicle kinematics model and PID control algorithm. This technology has the potential to markedly reduce manual dependence and establish the technical foundation for multi-machine cooperative operation networks. The theoretical capability of the BeiDou system to meet the demand for high-precision positioning in farmland is attributed to its ground reference station error correction technology. The multi-sensor cooperative strategy enhances the adaptability of the system in complex environments, such as vegetation cover and muddy paddy fields, and in situations where satellite signals are attenuated due to extreme weather, such as torrential rains and electromagnetic interference. Mitigation of these issues is achieved through visual SLAM and inertial navigation compensation. The future design can explore a deep learning-based multimodal data fusion algorithm to reduce the dependence on a single sensor, and combine with the 5G Internet of Things to build a multi-machine cooperative operation network. This will provide theoretical support and technical path reference for the intelligent development of smart agricultural equipment.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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