Review of open-field vegetable automatic following transportation technology and equipment

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Abstract: The vegetable industry is the largest sector within China's planting industry. The integration of modern information technologies such as big data and the Internet of Things (IoT) with agricultural equipment has facilitated the intelligent upgrading and transformation of the vegetable industry. This paper addresses the lack of automatic field transportation equipment for open-field vegetables. Around the main production scenarios of open-field vegetables, this paper summarizes the research status of field transportation equipment at home and abroad, and compares the characteristics of oil-powered and electric transporters. The paper also points out that the automatic following technology of field transportation equipment is a crucial technology for achieving coordinated harvesting and transportation. It proposes that automatic following technology is primarily realized through navigation and positioning technology and path tracking technology, and elaborates on the application research status of both. Based on this, the paper outlines the current application of field transporters in China, identifying issues such as poor integration of agricultural machinery and agronomy, poor adaptability of transport vehicles, poor navigation and positioning stability, insufficient environmental adaptability of path tracking algorithms, and immature multi-machine coordination technology for field transportation. The future development trends of standardized vegetable planting, optimization of transportation equipment structure, precision and intelligence of automatic following technology, multi-machine collaborative operation, and emphasis on energy utilization and environmental protection are proposed. Finally, the paper summarizes the applicable scenarios of field transportation equipment, navigation and positioning modes, and path tracking algorithms in conjunction with the content of the full text.
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1 Introduction

Vegetables are one of the major economic crops in China, cultivated throughout the year in various regions of both the north and the south, covering an area of 20 million hm^2 with an annual production exceeding 800 Mt, accounting for approximately 60% of the global total vegetable production[1,2]. Most vegetables are consumed fresh and harvested within a concentrated period, necessitating the completion of post-harvest field transportation within a short timeframe. The Sustainable Development Goals (SDGs) in the United Nations 2030 Agenda refer to "improving nutritional status and promoting sustainable agriculture". In this context, the overall mechanization rate of the vegetable industry in China is steadily increasing, with corresponding machinery available for tillage, planting, management, harvesting, and transportation. Some aspects have already achieved intelligent production[3]. Many vegetable harvesters have the ability to harvest efficiently, but since the research on intelligent equipment for field transportation is still in its infancy, there is few intelligent field transportation equipment that can cooperate with vegetable harvesting equipment for harvesting and transportation. A mode of synchronous operation of harvesting and transportation machinery is illustrated in Figure 1. The lack of intelligent vegetable transportation equipment has become an important factor restricting the development of the vegetable industry. Therefore, accelerating the mechanization and intelligence of vegetable transportation production is an important way to realize the "machine substitution" of the vegetable industry[4].

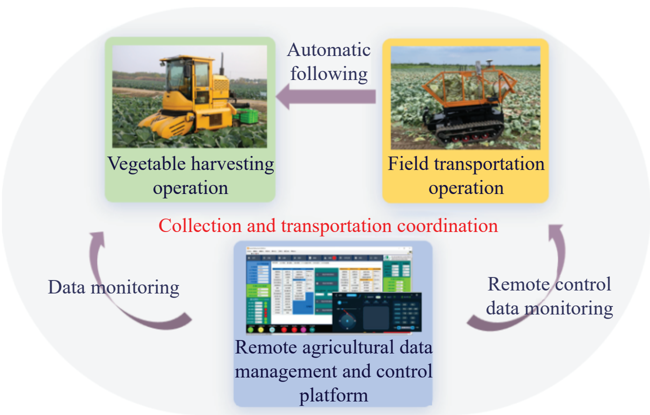

Figure 1 A mode of synchronous operation of harvesting and transportation machinery

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Common agricultural tricycles and motorcycles in China are unable to fulfill the transportation requirements of complex field terrains. The existing specialized field transportation machinery is limited in variety and low in intelligence. Importing intelligent field transportation machinery from abroad is costly and unsuitable for China's open-field vegetable cultivation model, making it difficult to integrate with China's existing vegetable harvesting machinery to complete field collection and transportation tasks. Therefore, farmers currently rely mainly on manual labor and traditional field transport machinery to transport vegetables to the field or to trucks. Problems such as increased labor, increased labor intensity, and increased production costs have become increasingly prominent. At the same time, the problem of population aging has led to labor shortages[5]. Therefore, developing specialized vegetable field transportation machinery that is suitable for China's major vegetable varieties and open-field cultivation practices, and can operate in tandem with harvesters, as well as leveraging intelligent technology to enhance the level of mechanization in vegetable production, has become a pivotal task in the current development of mechanized vegetable production.

The key to realize the collaborative operation of vegetable transport equipment and harvesting equipment is the realization of automatic follow-up technology. For the open-field farmland operating environment, the navigation positioning and path tracking method is more convenient to realize the cooperative operation of collection and transportation[6]. The key to navigation and positioning is to obtain accurate position information through positioning technologies such as sensors and satellites. Path tracking mainly ensures the stability of the following distance and corrects the deviation of the following path[7].

In summary, to clarify the future direction of vegetable field transportation and autonomous following technology, this paper integrates the characteristics of vegetable production operational scenarios. It summarizes and compares relevant global research on oil-powered and electric field transportation machinery conducted in recent years. Additionally, it organizes the applicable scenarios and characteristics of various navigation and positioning technologies, as well as path-following technologies within the realm of autonomous following technology. The paper concludes with a summary and analysis of the critical issues that urgently need to be addressed for the development of autonomous field transportation machinery, and proposes outlooks for the advancement of vegetable field transportation technology in China.

2 Current research status of vegetable field transportation machinery

Vegetable field transportation equipment is primarily classified into three forms: rail-mounted, wheeled, and tracked. Rail-mounted transporters are suitable for operating environments with limited workspace and narrow pathways in greenhouse vegetable farming, exemplified by the intelligent greenhouse transporter developed by Wu et al.[8] from Shanghai Maritime University, which offers both rail and ground transportation modes. However, their rail transportation routes are constrained by pre-installed tracks, resulting in poor flexibility and high construction costs. Additionally, ground transportation stability is insufficient, rendering them unsuitable for open-field transportation. Wheeled transporters can effectively handle the loading, unloading, and transportation of crops and fertilizers in open-field agriculture, as exemplified by the APC-600MCⅡ wheeled transporter produced by Asia Technology Co. in South Korea. Nevertheless, due to the inconsistency of vegetable planting patterns and different soil conditions in China, wheeled transporters face some problems in wet and slippery fields, including poor traffic capacity and low safety. In comparison, tracked transporters exhibit superior ground adhesion, stronger adaptability, and higher flexibility, making them better suited to complex operating environments. Therefore, the promotion of tracked transporters can effectively address current challenges in vegetable field transportation. Currently, the widely used tracked transporters are mainly categorized into fuel-powered and electric types.

2.1 Crawler-type fuel-powered transporter

The fuel-powered crawler transporter is a prevalent field transportation equipment in current agriculture, primarily utilized for the transportation of agricultural products within fields. These transporters predominantly adopt diesel or gasoline engines as their power sources and are equipped with crawler-based walking systems, offering exceptional field passability and operational stability. Furthermore, they are capable of adapting to complex and variable field environments.

Europe and the United States, Japan and South Korea, and other countries started oil transport machine research earlier, and their research and development of the equipment application range is relatively wide. At present, the open-field vegetable planting environment is mainly based on field, small plots, and hilly mountains. European and American crawler transporters are mostly suitable for open-field and large-scale planting large plot operation scenarios, with large load and sufficient power. For example, the EX60 multi-function crawler transporter produced by FECON company in the United States (Figure 2a) is designed with two auxiliary hydraulic circuits and load induction pumps, which can provide the required power for high-demand applications. The chassis design of this kind of machine adopts a wide rubber track, the center distance of the track chassis is large and the gap from the ground is low, and the steering flexibility is poor. The high horsepower diesel engine is mostly used as the power source, which is only suitable for wide road in the field or wide row spacing transportation, which does not match with most vegetable planting patterns in China. The crawler transporters made in Japan and South Korea are mostly suitable for small plots, sloping farmland in hilly and mountainous areas, and other working environments. They are compact, flexible and portable, and very suitable for small-scale planting bases and planting retail households. The representative model is the IBT-500RDH portable crawler transporter produced by IBEA SRL Company in Italy (Figure 2b). This type of machine adopts a narrow rubber crawler in structure, with small chassis center distance, low ground clearance, small load capacity, and strong steering flexibility. It mostly uses a small horsepower diesel engine or gasoline engine as the power source. The small ground clearance is not suitable for ridge planting environment, but it is suitable for flat planting environment in small plots and hilly and mountainous areas. Moreover, due to the small volume of the material box and the small load capacity, this kind of machine is not suitable for the field transportation of heading and rhizome vegetables. Similar crawler transporters include Japanese Yama MC95FT-X crawler transporter (Figure 2c), Japanese Orix LS-360 portable crawler transporter (Figure 2d), and so on.

After the introduction of crawler agricultural transporters in China in 2010, domestic enterprises have copied them according to the form of foreign machines, but the actual use effect is not ideal, and it is difficult to adapt to the domestic planting mode[9]. Aiming at the special terrain of hilly and mountainous areas, a single-crawler transport machine is developed, which can be flexibly transported in a narrow working channel. On behalf of Chen et al.[10] of Huazhong Agricultural University, a small walking single-crawler transport vehicle (Figure 3a) is designed. The whole machine adopts a small gasoline engine to provide power, walks through a single rubber crawler chassis, and installs unpowered wheels on both sides to assist in walking and maintain balance. The bearing platform is designed to place the basket and unload it by carrying the basket. The transportation flexibility is high, but the single transportation volume is small and the stability is poor. Therefore, a double-crawler small transport machine is designed, which has a smaller grounding specific pressure and effectively improves the transportation efficiency. It can be applied to the working environment of slope farmland, open field, and small plots in hilly and mountainous areas. Examples include the WM7B-220, a field transporter produced by Chongqing Weima Agricultural Machinery Co., Ltd. (Figure 3b), and the hilly mountain transporter developed by Zhou et al.[11]. Such transporters mostly use small gasoline engines and diesel engines to provide power. Most of them need to be driven by hand. The load-bearing box is small and does not have the unloading function. It can only be manually unloaded by opening the unloading port of the box. The structure is small and the operation is flexible, which can adapt to a variety of complex field areas. Facing the open-field large plot and flat terrain working environment, the field transportation efficiency can be further improved by expanding the size of the material box and increasing the size of the conveyor. For example, the AD-LS series crawler conveyor produced by Jining Aide Machinery Equipment Co., Ltd. is divided into two forms: walking (Figure 3c) and riding (Figure 3d). The walking maximum load is 1.5 t, and the riding load can reach 6 t, which can realize large-scale field transportation operations. Similar large-load transportation equipment also includes the HK-YS series crawler conveyor produced by Shandong Huake Machinery Co., Ltd. and the all-terrain crawler conveyor produced by Xingtai Dexu Machinery Manufacturing Plant. This kind of conveyor is mostly used to provide power for high-horsepower diesel engines. The material box is large in size and has an unloading function. The gantry rubber track chassis is mostly used. The track width is wide and the ground clearance is high. It is suitable for flat planting, ridge planting, and border planting environments.

2.2 Crawler-type electric transporter

Electric agricultural machinery and equipment have gradually replaced diesel-powered agricultural machinery as a new research focus in the field of agricultural engineering both domestically and internationally. Electric transporters, powered by electric motors, eliminate the need for designing complex mechanical transmission systems, effectively reducing the size of the power chassis while increasing loading capacity. Compared to traditional diesel and gasoline-powered transporters, electric transporters offer advantages such as lower pollution, reduced noise, higher energy efficiency, and lower maintenance costs[12]. In addition, it is convenient to integrate intelligent systems, which is conducive to the acceleration of the demand for "machine replacement". A detailed comparison of the specific performance characteristics between diesel-powered and electric transporters is listed in Table 1.

a. EX60 multi-functional crawler transporter

b. IBT-500RDH portable crawler transporter

c. Yanmar MC95FT-X crawler transporter

d. Orix LS-360 portable crawler transporter

Figure 2 Related research results of foreign traditional oil-powered transporters

a. Small hand-guided single-crawler transport vehicle

b. WM7B-220A field transporter

c. AD-LS1500 hand-guided transporter

d. AD-LS6000 type passenger crawler transporter

Figure 3 Related research results of domestic traditional oil-powered transporters

Table 1 Comparison of performance characteristics between fuel-powered transporters and electric transporters

Type	Vehicle range	Noise volume	Environmental protection	Economy	Driving experience	Structural complexity	Application scenarios
Crawler-Type Fuel-Powered Transporter	The fuel energy density is high and the endurance is long.	About 100 decibels, wear after aging can be more than 120 decibels, it is difficult to control noise	Field operations produce waste gas such as carbon dioxide and particulate matter, which pollutes the environment.	The fuel unit price is high, the fuel engine transmission efficiency is low, and the maintenance cost is high.	Powerful but slow to accelerate with lagging throttle response	Complex transmission system with components like clutch, gearbox, and differential	Open-field environment
Crawler-Type Electric Transporter	The battery has low energy density and short battery life.	Between 60-80 decibels, noise can be significantly reduced by sealing and adding sound insulation materials	Field work zero emissions, no pollution	The electric unit price is low, the motor transmission efficiency is high, the maintenance cost is low (no need to replace the oil, spark plug, etc.), but the battery replacement cost is high.	High torque output, quick acceleration response, and smoother driving experience	Simplified structure with electric motors replacing complex drivetrain systems	Open-field farmland or greenhouse facility environment

In foreign countries, small crawler transporters are designed for the working environment of small plots in hilly and mountainous areas and open fields. For example, the HTK3600Series crawler transporter (Figure 4a) produced by South Korea Chengfu Company provides power through a dual-motor crawler chassis. The rubber crawler has a narrow width and a low off-ground gap. It can achieve 60-135 cm lifting and 53° self-unloading, and the load-bearing material box can be expanded. At the same time, it is equipped with a working sliding table, which can assist picking. It has the function of independent straight-line driving and is suitable for transportation operations in flat planting and border planting environments. For the open field, flat open field, and other operating environments, a large load transportation platform is designed. For example, Uplifter Co., Ltd. in Germany launched the UPM1225 crawler-type autonomous transportation platform in 2022 (Figure 4b). The whole machine adopts a dual-motor crawler chassis with narrow crawler width and small chassis center distance. It has good passing performance and 12 cm wading ability. The bearing platform can be expanded with a high load capacity of 1.2 t. It can walk flexibly on a steep road section of 45 degrees and can be remotely controlled. However, the gap from the ground is small, which is not suitable for field transportation under ridge planting mode.

a. HTK3600 Series crawler transporter

b. UPM1225 crawler-based autonomous transport platform

Figure 4 Related research results of foreign crawler-type electric transporter

China's scientific research units and related enterprises are also actively promoting the research of electric transport machinery. In view of the elevated vegetable picking operation environment, Liu[13] of Hebei Agricultural University designed a lifting transport operation platform. The whole machine is manually operated to control walking, it features double motor drive, the center distance of the crawler chassis is narrow, and the bandwidth is narrow. There are safety and stability devices on both sides of the chassis. The lifting mechanism adopts hydraulic control, but it does not have the unloading function. The ground clearance is low, which is suitable for flat-field road transportation. The Noliwa 3GYP-500 electric crawler working platform (Figure 5a) produced by Linyi Wali Machinery Equipment Co., Ltd. can be operated manually and remotely. It mostly uses dual-motor crawler chassis to provide power. The width of the track is narrow, the size of the whole machine is small, and the trafficability is high. It is mostly loaded with vegetables in the form of baskets, but the ground clearance is low, and it can be operated flexibly in narrow and flat road conditions. In view of the complex working environment in hilly and mountainous areas, Han et al.[14] designed a mountain transporter with adaptive and adjustable center of gravity (Figure 5b), which effectively improved the ultimate roll angle, obstacle crossing height, and trench width of the transporter. The whole machine adopts remote control operation, double motor drive, small center distance of crawler chassis, narrow belt width, and high ground clearance, which is suitable for transportation in narrow field roads. In view of the open-field working environment, Yu[15] from Jiangsu University designed an autonomous vegetable harvesting and transportation platform (Figure 5c), which can walk by remote control and automatic follow, and has more than 300 kg load transport capacity. The triangular high ground clearance double track chassis is designed, which is driven by a single motor, and the bearing area on both sides of the bearing platform can be expanded. The automatic follow-up operation of small load transport equipment is realized by integrating UWB and vision technology, which can be flexibly transported under ridge, flat, and border planting modes. The Nanjing Agricultural Mechanization Research Institute of the Ministry of Agriculture and Rural Affairs has developed a large-load field intelligent transport machine (Figure 5d) that can cooperate with the vegetable harvester for collection and transportation operations. The whole machine can walk by manual, remote control, and automatic driving. It is driven by dual motors, with narrow track width, small chassis center distance, and high ground clearance. It can be used for vegetable transportation for ridge planting. It can carry 1 t of vegetables at a single time, and can be unloaded by flipping the material box. At the same time, it has intelligent operation functions such as automatic weighing, full-load alarm, fixed-point return, self-balancing, automatic entry and exit of the warehouse, obstacle avoidance perception, and cloud control.

a. Noliwa 3GYP-500 electric crawler operation platform

b. Center of gravity adaptive control transporter

c. Autonomous following vegetable harvesting and transportation platform

d. Heavy-duty intelligent field transporter

Figure 5 Domestic electric transporter related research results

3 Research status of automatic following technology

Automatic following technology for field transport machines is one of the key core technologies enabling coordinated operations of vegetable harvesting and transportation. There are two main ways of automatic follow-up: side follow-up and rear follow-up. The side follow-up needs to be connected with the lateral conveying mechanism at the rear end of the harvester to convey the harvested vegetables to the conveyor material box. The rear follow-up needs to determine whether it is necessary to add a longitudinal conveying mechanism according to the structure of the harvester to ensure that the vegetables can fall into the material box of the conveyor. Currently, positioning technologies are predominantly utilized to attain precise acquisition of location data for both the transporter and the target it trails. Moreover, path tracking control methodologies are employed to ensure consistent maintenance of the following distance and prompt rectification of deviations in the travel path. Among the navigation and positioning technologies, ranging sensors, satellite positioning, inertial navigation, visual navigation, UWB (Ultra-Wideband) positioning, and other advanced techniques play crucial roles. Similarly, path tracking control methods encompass a variety of approaches such as front-wheel feedback, pure pursuit, fuzzy control, and PID (Proportional-Integral-Derivative) control[16,17]. The effective integration of path tracking and navigation positioning technologies provides the field transport machines with robust and stable following capabilities, enabling them to perform consistent and reliable operations within agricultural fields.

3.1 Research status of navigation and positioning technology

Navigation and positioning technology is primarily used to acquire information such as the location, heading, speed, and attitude of agricultural machinery equipment. Currently, the primary positioning methods employed for automatic following of agricultural machinery equipment include sensor-based ranging positioning, Light Detection and Ranging (LiDAR), Global Navigation Satellite System (GNSS), Inertial Navigation System (INS), and vision-based navigation systems. Sensor-based ranging and vision-based navigation are susceptible to lighting conditions, satellite signals in greenhouse environments are poor, and INS accumulates errors over time. While LiDAR is less affected by environmental factors, it still faces issues of high cost and demanding data processing requirements[18]. Most of the agricultural machinery equipment operating environments are more complex, and, combined with the shortcomings of a single navigation, a multi-sensor fusion positioning method is therefore more suitable for field operations[19]. The navigation and positioning methods are listed in Table 2.

Table 2 Comparison of navigation and positioning methods

Name	Typical positioning method	Precision	Application scene	Advantages	Precision
Sensor ranging and positioning technology	The time interval between the measured signal emitted from the transmitting source and reflected to the receiver is calculated to obtain the distance from the target object.	cm-level	Small-area vegetable field transporter positioning, or scenes with low positioning accuracy and limited cost	It has low cost, does not depend on external signals, and can achieve high precision in a short distance.	The measurement range is limited, and it is greatly affected by environmental factors such as light and humidity.
Satellite positioning technique	The position is determined by solving three observation equations, and the positioning data is corrected by DGNSS, RTK, PPK, precise PPP, and other methods.	cm-level	Large-area positioning of the field operating environment, especially in the open, no obstacles in the farmland	It has a wide coverage and can provide positioning services worldwide.	In complex terrain or signal occlusion areas (such as forests, buildings), the positioning accuracy will be affected, and it is vulnerable to weather and electromagnetic interference.
Inertial navigation positioning technology	Dead Reckoning Based	cm-level	The field operation environment with short time positioning, or the scene with high real-time requirements, but does not need to maintain high precision for a long time	It has autonomy and does not depend on external signals, and can provide continuous position, velocity, and attitude information.	The positioning error accumulates over time, and the long-term accuracy is poor. Initial alignment is required and takes a long time.
UWB positioning technology	Based on TOA, TOF, TDOA, AOA	cm-level	Field operation environments that require high-precision positioning, such as warehouses, greenhouses	It has strong anti-interference ability and can work stably in complex environment.	The cost is high, and more base stations and tags need to be arranged, which is suitable for short-distance positioning.

3.1.1 Research status of ranging sensor positioning technology

By installing a ranging sensor in the vegetable transport machinery, the relative position of the vegetable transport machinery and the following machinery can be obtained, and the precise positioning of the vegetable transport machine can also be realized, thereby ensuring the following distance and accuracy. It can be realized by using sensors such as infrared, ultrasonic, laser, millimeter wave, and Light Detection and Ranging (LiDAR). The fundamental principle underlying this method is the measurement of the time interval between the emission of a signal from the source and its reception after being reflected by the target object. This measured time interval is then processed to calculate the distance to the target object.

Yang et al.[20] designed an intelligent vehicle control system based on a microcontroller, utilizing infrared sensors to accomplish distance measurement for obstacle avoidance in intelligent vehicles. Essien et al.[21] and Krishnan[22] developed obstacle avoidance systems based on ultrasonic sensors, which can accurately obtain the relative distance between the vehicle and the measured target. Shen[23], Song et al.[24], Qi et al.[25], and others employed laser ranging sensors to collect environmental distance information, providing precise distance and position data for the construction of obstacle avoidance, positioning, and detection systems. Zhao et al.[26] and Ikram et al.[27] designed ranging systems utilizing millimeter-wave radar sensors, obtaining distance and velocity information of target objects by filtering and matching the differential frequency signals outputted by the radar. Compared to the aforementioned methods, LiDAR, apart from achieving distance measurement, can also process data to generate three-dimensional point cloud maps, capturing the position and shape of the tracked target, thereby enabling comprehensive environmental perception and localization. Wang et al.[28] established a sensing system based on LiDAR for vehicle positioning and obstacle detection. Gao et al.[29] leveraged the high-precision ranging and mapping technology of LiDAR to achieve precise map construction and localization.

The biggest measurement advantage of the infrared sensor is high precision, fast response, small size, and low cost, but it is susceptible to strong light interference, it is only suitable for front measurement, and the measurement range is small. The ultrasonic sensor has fast response, low cost, and high reliability, but its accuracy is low, it is not suitable for long-distance ranging, and it is susceptible to signal interference. The laser ranging sensor can respond quickly and achieve high-precision measurement at the sub-millimeter level. The measurement distance is from several centimeters to several hundred meters, but the cost is high and the accuracy is low under strong light. The cost of ranging sensor is lower than other positioning methods, and it can achieve high-precision distance measurement. However, due to the vulnerability to environmental factors, it is mostly used in indoor ranging, obstacle avoidance, and automatic follow-up operation scenarios. Laser radar has a wider measurement range, higher accuracy, and environmental perception function, which is suitable for complex operating environments, but it is expensive, bulky, and computationally intensive. It is not suitable for small devices, and the richness of perceptual information is worse than that of visual sensors. It is mostly used in scenarios such as automatic driving of vehicles and geographic information data collection.

3.1.2 Research status of GNSS satellite navigation and positioning technology

Global Navigation Satellite Systems (GNSS) utilize satellite signals to compute distances, furnishing users with highly accurate positioning and timing information for global positioning and navigation. Currently, the widely implemented satellite navigation systems encompass the Global Positioning System (GPS), BeiDou Navigation Satellite System (BDS), Global Navigation Satellite System (GLONASS), and Galileo. Given the inherent standard positional biases in satellite positioning receivers, techniques such as Differential GNSS (DGNSS), Real-Time Kinematic (RTK), Post-Processed Kinematic (PPK), and Precise Point Positioning (PPP) are commonly employed to enhance the accuracy of positioning data[30].

Qi[31] designed a differential GNSS positioning algorithm and further proposed a pseudorange positioning method based on the differential evolution algorithm, achieving meter-level positioning accuracy. Zhou et al.[32], Morales et al.[33], and Liao et al.[34] developed GNSS-RTK positioning systems, achieving centimeter-level positioning accuracy. Wei et al.[35] introduced a BeiDou triple-frequency PPK positioning method, significantly enhancing positioning accuracy in complex observation environments such as urban areas. Guo et al.[36] integrated GPS, BDS, GLONASS, and Galileo positioning systems and utilized precise point positioning technology (PPP), demonstrating that it could achieve centimeter-level positioning accuracy similar to RTK.

Standard DGNSS technology is cost-effective and suitable for operational scenarios with low positioning accuracy requirements. RTK technology, relying on ground reference stations, can achieve centimeter-level positioning and is suitable for operational scenarios requiring real-time communication, with widespread practical applications. PPK offers higher positioning accuracy than RTK, also relying on ground reference stations, and is suitable for scenarios that do not depend on real-time communication. Compared to RTK and PPK technologies, PPP does not require the establishment of a dense network of reference stations to ensure centimeter-level positioning accuracy, making it suitable for large-scale, high-precision positioning operational scenarios. However, a single satellite navigation system performs poorly in shaded or building-obstructed environments. Integrating Multi-GNSS positioning can effectively improve positioning accuracy.

3.1.3 Research status of inertial navigation system positioning technology

An inertial navigation system (INS) primarily consists of gyroscopes and accelerometers. The accelerometers measure the acceleration of the target in the X, Y, and Z directions, while the gyroscopes measure the angular velocity of the target around the X-, Y-, and Z-axes. By integrating the acceleration and angular velocity data, the system obtains the target's position, velocity, and attitude information, enabling navigation and positioning.

Wang[37] developed an indoor inertial navigation and positioning system. He designed a gait detection method based on inertial sensors, optimized a zero-velocity update algorithm using a Kalman filter, and achieved high-precision indoor positioning. Huang et al.[38] designed a vehicle inertial navigation method, utilizing an improved dilated convolutional network to calibrate and compensate for gyroscope drift. They also combined temporal convolutional neural networks with the invariant extended Kalman filter for dynamic detection and information fusion of vehicle motion states, reducing both the absolute trajectory error and relative trajectory error of the vehicle's horizontal position.

Inertial navigation can operate independently in environments without signal coverage. However, INS errors accumulate over time, leading to positioning drift. Although Chinese researchers have employed optimization and compensation methods to reduce errors, the optimization process is complex and costly. Therefore, INS is not solely used for high-precision positioning but is typically combined with other positioning systems, such as GPS or visual navigation.

3.1.4 Research status of Ultra-Wideband (UWB) navigation and positioning technology.

Ultra-Wideband (UWB) navigation technology is a wireless communication technology with a frequency bandwidth exceeding 1 GHz. This technology determines the position of a receiver relative to a transmitter by measuring information such as the time delay and signal strength of wireless signals, thereby enabling navigation and positioning. The four commonly used UWB positioning methods are Time of Arrival (TOA), Time of Flight (TOF) ranging, Time Difference of Arrival (TDOA), and Angle of Arrival (AOA)[39,40].

Yu et al.[41] proposed a clock calibration method for a TOA indoor positioning system using UWB, addressing the issue of desynchronization between base stations and tag clocks, thereby improving positioning efficiency and accuracy. Fang et al.[42] proposed an improved positioning algorithm based on TOF and Adaptive Robust Kalman Filtering (ARKF) to effectively enhance positioning accuracy, addressing the susceptibility of UWB indoor environments to interference. Wu et al.[43] designed a UWB vehicle-mounted tag tracking method, utilizing a TDOA-based and adaptive Kalman filtering approach to effectively estimate tag positions. Tunc et al.[44] introduced a hybrid localization approach that combines multiple Time Difference of Arrival (TDOA) and Angle of Arrival (AOA) measurements. Employing this method for position estimation significantly reduced the location error.

In UWB positioning, TOA, TOF, and TDOA can be used alone. TOA receives the time positioning of the tag signal through each base station, and the time synchronization between the tag and each base station should be ensured. TOF is an application of TOA, which emphasizes the flight time of signal propagation and is suitable for indoor and outdoor scenarios with close distance to the base station. TDOA is located by the time difference between the tag signal and the base station. Compared with TOA, it is not necessary to ensure the time synchronization between the tag and each base station, but the time of each base station must be synchronized, which is suitable for multi-base station, high precision, and large-scale scenarios. By measuring the angle of arrival of the signal, the AOA can be used for multi-fusion TDOA or TOF, and the positioning can be completed by a single base station, which is suitable for scenarios with limited signal propagation and multiple interferences.

3.1.5 Research status of visual positioning technology

Visual localization technology utilizes visual sensors to capture images from the environment and estimates the position and orientation of the localization device through image processing and analysis. Based on the type of visual sensor, visual localization technology can be classified into monocular vision, binocular vision, and depth vision.

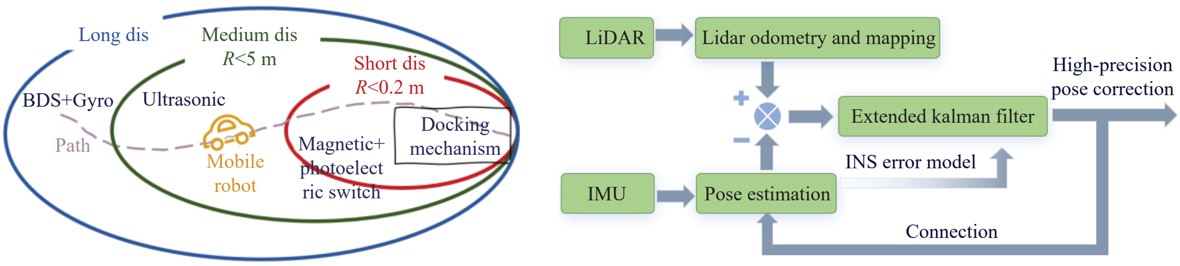
Monocular vision employs a single camera to capture images and infers distance information by analyzing visual features in the image, such as object size, shape, and occlusion. Ji et al.[45] used monocular vision to recognize targets and employed LiDAR for auxiliary positioning, achieving precise ranging and target category recognition. Binocular vision obtains three-dimensional coordinate information from images and calculates the distance to the target. Sun et al.[46] and his team proposed a ranging system based on binocular stereo vision, which combines MATLAB calibration and OpenCV matching to ensure accurate camera intrinsic and extrinsic parameters, addressing issues caused by parallax and enhancing overall robustness. Depth vision utilizes depth sensors or depth cameras to acquire three-dimensional depth information of targets and employs deep learning algorithms to learn and measure the distance and position of objects from images. Zheng et al.[47] verified the high-precision detection capability of depth cameras. Yang et al.[48] improved the ranging accuracy of a depth camera-based following system by combining instance segmentation algorithms with depth estimation algorithms.

Monocular vision cannot directly obtain three-dimensional information about target objects and is typically used for distance estimation, often requiring additional ranging sensors such as LiDAR to achieve accurate distance position measurement. Binocular vision offers high precision and efficiency but demands high camera calibration and synchronization, involves significant computation, and can be challenging to achieve real-time performance[49,50]. Depth cameras are widely used in autonomous driving, three-dimensional reconstruction, environmental perception, virtual reality, and other fields. However, extracting useful information requires complex algorithms and processing, and the cost is relatively high.

3.1.6 Research status of multi-sensor fusion positioning technology

Traditional ranging sensors and single navigation and positioning systems are limited by their working principles and technical characteristics, making them unable to adapt to complex and varied operational scenarios. Single ranging sensors lack comprehensive environmental perception and have limited measurement scenarios. Global Navigation Satellite Systems (GNSS) experience signal obstruction in environments with obstacles such as trees, buildings, or within facilities like greenhouses, leading to decreased positioning accuracy or even signal loss[51]. Although Inertial Navigation Systems (INS) are not affected by external interference and do not rely on any external information, they suffer from error accumulation, resulting in decreased positioning accuracy over extended use. Vision-based navigation systems have high environmental requirements and exhibit unstable positioning accuracy under varying lighting conditions, shadows, and occlusion. Ultra-Wideband (UWB) signals have poor penetration and are affected by vegetation, soil, and buildings in agricultural operations. They are primarily used for short-range, high-precision positioning, requiring multiple base stations and high costs for large-scale positioning.

To address the issues associated with single navigation systems, the adoption of integrated navigation and positioning systems can effectively overcome the limitations of each navigation system and achieve efficient and precise positioning. In enclosed environments such as greenhouses, where satellite signals are strongly interfered, methods for fusion positioning using sensors such as LiDAR, cameras, and INS are often employed. For example, Yuan et al.[52] proposed an indoor navigation and positioning method for Automated Guided Vehicles (AGVs) that integrates IMU, LiDAR, and UWB sensors. By using UWB positioning to reduce the cumulative errors introduced by the IMU, the stability and positioning accuracy of the navigation system in indoor environments are effectively improved. Guan et al. designed an unmanned vegetable harvesting truck, and the SLAM system based on LiDAR and inertial navigation fusion realized greenhouse autonomous navigation and positioning[53]. In open environments like outdoor fields, integrated navigation systems built with sensors such as GNSS and INS can effectively control the accumulation of INS errors and compensate for signal loss in satellite navigation[54,55]. For instance, Shentu et al.[56] proposed a hybrid navigation autonomous positioning system (Figure 6a), which integrates BeiDou Satellite Navigation, gyroscopes, ultra-sonic sensors, and establishes a Kalman filter to process the guidance signals and control outputs of the motion controller, enabling autonomous positioning and navigation of robots in unstructured environments. Long from Southwest University[57] designed an experimental platform for crawler transporters, employing an integrated navigation system with GNSS, INS, and LiDAR (Figure 6b). She proposed an adaptive Kalman filtering algorithm based on Mahalanobis distance and optimized the path tracking controller. Experimental validation demonstrated that the system can effectively fuse navigation information and achieve positioning accuracy that meets the requirements for autonomous driving.



a. Schematic diagram of hybrid navigation system b. Laser radar/INS combination schematic diagram

Figure 6 Related research results of integrated navigation

3.2 Research status of path tracking control method

In terms of motion control for autonomous following of field transport vehicles, path tracking control methods are commonly used to meet the requirements of following operations. These control algorithms typically integrate precise positioning information obtained from navigation and positioning systems, use relevant algorithms to determine appropriate control parameters, and control the maintenance of distance and relative position between the transport vehicle and the target machine. At the same time, they ensure the accuracy and stability of the following path. Path tracking control algorithms are mainly divided into two categories[58]. One category is based on geometric kinematics, focusing primarily on the kinematic characteristics of the system and considering only geometric parameters such as system position, velocity, and acceleration. Typical algorithms in this category include the Pure Pursuit (PP) algorithm and the Stanley algorithm.

The other category is based on system dynamics, where controllers are designed to achieve trajectory tracking objectives by establishing dynamic equations or state-space models of the system. Currently, widely used algorithms in this category include Model Predictive Control (MPC), Linear Quadratic Regulator (LQR) algorithm, Proportional-Integral-Derivative (PID) control algorithm, and fuzzy control algorithm; the comparison of each algorithm is listed in Table 3.

Table 3 Comparison of path tracking control methods

Classification	Name	Advantages	Disadvantages	Applicable scene
Based on geometric kinematics	Pure pursuit algorithm	Simple and easy to implement; smooth steering instruction can be generated at low speed	When the speed is high or the path curvature changes greatly, the tracking accuracy is low.	Scenes where the field path is relatively gentle and the speed of the transporter is not high, such as simple straight-line transportation or slightly curved field roads
	Front wheel feedback algorithm	It can eliminate lateral error and heading error at the same time; the effect of processing curve and curve path is better.	The effect of straight path processing is not good enough; the control effect depends on the control gain.	Scenes with more curves and curves in the field path, such as vegetable fields requiring frequent turning transportation tasks
Based on system dynamics	Model predictive control algorithm	Predict the state change of the transport aircraft and make control decisions in advance; based on the optimization objective function and considering various constraints, the efficient and stable operation of the transport aircraft can be realized	The optimization problem needs to be solved in real time, and the computational complexity is high. The accuracy of the dynamic model of the transporter is required to be high, and the model deviation may lead to poor control effect.	Scenes with complex field environment and high requirements for the operation performance of the transporter, such as transportation tasks that require accurate obstacle avoidance or stable driving in variable terrain
	Linear quadratic regulator (LQR)	Achieves optimal control through state-feedback optimization; offers fast response, high computational efficiency, and good robustness for linear systems	Strong dependence on an accurate mathematical model; parameter tuning is difficult and performance deteriorates under highly nonlinear conditions.	High-precision path tracking tasks with relatively accurate vehicle models, such as autonomous transportation on structured field roads
	Fuzzy control algorithm	Strong adaptability to nonlinear and uncertain environments; does not rely on precise mathematical models; improves system robustness	Controller performance depends heavily on fuzzy rule design and parameter tuning; computational complexity increases with rule number.	Low-speed agricultural machinery operating in complex field environments with uncertain disturbances, such as vegetable field transportation and automatic following

3.2.1 Pure tracking algorithm (PP)

Pure Pursuit is a geometric tracking control algorithm, also known as the Pure Pursuit Control algorithm (Figure 7). Since its proposal by R. Wallace in 1985, this algorithm has been widely applied. Its main principle is based on the center position of the vehicle's rear wheels, where a lookahead point C is set on the reference path at a lookahead distance Ld. Assuming that the vehicle's rear wheels can travel to this lookahead point with a certain turning radius R, the front wheel steering angle δ is then calculated based on the geometric relationship between the lookahead point C, the lookahead distance Ld, the current direction of travel of the vehicle, and the orientation angle α towards the lookahead point C. The vehicle is steered towards the lookahead point C at the angle δ, ensuring that the vehicle's trajectory remains on the reference path[59].

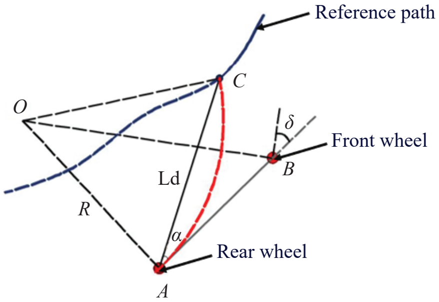


Figure 7 Pure tracking algorithm schematic diagram

Wang et al.[60] from Southeast University designed an adaptive Pure Pursuit algorithm based on GNSS, which can achieve adaptive dynamic adjustment of the lookahead distance in the Pure Pursuit algorithm. This method has a standard deviation of tracking lateral error below 2.5 cm. Wang et al.[61] proposed an Optimized Lookahead Distance Pure Pursuit Algorithm (OLDPPA), incorporating the Salp swarm algorithm in the Pure Pursuit algorithm to improve the accuracy of path tracking. Xiao et al.[62] from Southwest Jiaotong University proposed a two-stage Pure Pursuit algorithm based on lateral deviation and yaw angle, which significantly enhances path tracking performance under low-speed driving conditions.

The performance of the Pure Pursuit algorithm is primarily influenced by the size of the lookahead distance[63]. A shorter lookahead distance helps to reduce path deviation, but frequent adjustments to the travel path may cause the system to become overly sensitive, leading to oscillation phenomena and affecting system stability. Conversely, a longer lookahead distance causes the vehicle to respond more slowly to path changes, resulting in smoother path trajectories and higher stability, but it may also lead to tangent angle issues. However, due to its excessive dependence on the lookahead distance and the difficulty in determining the optimal lookahead distance, the algorithm is usually applied to the path tracking scenario with slow driving speed[64].

3.2.2 Front wheel feedback algorithm (Stanley)

The Stanley algorithm is a nonlinear feedback function of path tracking based on a simplified vehicle motion model. The model typically includes information such as the vehicle's position, heading angle, and speed. Initially, a target path is preset, and the appropriate front wheel steering angle is calculated using the relative geometric relationship between the vehicle's position information and the target path, thereby enabling the vehicle to follow the path.

Wang Liang et al.[65] proposed an improved Stanley controller (IMP-ST) and optimized its controller parameters using a multi-population genetic algorithm, enhancing the control stability of IMP-ST. Cui et al.[66] from Jiangsu University proposed a gain coefficient adaptive front wheel feedback path tracking algorithm, which improves the adaptability of the front wheel feedback algorithm to complex paths. Liu et al.[67] integrated the time elastic band algorithm with the Stanley algorithm to achieve high-precision and smooth path planning control for wheeled robots. Sun Yu et al.[68] proposed an improved fuzzy Stanley model based on particle swarm optimization (PSO), which adaptively modifies control gains based on tracking errors, speeds, and steering actuator saturation levels, thereby improving path tracking accuracy.

The front wheel feedback algorithm is relatively simple.

Compared with the Pure Pursuit algorithm, the Stanley algorithm can effectively avoid tangent angle issues during turns because it considers the vehicle's current state and path curvature. However, the algorithm mainly focuses on the current state, and has weak adaptability to external interference and complex road conditions, resulting in relatively low robustness.

3.2.3 Model Predictive Control algorithm

Model Predictive Control (MPC) originated in Europe and the United States and has been widely used in the field of intelligent control[69]. The basic principle of MPC is to generate the optimal control inputs through predictions of the system's future states, thereby achieving optimized control of the system. It follows the fundamental principles of predictive modeling, rolling optimization, and feedback correction.

Yue et al.[70] applied Model Predictive Control (MPC) in the control design of tractor-trailer systems to achieve trailer position trajectory tracking. They also incorporated Sliding Mode Control (SMC) and Global Terminal Sliding Mode Control (GTSMC), providing enhanced control performance for the system. Zhao et al.[71] proposed a multi-objective optimization MPC control strategy based on an extended state observer, which performs online estimation and feedforward compensation of dynamic disturbances during vehicle tracking, enhancing the accuracy and robustness of tracking control in complex curved road conditions. Kovacs et al.[72] addressed vehicle path planning and tracking issues by proposing a control system based on an online optimization model predictive algorithm. They integrated two parts using a cascaded structure, processed both lateral and longitudinal components and trajectory planning and tracking, and formulated the optimization problem in the predictive method, thereby improving system stability.

MPC is a control strategy that uses future behavior prediction to optimize current control decisions. It can consider multiple control variables and can be adjusted and optimized according to requirements. It is suitable for complex agricultural systems, but it has high dependence on models and high computational complexity. It requires a high-performance computing platform and has high cost of use. It is often used in automatic navigation and precision operation of agricultural machinery, including master-slave operation tracking, trajectory tracking control, path planning, and automatic navigation driving.

3.2.4 Proportional-Integral-Derivative control algorithm (PID)

The PID control algorithm is one of the most basic and commonly used algorithms in trajectory tracking control. Its core lies in adjusting the output of the control system by regulating the proportional (P), integral (I), and derivative (D) components of the error signal, thereby bringing the system output as close as possible to the desired target or trajectory.

Chen et al.[73] developed an automated vehicle-following system that utilizes a PID control algorithm to precisely regulate the distance between the subject vehicle and the preceding one. Luo et al.[74] designed a PID-controlled automatic parking path-following system based on preview error, which, despite its straightforward principle, achieves high-precision tracking. Wang et al.[75] designed a discrete PID path tracking algorithm for simultaneous compensation of position and angle deviations, and developed a path tracking system based on an industrial computer and motion control card. Experimental validation demonstrated that on Z-shaped and U-shaped paths, the maximum tracking deviation of the robot was reduced by 84.8% and 64.0%, respectively, meeting the requirements for high-precision path tracking.

Proportional (P) control acts to quickly respond and adjust the system output based on the current error. As the proportional gain increases, the control effect becomes stronger and the response speed becomes faster, but excessively high gains can cause overshoot or oscillation, resulting in poor system stability. Integral (I) control integrates accumulated errors to eliminate static errors in the system, but excessively high integral gains can easily lead to integral saturation oscillation. Derivative (D) control predicts future error trends and controls based on the rate of error change. By adjusting the derivative term, the dynamic performance of the system can be improved, and the stability and response speed of the system can be improved. Through stable cooperation of these three control components, the PID controller can achieve precise trajectory tracking. The design of the controller typically requires tuning the parameters of P, I, and D according to specific applications to achieve optimal control performance.

3.2.5 Linear quadratic regulator (LQR)

Linear quadratic regulator (LQR) is a classic control design method used for control design in the state-space model of linear dynamic systems. It employs a full-state linear feedback controller to achieve optimal control by minimizing a quadratic function of the system state and control input. This quadratic function is typically composed of a system state weight matrix and a control input weight matrix, and by adjusting these weight matrices, one can prioritize the system state and control input to achieve optimal control of the target path.

Piao et al.[76] proposed an LQR optimal controller for lateral control, utilizing the Simultaneous Perturbation Stochastic Approximation (SPSA) algorithm to optimize the state weight matrix Q and input weight matrix R, thereby enhancing the robustness of the lateral control system. Li et al.[77] proposed LQR control based on an improved path planning algorithm, constructing a feedforward-feedback LQR control system. By solving path planning information and control input parameters in real time, they reduced tracking errors and improved tracking accuracy. Zhou et al.[78] optimized a path tracking control strategy based on the LQR, adding feedforward control to the controller to improve the lateral control accuracy of path tracking.

In lateral control, LQR achieves optimal control by minimizing a cost function, offering the advantages of high computational efficiency and robustness. However, it also has drawbacks such as strong model dependence and difficulty in parameter tuning. Through algorithm improvements and parameter optimization, these drawbacks can be overcome to some extent, enhancing control performance.

3.2.6 Fuzzy control algorithm

Fuzzy control algorithm is a control method that utilizes computers to mimic human fuzzy reasoning and decision-making rules. The core component of a fuzzy control system is the fuzzy controller (Figure 8), which is basically composed of four parts: a fuzzification interface, a knowledge base, a fuzzy inference engine, and a defuzzification interface. The knowledge base includes a fuzzy control rule base and a fuzzy database, where the fuzzy rules are compiled based on expert experience or relevant theoretical knowledge.

Liu et al.[79] designed a fuzzy control method for path tracking based on a pure pursuit model, with the path tracking control block diagram shown in Figure 9. The fuzzification interface of the fuzzy controller receives speed and lateral deviation as inputs, and lookahead distance as the output. In this way, the system can dynamically adjust the lookahead distance based on actual conditions, thereby improving the accuracy and adaptability of path tracking. Zhang et al.[80] proposed a 4WS agricultural machinery path tracking algorithm based on a fuzzy-controlled pure pursuit model. Utilizing the pure pursuit algorithm model and fuzzy controller, they converted heading deviation and lateral deviation into the sum of lateral deviations over a control cycle, which served as the first input. With vehicle speed as the second input, the lookahead distance was set as the output, thereby outputting the actual lookahead distance to achieve precise control of path tracking.

When the fuzzy controller is working, firstly, the real-time input signal from the sensor is received by the fuzzification interface and converted into fuzzy quantity. Then, the fuzzy inference machine performs fuzzy inference according to the fuzzy control rules and the input fuzzy quantity to obtain the output fuzzy quantity. Finally, the output fuzzy quantity is converted into accurate output quantity by the defuzzification interface and applied to the actuator. The application of fuzzy control in agricultural machinery path tracking control can improve the robustness and adaptability of the system, and can deal with the problems of nonlinearity, time-varying, lag, and incomplete model. However, it also faces the challenge of rule base design and computational complexity, which is often used in low-speed agricultural machinery operation control.

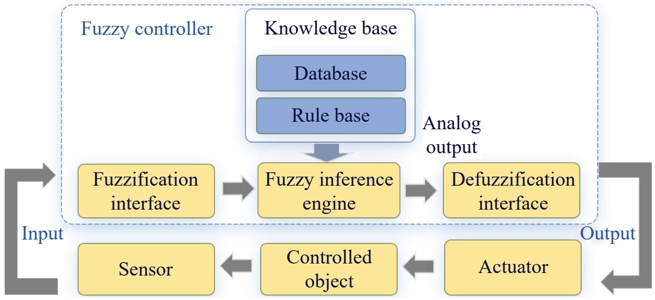


Figure 8 Fuzzy control system

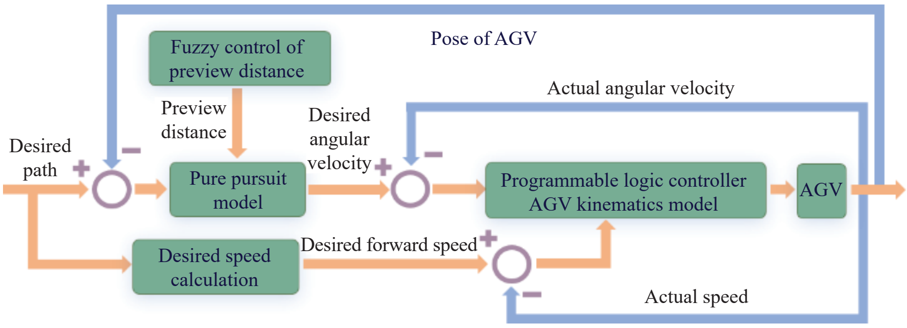


Figure 9 Path tracking control block diagram

3.3 Coupling analysis of navigation and path tracking technologies

Navigation and positioning technologies and path tracking algorithms are the two core components of automatic following systems, and their performance jointly determines the operational accuracy and stability of field transportation. Overall, navigation technologies have evolved from single-sensor positioning to multi-sensor fusion, while path tracking algorithms have gradually developed from geometric methods to intelligent and model-based control strategies. Different navigation methods and tracking algorithms exhibit varying applicability under different operating environments, and no single technology can satisfy all field conditions. Therefore, the coordinated integration of multi-sensor navigation and adaptive path tracking algorithms has become the mainstream trend for improving the robustness and intelligence of open-field vegetable automatic following systems.

4 The main problems existing in the current research

The existing challenges of open-field vegetable automatic following transportation are closely related rather than independent[81]. According to their characteristics, these challenges can be classified into four dimensions: environmental constraints, equipment limitations, technical bottlenecks, and system-level collaboration. Specifically, the non-standardized cultivation environment increases the design complexity of transportation equipment, and the equipment performance directly affects the implementation of navigation and path tracking technologies, while insufficient system collaboration further limits large-scale intelligent applications.

4.1 Lack of standardized planting

The planting mode is not uniform, and the integration of agricultural machinery and agronomy is poor. At present, China's vegetable planting mode is mainly based on individual farmers' management, and there are problems such as diverse vegetable planting modes, inconsistent planting spacing, and complex and diverse agricultural production modes. Farmers did not consider the subsequent realization of mechanized operations in the vegetable planting link, and agricultural machinery could not work on the ground. In addition, the crop planting mode is not fully considered in the design of transportation machinery, resulting in insufficient combination of agricultural machinery and agronomy.

4.2 Defective transport machinery performance

The performance of open-field vegetable transport machinery still needs to be optimized. Some of the conveyors are designed to improve the flexibility to adapt to the narrow field channels; at the same time, they will sacrifice certain stability, and are prone to bumps or rollovers on uneven field roads, affecting transportation safety and vegetable quality. Some models that focus on stability may not be flexible enough in narrow or muddy soil. Although some existing models have a large load capacity, they lack a convenient unloading function. They need to unload vegetables manually, which reduces the operation efficiency and easily causes damage to vegetables during unloading. Some models with unloading function may not be able to meet the needs of large-scale transportation. Most transportation machinery lacks advanced intelligent functions, such as automatic navigation, path planning, obstacle avoidance, etc., and still requires manual driving and operation. It is impossible to achieve efficient and accurate automatic transportation operations, increasing labor intensity and cost.

4.3 Poor anti-interference ability of field navigation

There are many interference problems in the use of single navigation. For example, the GNSS signal is susceptible to interference in the area where the global satellite positioning system is on the edge of the open field and there are many trees in the hilly and mountainous areas. The error accumulation of inertial navigation system in field operation is obvious, which needs frequent correction, and it is difficult to ensure high-precision positioning for a long time; the traditional ranging sensor is greatly affected by light in the field operation. The positioning accuracy of visual navigation system is unstable in different illumination, shadow, and occlusion environments. High-precision navigation and positioning systems (such as laser radar, multi-sensor fusion systems, etc.) have difficulties and high prices in data fusion, algorithm complexity, and data fusion levels in dynamic environments. For some small-scale planting bases or retail growers, the economic burden is heavy, resulting in limited promotion and application, and low-cost single sensors or simple navigation systems cannot meet the requirements of field operations for high precision and high stability. In addition, in the rapidly changing field environment, some navigation and positioning systems have difficulty in achieving real-time and stable positioning. Furthermore, navigation accuracy directly affects the performance of subsequent path tracking, indicating that positioning and control should be considered as a coupled system rather than two independent technologies.

4.4 Weak algorithm adaptability

The path tracking algorithm has insufficient adaptability to the environment in the open-field vegetable planting environment. The pure tracking algorithm and the front wheel feedback algorithm mainly consider the ideal or relatively simple environmental conditions in the design, and have poor adaptability to the complex factors in the field operation environment (such as uneven terrain, muddy soil, changeable climate, etc.), which can easily lead to the decrease of tracking accuracy or deviation. Although the model predictive control algorithm can predict the future state of the system, its prediction accuracy and response speed may be limited in the rapidly changing field environment, which affects the tracking performance. The PID control algorithm is prone to overshoot or oscillation when the parameters are improperly adjusted or in the face of large interference, resulting in system instability. At the same time, some path tracking algorithms (such as model predictive control algorithm, linear quadratic regulator, etc.) have strong dependence on the system model. However, the mechanical system in the field operation environment often has nonlinear and time-varying characteristics, and it is difficult to establish an accurate mathematical model, which limits the application effect and accuracy of these algorithms.

There are few studies on multi-machine cooperative technology of field transportation. In the current research results, there are vacancies in the research on the cooperative operation of field transportation and harvesting and the cooperative operation of multiple vegetable transporters. It is still mainly based on manual remote control, and there are few studies on the decision-making, task allocation, path replanning, and implementation of agricultural machinery multi-machine collaborative decision-making.

5 Prospection

Based on the current research status and existing issues of technological equipment, the following outlooks are proposed for the future development of vegetable field transportation equipment and automatic following technology:

5.1 Standardized vegetable cultivation

Achieve standardized planting of vegetables and unify the planting patterns of similar vegetables. On the premise of not affecting crop yield, the same type of vegetables under the ridge planting mode should unify the parameters such as ridge spacing, ridge width, and furrow depth, and ensure that the ridge surface is flat and the ridge type is vertical. Under flat planting and border planting modes, the row spacing should be unified, and the laying position of drip irrigation belt and ditch position should be reasonably planned. The traditional vegetable garden is upgraded to determine the parameters such as the width of the ground and the position and size of the ditch, and the operation channel of the machine is reasonably planned to ensure that the transportation machinery has enough turning space and traffic roads, so as to reduce the efficiency loss caused by turning or insufficient working space. Future research should establish standardized cultivation specifications and machinery-operation matching schemes to improve the adaptability of automatic following transportation systems.

5.2 Machinery-agronomy integrated optimization

Optimize the structure of field transportation machinery and pay attention to the combination of agricultural machinery and agronomy. Vegetable transport machinery should adapt to different vegetable varieties, cultivation modes, and soil conditions to improve stability and reliability. When the structural parameters of the transport machine are determined, the design of the center distance of the chassis of the transport machine should consider the ridge distance under the ridge planting mode and the row spacing under the flat planting mode and the border planting mode. Ridge height, furrow depth, and crop growth height should be considered in the design of ground clearance. The selection of furrow width should consider the furrow width under ridge planting mode, and the row spacing under flat planting mode and border planting mode. The parameters such as carrying capacity, soil viscosity, and ground slope should be considered in the power selection. The shape, size, height, and unloading position of the carrying material box of the harvester should be considered in the design of the height and conveying position of the harvester conveying mechanism. The blanking position of the conveying mechanism should be at the center of the material box, so as to ensure that the vegetables can fall into the material box accurately, so as to realize the height coordination of the cooperative operation. At the same time, it can develop towards multi-functional modularization, and can be customized according to the characteristics of different transportation products to provide targeted transportation solutions. The development of modular and lightweight transport equipment with improved terrain adaptability will further enhance transportation efficiency and operational reliability.

5.3 High-precision intelligent following

Automatic following technology should be more accurate and intelligent[82,83]. In terms of precise control, by integrating advanced sensors and control algorithms, vegetable transport machinery can achieve real-time environmental perception and dynamic adjustment. For example, using multi-information fusion technologies such as LiDAR, camera, and ultrasonic sensors, machinery can obtain real-time geographic information, crop distribution, and obstacle location of farmland, so as to accurately control the direction and speed of travel, and ensure stability and accuracy during transportation. In terms of path planning, vegetable transportation machinery can adopt advanced planning algorithms and models for intelligent path planning and decision-making.

Combined with the actual layout of farmland and crop planting, the machine can automatically generate the optimal transportation path, avoid obstacles and potential risk areas, and improve transportation efficiency. At the same time, machine learning and deep learning technology can be applied to vegetable transportation machinery to make it acquire stronger self-learning and optimization capabilities. Through a large amount of farmland data training, the machine can continuously learn and master the behavior patterns under various complex environments and job requirements, automatically adjust the transportation strategy, and improve the adaptability and flexibility of the operation. For example, in the face of different weather conditions, soil types, and crop growth conditions, the machine can automatically adjust the transportation mode and parameters to ensure the best operation effect. Integrating multi-sensor fusion with adaptive path planning and intelligent control algorithms is expected to achieve more stable and accurate automatic following under complex field environments.

5.4 Intelligent multi-machine cooperation

Promote the development of intelligent collaborative operations for transportation machinery. The realization of intelligent collaborative operation of vegetable transportation machinery and vegetable harvesting machinery can realize data sharing and information exchange through the establishment of a cloud platform, so as to improve the level of collaborative operation. Firstly, the appropriate cloud platform architecture can be selected according to business needs, and the necessary security measures such as servers, storage, network equipment, and firewalls can be deployed on the cloud platform to develop a cloud resource system for managing and monitoring vegetable harvesting and transportation. This system should be able to realize centralized information management, remote monitoring, and intelligent scheduling of transportation machinery and vegetable harvesting machinery. Secondly, transportation machinery and vegetable harvesting machinery can complete real-time collection and sharing of operation data through the Internet of Things and wireless communication technology, such as location information, operation status, and energy consumption. The cloud platform needs to have the ability to fuse and analyze these data in depth, so as to provide a scientific basis for optimizing the operation strategy and improving the accuracy and efficiency of the operation. Finally, an intuitive and easy-to-use user interface should be developed to display the status, progress, alarm information, and other key contents of vegetable harvesting and transportation operations. This interface should also allow users to manually adjust the job plan or perform remote control according to actual needs. At the same time, it is necessary to ensure the friendliness and ease of use of the user interface, reduce the user's learning cost, and improve the overall use experience of the system.

5.5 Energy-saving and eco-friendly design

Focus on energy efficiency and environmental protection. The research and development of vegetable transporters can be carried out by adopting more environmentally friendly and energy-saving technologies, such as adopting pure electric systems or combining the advantages of internal combustion engines and motors to design efficient hybrid power systems. Additionally, through intelligent control systems, it can automatically switch power or hybrid power according to working conditions. An advanced energy management system is developed to monitor the battery status in real time, predict the energy consumption demand, and intelligently adjust the output of the power system to achieve the purpose of energy saving and emission reduction. At the same time, energy-saving measures can also be applied, such as the use of kinetic energy recovery technology in the braking process to convert the energy generated by the vehicle during deceleration or braking into electrical energy for storage for subsequent driving. Secondly, the design of vegetable transporters can use low-noise motors, sound insulation materials, and silencers to reduce noise pollution during vehicle operation and improve the comfort of the working environment, and can use biodegradable materials in vehicle interior and exterior design to reduce environmental pollution after vehicle scrapping. The integration of electric drive, intelligent energy management, and low-carbon technologies will further improve the sustainability of automatic following transportation equipment.

6 Conclusions

The research on automatic follow-up transportation equipment and technology of open-field vegetables can greatly improve the efficiency of mechanized harvesting and transportation of vegetables, and effectively solve the current shortage of labor and the difficulty of post-harvest transportation of vegetables. The navigation and positioning technology is used to obtain the precise position of the vegetable transportation machinery, and the path tracking control method is combined to effectively complete the synchronous field transportation of the vegetable transportation machinery automatically following the harvesting machinery, so as to realize the cooperative operation of the harvesting and transportation links. In order to improve the efficiency of vegetable field transportation and the stability of automatic following technology, researchers have conducted a lot of research. In this paper, the development progress of vegetable field transport machinery and automatic follow-up key technologies is systematically reviewed from three directions: vegetable transport machinery, navigation and positioning technology, and path tracking method. Although the development of vegetable transportation machinery and its automatic follow-up technology has great potential, it still faces many challenges and problems in practical application. Under the condition of open-field vegetable planting, there are still problems such as inconsistent planting patterns, optimization of mechanical structure performance, navigation interference and poor stability, and insufficient adaptability of path tracking algorithm to the environment, which need to be further improved. Through systematic summary and evaluation, the following main conclusions are drawn:

The main reason why foreign models are not suitable for vegetable field transportation in China is that their design concepts and structural characteristics are quite different from China's planting environment and operation requirements. Foreign transporters are mostly designed for specific environments such as field, large-scale planting or small plots, and hilly and mountainous areas. However, China's open-field vegetable planting patterns are diverse and there is a big gap with foreign countries, and the field roads are narrow. Foreign models are difficult to adapt to these factors. In addition, due to the lack of load, stability, and flexibility of foreign models, it is difficult to land with large load capacity, and the load capacity that can be landed is small, which also limits its application effect in China. The characteristics of domestic models are mainly reflected in the adaptability to the local planting environment. The field transport machinery improves the structural design, such as the use of narrow rubber tracks, high clearance chassis, etc., to improve the trafficability and flexibility in narrow field channels. At the same time, some models are also trying to introduce intelligent technology, such as remote operation, automatic follow-up, etc., to improve operation efficiency and automation level.

Due to the diverse working environment of open-field vegetable cultivation in China, although the single navigation method is low in cost, it is difficult to adapt to the complex field environment. The multi-sensor fusion method is more conducive to accurate positioning. In this paper, some application suggestions are put forward for different types of planting environment: (1) The integrated navigation system built by GNSS and INS sensors is suitable for the open-field environment. Because the environment is relatively open, the GNSS signal coverage is good, and it can provide high-precision positioning information. INS can maintain the positioning ability of the system when the GNSS signal is briefly lost or interfered, effectively control the accumulation of inertial navigation errors, make up for the lack of satellite navigation signals, and ensure the stable follow-up operation of the field transporter in a large range. (2) Due to the complex terrain of hilly and mountainous areas, there are many trees, buildings, and other shelters, and GNSS signals are vulnerable to interference. Laser radar can provide high-precision distance measurement and environmental perception. Camera can obtain rich visual information. Combined with inertial navigation, it can realize accurate perception and positioning of complex terrain, and improve the stability and flexibility of field transporters in narrow channels, gentle slopes, and other terrain. (3) The positioning technology combined with UWB, visual navigation, and ranging sensor is suitable for small-plot environment. The environmental space of small plots is limited, and the positioning accuracy is required to be high. UWB has the characteristics of high precision and low delay, which can achieve accurate positioning in a short distance. Visual navigation can provide rich environmental information, and ranging sensor can obtain accurate distance information. The combination of the three can improve the accuracy and stability of positioning.

The research of path tracking control method is relatively mature, but there are many restrictions in the field environment. The choice of path tracking control method needs to be studied according to the different working environment. Some application suggestions are put forward for different types of planting environment: (1) Model predictive control algorithm (MPC) is suitable for open-field environment. In this environment, the dynamic characteristics and environmental changes of mechanical motion are more complex. MPC can generate the optimal control input by predicting the future state of the system. It is suitable for dealing with multi-variable and multi-constrained complex systems. It can effectively deal with dynamic changes and uncertainties in field operations and improve the tracking accuracy and stability of the transporter. At the same time, the demand for computing resources in the open-field environment is relatively low, and the high computational complexity of MPC can be alleviated to a certain extent. (2) Hilly and mountainous environment is suitable for fuzzy control algorithm. There are many nonlinear factors and uncertainties in hilly and mountainous areas. Fuzzy control algorithm can imitate human fuzzy reasoning and decision rules, and has strong processing ability for nonlinear, time-varying, lagging, and incomplete model problems. It can realize effective path tracking control without relying on an accurate mathematical model. (3) The front wheel feedback algorithm (Stanley) is suitable for small-plot environment. The environment space of small plots is limited and the route is short, which requires high flexibility and accuracy of the transporter. The computational complexity of the Stanley algorithm is low, which can effectively avoid the corner cutting problem when turning, and the dependence on the model is relatively small, which is suitable for small-scale and high-precision path tracking tasks.

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