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Autonomous Navigation for Orchard Mobile Robots: A Rough Review

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***Abstract*—Autonomous navigation is the premise of the application of intelligent orchard machinery, which can help the orchard mobile robot to carry out multi-functional operations without human control. This paper describes the current research status of orchard autonomous navigation technologies, mainly discusses sensing solutions for autonomous navigation in orchard, navigation data processing algorithms and navigation control strategies. First, existing single-sensor based navigation solutions in orchard and their limitations are described. Multi-sensor based navigation has high accuracy, which is the development trend of orchard navigation in the future. Second, navigation data processing algorithms is the key of environmental perception and path planning for orchard robots. Different algorithms for orchard feature extraction and data fusion are introduced. Third, navigation control strategies are discussed.**

Keywords—Orchard mobile robots; autonomous navigation; multi-sensor fusion; navigation data processing; control strategy

I. Introduction

At present, China is the largest fruit producing area and consumer market in the world. Fruit industry plays an important role in agricultural economic activities of China [1]. The rapid decline of agricultural labor force requires wide application of mechanical and automatic equipment. However, compared with other agricultural fields, the mechanization level of fruit industry, especially orchard, is relatively backward. As a result, it is urgent to improve the mechanization and intelligence level of orchard equipment for solving the problem of agricultural labor force decline and enhancing the production efficiency [2].

With the support of information infrastructures, intelligent agriculture has a promising inspect. It uses modern information technology to integrate automation and intelligence into agricultural machinery, and can greatly increase the work efficiency of planting, field management and harvesting. Orchard environment is semi-structured, it is difficult for large machinery to operate inside, which limits the development of intelligent orchard machinery. Robot is an important part of intelligent orchard equipment because of its good environmental adaptability, which can greatly reduce labor input and improve labor efficiency [3].

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Autonomous navigation technology is a key component of orchard robotic systems for precise positioning, path planning and trajectory tracking, etc. It consists of three main parts: sensing solutions, navigation data processing algorithms and navigation control strategies [4]. This paper summarizes the research progress of orchard robot autonomous navigation, expounds the advantages and disadvantages of existing methods, and prospects the future development of orchard robot navigation.

II. Sensing Solutions for Autonomous Navigation in Orchard

The use of sensing solutions in agricultural vehicles is increasing rapidly. Navigation sensors can not only provide the vehicle's own speed and attitude, but also the information of surrounding environment. The application of navigation sensors can provide the absolute and relative positioning information of the robot, so as to the accurate positions of robots in orchards. Different sensing solutions, such as GNSS (Global Navigation Satellite System), IMU (inertial measurement unit), computer vision and lidar, are used as the main sensors of orchard autonomous navigation robot. 里程计 Odometer, gyroscope 陀螺仪 and other sensors as auxiliary equipment can also provide important supplementary information for autonomous navigation system.

GNSS-based navigation solutions

GNSS can provide absolute positioning information in real time when there is no shelter outside. It has the advantages of high precision and all-weather, so GNSS navigation is widely used in open-air agricultural environment[5].

Nørremark et al. [6] developed a self-propelled unmanned weeding system based on RTK-GNSS (Real-Time Kinematic Global Navigation Satellite System) solution. Han et al. [7] developed an automated driving system using RTK-GNSS for commercial agricultural high-speed sprayers. In the system, drivers can manually set the path based on GNSS information. As a result, they don't need to build the orchard map for path generation, which reduces the calculation cost. In path tracking, the control parameters of the robot platform are calculated with the position, heading and speed of the waypoint and GNSS real-time positioning. The positioning accuracy of the system reaches 0.01m in a relatively wide row of fruit trees. Min et al. [8] evaluated the accuracy of six GNSS receivers under different static/dynamic conditions in citrus garden, and concluded that the receiver type and GNSS antenna height have significant influences on the accuracy. Although GNSS navigation shows superiority and great potential in the open environment, GNSS system can't receive satellite signals stably due to the dense canopy and branches of trees in the orchard [9]. Therefore, it is defective to use GNSS navigation system alone..

Lidar-based navigation solutins

The principle of laser ranging can be categorized into triangulation method, time-of-flight method and interferometry method [10]. In recent years, laser rangefinder is widely used on autonomous navigation systems of mobile robots because of its high measurement accuracy, long distance and large amount of distance information.

Jones et al. [11] designed a heavy platform for autonomous navigation of macaque peach garden based on multi-line lidar. Zhou et al. [12] developed an orchard robot based on lidar navigation. In the navigation solution, the center point of the trunk is determined and recorded in the world coordinate system with the help of circular clustering. The standard deviation of robot positioning error in the world coordinate system is about 0.08m.

Lidar employs geometrical features to carry out local positioning, whose global positioning greatly relies on obvious landmarks. In orchard, finding enough obvious geometrical features and landmarks for accurate global positioning is a tough task. As a result, Lidar-based navigation solution is seldom applied only.

Vision-based navigation solutions

With the development of image technologies, vision-based navigation solutions are widely used in the field of agricultural robots because of their abundant information and low cost [13].

Radcliffe et al. [14] proposed a machine vision based system, which captures tree crown and sky features with a multi-spectral camera to guide an unmanned ground vehicle traveling between tree rows (Fig.1). Durand-Petiteville et al [15]. employed four stereo cameras to generate point clouds and detect tree trunks (Fig.2), which improved the robustness of the navigation strategy. According to the characteristics of orchard environment, Nie et al. [16] presented a navigation fitting method based on HSV (Hue, Saturation, Value) color model and maximization of interclass variance algorithm. Although visual navigation has many advantages, it is easy to be affected by light conditions under outdoor scenarios.

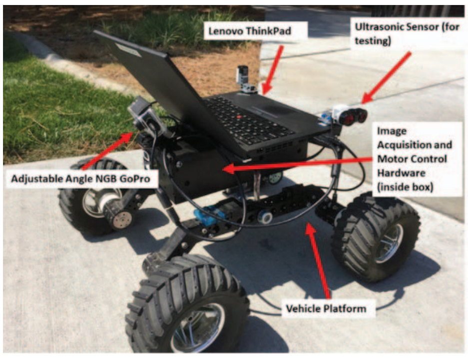


Fig. 1 Unmanned ground vehicle with vision-based navigation system

Fig. 2. 4 stereo cameras on Toro workman MDE vehicle

Multi-sensor-based navigation solutions

As each type of sensors has its own defects, navigation solutions based on single sensing sources are not stable under complex environment [17]. Multi-sensor fusion can solve this problem.

Shalal et al. [18] proposed a method of constructing orchard maps based on multi-sensor data fusion of RTK-GNSS, camera and laser scanner. Javier-Hansen et al. fused the lidar scan matching results and GNSS localization results. Experiments showed that the overall accuracy is improved by 50% compared to only using GNSS [19].

TABLE I. PART OF OTHER RESEARCHES ON MULTI-SENSOR FUSION BASED NAVIGATION IN AGRICULTURE

Sensor type		Application scenarios	References
Main sensor	***Secondary sensor***		
GNSS	Camera/digital compass	Rice field	Kanagasingham et al. [20]
GNSS	Lidar/IMU	Vineyard	Costley et al. [21]
Lidar	GPS/INS	Indoor /outdoor	Gao et al. [22]
CCD camera	GPS	Wheat land	Chen et al. [23]

III. NAVIGATION DATA PROCESSING ALGORITHMS

After data collection, orchard mobile robots need to use algorithms to process environmental data. The main navigation data processing algorithms for orchard mobile robots can be categorized into three groups: filtering-based data processing, segmentation-based data processing and other algorithms.

Filtering-based data processing algorithms

When the robot moves autonomously, the sensor data will be affected by noise due to the soft and uneven road surface in the orchard. The calculation method based on filtering can filter and reduce the noise. When multi-sensor fusion is used, it is also necessary to analyze and process redundant or complementary information to realize the optimal estimation of the robot's surrounding environment and its own state. The commonly used calculation methods based on filtering include KF (Kalman Filter), PF (Particle Filter), EKF (Extended Kalman Filter), etc.

KF is a linear filtering and prediction method, which provides a robust mathematical method for noise reduction and real-time multi-sensor fusion. Because mobile robot systems have nonlinear characteristics in most cases, EKF is employed to solve the nonlinear system problems of mobile robots. EKF linearizes the nonlinear system with Taylor expansion of the nonlinear function, and then performs as a normal Kalman filter. Tang et al. [24] proposed an algorithm combining differential adaptive and extended Kalman filter, and verified its effectiveness. Particle filter is a nonlinear filtering method combining Bayesian and Monte Carlo random sampling methods, which is not limited by the assumptions of linear system and Gaussian noise. Ji et al. [25] used particle filter method for multi-sensor data fusion, and added anti-outlier steps in the algorithm, which effectively weakens the errors caused by GPS jump, thus obtained accurate navigation and positioning information. As the key technologies of multi-sensor fusion, EKF and PF are also widely used to solve SLAM (Simultaneous Localization And Mapping) problems.

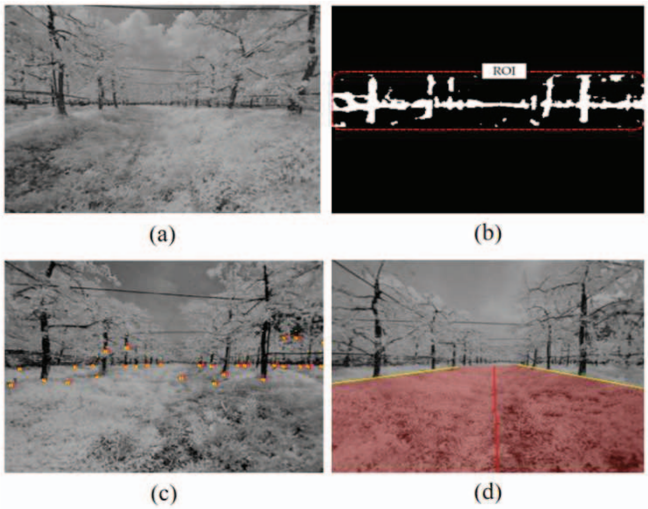
SLAM can give real-time and high-precision positioning and mapping information for robots. More and more scholars apply SLAM to the research of orchard navigation. There are three groups of methods to solve SLAM problem: extended Kalman filter method, particle filter method and graph-based optimization method. Chiang et al. [26] presented a new method for tightly integrating INS, GNSS and lidar systems through EKF-SLAM. Qian et al. [27] assisted EKF-SLAM to extract rich features with high-precision attitude and velocity information obtained by GNSS/INS, greatly improving the accuracy and robustness of positioning. Sun et al. [28] presented a method to improve the quality of laser SLAM point cloud based on geometric primitives to improve the accuracy of mapping. Li et al. [29] obtained a 3D map with texture mapping from depth camera and lidar data under SLAM framework. Droeschel et al. [30], Koide et al. [31] presented a SLAM correction method based on graph optimization to improve the accuracy of mapping. Ni et al. [32] presented a SLAM method using factor graph to fuse 3D lidar and RTK, which can reduce accumulated errors by adding constraints to pose information. Pierzchaa et al. [33] evaluated the tree location accuracy of SLAM based on graph optimization through experiments, and the average error was 0.0476 meters.

Segmentation-based data processing algorithms

For visual navigation, the robot divides the image into different regions through segmentation algorithms, and identifies the objects' locations and boundary points in the image. Many literatures have studied the extraction of navigation information with the help of image segmentation.

Lyu et al. [34] proposed an algorithm for determining the inter-row centerline of fruit trees (Fig.3). The orchard image is obtained with a monocular infrared camera. The image is converted into binary image, and the lowest point of trunk is determined by Naive Bayesian classifier. Gao et al. [35] presented a color-depth fusion segmentation method (CDFS). Combining the Otsu segmentation results of color images with the K-means clustering results of depth images, the target is detected, and the region of interest is divided by image corrosion methods. Finally, the center point of the region of interest is detected to plan the path. Li et al. [36] proposed a visual navigation path detection method based on RANSAC (random sample senses). Experimental results show that the detection rate of navigation path can reach 93.8%.

As one of the most influential algorithms in the field of machine vision, CNN (Convolutional Neural Network) is also widely used in image processing problems. Li et al. [37] designed a convolutional neural network for detecting feature points and descriptors, which improves the accuracy and stability of the visual SLAM system. Kim et al. [38] proposed a block-based convolutional neural network for image classification to detect path regions in citrus orchard. The results show that the average lateral and angular errors of path region positioning are 0.051m and 7.8°, respectively. Ponnambalam et al. [39] proposed a CNN-based Semantic Segmentation (SegNet) algorithm to identify crops and lanes. Based on the U Net semantic segmentation algorithm, Han et al.[40] obtained a path recognition method for orchard visual navigation by training the full convolutional neural network. With a critical threshold of 0.4 and different illumination conditions, the segmentation and intersection ratio is above 86%, and the orchard road pixel-level segmentation can be achieved smoothly.



(a) (b)
(c) (d)

Fig. 3. Determing the centerline of tree rows

(a) is the input image, (b) is the ROI（Region of interest）of the binary image, (c) is the extracted local lowest points of white segments in ROI, (d) shows the estimated two boundaries (yellow lines) and alley center (red line).

Other data processing algorithms

In addition to the calculation methods based on filtering and segmentation, there are also some methods to extract orchard road navigation lines. Wang et al. [41] extracted feature points from orchard road images through convolution neural network and fitted navigation lines through least square method. Zhang et al. [42] used clustering and shortest path method to determine the feature point set through image segmentation, and fitted the object line according to the least square method. Experiments show that the detection accuracy is 0.5 °. Li et al. [43] presented an autonomous navigation algorithm based on adaptive algorithm and spline curve. When the robot moves at a speed of 0.15 m/s for 20m, the maximum lateral deviation is only 0.016 m.

Hough transform is a feature extraction algorithm for image analysis and machine vision processing. Hough transform algorithm is widely used for line recognition of autonomous navigation in orchards, because most trees are planted in rows in orchard environment. Chen et al. [44] employed automatic Hough transform accumulation threshold to extract multi-crop-row. Ye et al. [45] used image processing methods such as threshold segmentation and edge detection to identify fruit trees, and used Hough transform to extract straight line features of tree rows to obtain the robot's traveling route. Barawid et al. [46] developed an orchard navigation system based on a laser scanner using Hough transform algorithm to identify fruit tree rows. Through experiments, the lateral error of orchard robot navigation between orchard rows is about 0.11 m, and the heading angle error is about 1.5°. Chen et al. [47] presented a Hough transform based algorithm to fit the navigation path, the average error is less than 0.5 °, and the calculation time is one third of the traditional Hough transform, which greatly improves the calculation efficiency.

IV. Navigation Control Strategy

Navigation control strategy plays an important role in the application of robot autonomous navigation. The orchard ground environment is complex, and the road surface is soft and uneven, which will affect the heading and speed control accuracies of the robot. Different control strategies, such as proportional integral derivative (PID), fuzzy logic and pure tracking algorithm, are applied to the orchard robot navigation, which can make the autonomous navigation system enjoy sufficient adaptability and robustness.

PID controller

PID controller is widely used in the research of mobile robot autonomous navigation. According to the deviation value of input, it carries out operations according to the functional relationship of proportion, integral and differential, and the operation result is used to control the output. Qi et al. [48] got the center line of the corridor between two tree rows with lidar, and controlled the walking of the mobile robot based on PID theory. Liu et al. [49] designed a navigation controller based on PID controller and laser navigation to carry out the automatic navigation of orchard machinery. In the experimental test, a tractor marched 30 meters in a straight line at the speed of 0.27 m/s, and the maximum lateral deviation was 0.15m. Wu et al. [50] presented a control algorithm based on cascade PID and fuzzy controller, which can reduce the time cost of parameter adjustment. Xiong et al. [51] presented an immune fuzzy PID based intelligent path tracking control method. When the transplanter is moving at a speed of 1m / s, the maximum trajectory tracking error is 4cm and the average tracking error is 0.84cm.

Fuzzy controller

As an intelligent control algorithm, fuzzy control can infer and make decisions in complex and nonlinear environment. Zhang et al. [52] designed a control algorithm of orchard vehicle automatic navigation system based on 2D laser scanner, and realized the dynamic adjustment of pure tracking model by using fuzzy control. Guo et al. [53] developed an automatic navigation control system based on RTK-BDS, and designed a linear tracking navigation controller by combining fuzzy control with pure tracking model. The experimental results show that the maximum lateral error is no more than 0.086m and the average error is no more than 0.036m when the vehicle is marching at a speed of 0.5m/s. Bai et al. [54] proposed a self-tuning model control method for agricultural machinery navigation, in which the fuzzy control method adjusts the model control law online. This idea makes up for the deficiency of fuzzy control method in curve path tracking. When the robot moves at the speed of 1m/s, the root mean square error of straight line tracking and curve tracking is 4.30cm and 5.95cm, respectively. Meng et al. [55] proposed an agricultural machinery navigation control method based on improved particle swarm optimization and adaptive fuzzy control. When the vehicle speed is 0.8m/s, the maximum lateral deviation of linear tracking is less than 4.2cm. Compared with the conventional fuzzy control, the navigation accuracy of the algorithm is significantly improved.

Pure tracking controller

Pure tracking control is a forward path model to determine the appropriate forward-looking distance according to the kinematics and geometry equations of the robot. Li et al. [56] used 3D lidar and random sampling consistency algorithm to obtain orchard traveling lines, and designed an orchard autonomous navigation algorithm with differential model and pure tracking control algorithms. Xiong et al. [57] used the positioning data provided by RTK-BDS and the path tracking algorithm of pure tracking to carry out the straight-line tracking navigation and ground steering control of the sprayer. The experimental results show that the maximum tracking error of the algorithm is less than 0.13m and the average tracking error is less than 0.03m. Wei et al. [58] proposed a pure tracking model based on preview point searching, which greatly improved the navigation accuracy comparing with common fuzzy control methods.

V. Conclusions And Prospects

(1) Orchard environment is complex, single sensor can't meet the needs of navigation. The accurate estimation of the environment and robot position can be achieved by using complementary advantages of different sensors. The autonomous navigation system using multi-sensor fusion is more robust and adaptable to the environment.

(2) EKF is a key technology of multi-sensor data fusion, which can accurately estimate the position and attitude of robots. SLAM algorithm has been widely used in orchard navigation because of its good perception capability for complex environment. However, for outdoor applications, data processing becomes more difficult, and loop detection needs to be further studied. The application of deep learning brings a promising prospect for orchard navigation and place recognition.

(3) Traditional control theories, such as PID, can't give ideal control performances in nonlinear or uncertain systems. The advantages of different control methods can be complementary to achieve better control effect and improve the accuracy and robustness of autonomous navigation system.

With the development of orchard cultivation agronomy, orchard management will be standardized and more large-scale orchards will appear in the future. These changes will bring more opportunities for the applications of orchard robots. With the rapid development of manufacturing technology, computer science and intelligent control algorithms, autonomous navigation technologies will be able to break through the technical problems and meet the demands of orchard autonomous navigation.

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