Research Status and Trend of Vision and Laser in Agricultural Machinery Navigation

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Abstract

With the aging of the population and the development of urban and rural integration, the shortage of agricultural productivity restricts the development of agricultural economy. The automatic navigation technology of agricultural machinery can effectively reduce the input of manpower in agricultural production, which is the key direction of agricultural machinery automation research. In the agricultural environment with lush vegetation, the signal interference is more serious, and the visual and laser sensors are less affected in this case, which is widely used in the research of agricultural machinery navigation. This paper mainly summarizes the methods of vision and laser navigation information acquisition in agricultural machinery navigation, analyzes the advantages and disadvantages of different types of sensors, and points out the research status of multi-source data fusion methods. Finally, the problems and development trends of vision and laser technology in agricultural machinery navigation are proposed.

Keywords

Vision, Lidar, Data fusion, Agricultural machinery navigation.

1. INTRODUCTION

In recent years, with the increasing trend of population aging in China and the acceleration of urban-rural integration, a large number of rural young and middle-aged laborers have entered the city to work, resulting in the continuous reduction of rural laborers and rising labor costs, which has greatly restricted the development of China 's agricultural economy. In order to solve the problems faced by agricultural production, many universities and research institutions focus on the research of automatic navigation technology of agricultural machinery, so as to improve the automation and intelligence level of agricultural machinery. The automatic navigation technology of agricultural machinery can reduce the labor intensity of agricultural machinery drivers, reduce the input of labor costs, and improve the accuracy of operations. It is the basis for achieving precision agriculture [1,2].

In agricultural production, agricultural machinery navigation technology has a wide range of application scenarios. In some processes, it can replace manual operation, such as sowing, fertilization, spraying and harvesting [3].With the gradual maturity of agricultural machinery navigation technology, the labor force will be greatly liberated. The accurate acquisition of navigation information is the premise of navigation [4].At present, in the field of agricultural machinery navigation, in some lush vegetation environments, signal interference is serious, but machine vision and lidar perception technology are less affected and widely used. More and more experts and scholars have carried out research related to this, which is of great

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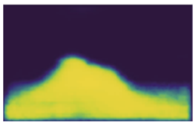
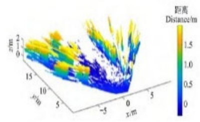
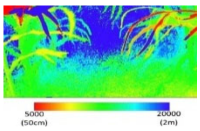
significance in promoting the development of agricultural intelligence and improving the industrial structure.

This paper mainly summarizes the research status of vision and laser in the field of agricultural machinery navigation, compares the navigation information acquisition methods based on vision and laser sensors in intelligent agricultural machinery navigation at home and abroad, and analyzes the advantages and disadvantages of various sensors. Finally, it points out the problems and development trends of vision and laser technology in agricultural machinery navigation

2. RESEARCH ON VISION IN AGRICULTURAL MACHINERY NAVIGATION

Vision has a place in the field of automatic navigation because of its advantages of rich information, high real-time performance, high precision and low cost. At present, visual navigation has become the focus of research in the field of agricultural machinery navigation. The visual navigation system detects and recognizes the images collected in the agricultural environment, divides the road and crop information, and finally extracts the navigation baseline and applies it to the path planning and automatic control of agricultural machinery [5]. In the research of visual navigation system, the main visual sensors used are monocular camera, binocular camera and depth camera. Table 1 is the classification and comparison of cameras suitable for agricultural machinery navigation.

Table 1. Camera classification and comparison for agricultural machinery navigation

Classification	Image data type	Advantages	Disadvantages
Monocular		Simple structure, low cost, and easy to identify and calibrate	Unable to obtain depth and scale information
Stereo		Large field of view and small binocular ranging error	Both configuration and calibration are relatively complex and consume a lot of computing resources.
Depth Camera		Easy access to environmental location	The measurement range is narrow and susceptible to interference.

At present, the most widely used in the research of agricultural machinery navigation is monocular vision navigation, which mainly focuses on image preprocessing and navigation line extraction.

2.1. Image preprocessing

Image preprocessing is to perform color conversion and denoising on the images collected by the visual system, and then segment the path area and the crop area according to the features to obtain the boundary information of the path area. In the RGB tricolor image information of crops in the farmland environment, the G value of crops is usually higher, while the R and B values of soil are higher. Therefore, many studies use 2G-R-B to perform grayscale conversion to increase their separation. Then, the Otsu method (OTSU) is used to binarize the grayscale image to segment the crop row and background information. This method can perform self-use

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threshold segmentation, which can adapt to the threshold requirements of different time and place, and effectively suppress noise interference [6-15].

In addition to 2G-R-G grayscale conversion and OTUS segmentation methods, there are other color models and segmentation methods that have also been studied. Meng et al. [16] proposed the YCrCg (YUV) color model. In this model, the Cg value is independent of the light intensity. This paper compares the gray images of corn color images converted to HIS, YCrCg and RGB color models. It is found that the three models can better classify corn crops from the soil background, but the gray image in the YCrCg model is clearer and more complete. Then, the fuzzy C-means clustering (FCM) of the two-dimensional histogram is used to segment the image and extract the road boundary. This method effectively improves the anti-noise ability. Gao Guoqin et al. [17] transformed the visual image into HSI color channel, performed median filtering according to different H values, and converted it into a grayscale image. Then, the K-means algorithm was used to distance the pixels with different grayscale values, and finally the path boundary information was obtained. The segmentation threshold of the algorithm is more accurate, the road extraction rate is as high as 95 %, and the single image processing time consumption is reduced by 53.26 %. Li et al. [18] used the S and V component points of the HSV color model, and then performed weighted fusion for gray processing, and used threshold segmentation to obtain the road area.

With the development of artificial intelligence technology, neural network models are gradually applied to path semantic segmentation [19]. Yang Yang et al. [20] based on Faster R-CNN network, detected the characteristics of maize rhizomes, extracted the fixed points in the boundary frame of the target detector, and formed the navigation points of the path. Wang Yi et al. [21] used a neural network model based on YoLo v3 to detect the feature information of the contact point between the citrus trunk and the ground, and then fitted the navigation line by the detection information. The average recognition feature rate of this detection method is 95.37 %. Han Zhenhao et al. [22] proposed an orchard navigation path recognition method based on U-Net neural network. This method is based on the U-Net semantic segmentation algorithm. On the basis of data enhancement, the neural network is trained to obtain the neural network model. Through this model, the real-time image can be segmented, and the path can be extracted after binarization processing. Bisong et al. [23] extracted road and fruit tree masks based on the Mask R-CNN network, extracted road boundaries and vanishing points, and then obtained navigation information.

2.2. Navigation line extraction

In the visual navigation technology of agricultural machinery, most of the researches focus on the straight line driving between rows in agricultural environment, and the crop line detection algorithm based on Hough transform and least square method is widely used [24-30].

Astrand et al. [31] proposed a plant row recognition method based on Hough transform. The method adapts to the size of the plant and can fuse two or more rows of information. The standard deviation of the position of the navigation robot in the experiment is 2.3 cm. Luo et al. [32] proposed a ridge recognition optimization algorithm based on Hough transform and Fisher criterion, which improved the accuracy and adaptability of the system. Wu et al. [33] proposed a line fitting method based on improved random Hough transform. Compared with the traditional random Hough transform, this method avoids invalid sampling and accumulation problems.

Si et al. [34] performed two least squares fittings on the extracted feature points in early crop environments of corn and soybean with weeds to obtain the central navigation line of the crop. The experiment proved that the method can overcome the influence of weeds and crop absence and extract crop rows in real time. Song et al. [35] estimated the navigation baseline by using the least square method to fit the slope of the left and right rows of the crop, and the detection

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accuracy in a variety of environments reached more than 90 %. [36] used the least square method to fit the navigation line. The lateral deviation of the final navigation line was 5.1 pixels, and the actual average deviation was 0.052 m. Jiang et al. [37] proposed a linear regression method to fit crop rows. Experiments were carried out in three environments of wheat, corn and soybean, and the detection rate, detection accuracy and processing time were evaluated. It was found that the three indicators were better than the standard Hough transform.

With the deepening of research, Han Zhenhao and Guan Zhuohua used the method based on B-spline curve to fit the navigation line and obtain the path navigation information of the curve path. The path obtained by this method is relatively smooth, which greatly improves the adaptability of agricultural machinery in different environments.

2.3. Research on 3D visual navigation

In recent years, with the development of binocular stereo vision and RGB-D depth camera, the visual navigation of agricultural machinery has gradually begun to adopt the strategy of three-dimensional information perception, and the stereo vision navigation of agricultural machinery has gradually become a new research hotspot. After three-dimensional reconstruction of binocular images, Kneip et al. [38] obtained the crop and ground point cloud information in front of the agriculture. Through the three-dimensional morphological characteristics and the ground height difference, the crop area identification and positioning were realized, and finally the drivable area and navigation path were obtained. Zhang et al. [39] proposed an inspection path method based on binocular vision. This method performs two-dimensional projection and gridding on the binocular image, and then separates the crops on both sides based on the K-means algorithm. Finally, the navigation path is extracted based on the minimum bounding rectangle. The average lateral deviation of the extracted navigation path is 0.1427 m. Gai et al. [40] used TOF depth camera to collect farmland images and converted them into three-dimensional point clouds, separated soil point clouds, extracted vegetation points, and then used linear fitting to obtain crop rows. The experiment showed that the average error of crop row extraction was less than 0.036 m.

Visual technology has a wide range of applications and a wide range of research foundations. Because the monocular camera has the advantages of low cost and fast processing speed, it is the most widely studied in the field of agricultural machinery navigation. However, with the improvement of processor performance and the development of visual perception sensors, binocular vision and depth cameras have also begun to be used in agricultural machinery navigation. Research, and it has richer environmental information and improves system reliability, but the corresponding processing algorithm and processor performance put forward higher requirements, so the difficulty of implementation is higher than that of monocular camera.

3. THE RESEARCH OF LASER IN AGRICULTURAL MACHINERY NAVIGATION

The advantages of laser in long-distance measurement and fast feedback make it occupy an important position in the field of agricultural sensors. At present, the application and research of lidar are extremely extensive in agricultural machinery navigation. Laser radar, also known as laser range finder, is a system that detects the position, velocity and other information of the target by emitting a laser beam. Its working principle is to transmit the laser signal, and then compare the received reflected signal with the transmitted signal. After proper processing, the distance, orientation, height and other parameter information of the environment are obtained [41]. Table 2 is the classification and comparison of lidar.

Table 2. Classification and comparison of lidar

Classification criteria	Classification	Advantages	Disadvantages
Principle	range of triangle	Short distance, high precision and low cost.	The frame rate is low and the effective detection distance is short.
	TOF ranging	Far distance, anti-interference	High cost, low resolution
Dimension	two-dimensions	Low cost	Less data information
	three-dimension	Rich spatial data	High cost
Scanning mode	Flash type	No delay, stability, small size	The detectable distance is short.
	OPA type	High integration and strong adaptability	Ambient light interference is serious
	MEMS type	High reliability and high resolution	Narrow field of view, limited by the area of the galvanometer
	Mechanical type	Fast scanning, anti-interference, mature	Difficult assembly, high cost and low life.

At present, in the research of agricultural machinery navigation, mechanical TOF ranging lidar is widely used. The navigation research of two-dimensional and three-dimensional lidar has been carried out, mainly used in the extraction of navigation path, and has its own advantages in use.

3.1. Two-dimensional lidar research

Due to the efficient and reliable reflection principle of two-dimensional laser, less information and simple operation, it is very suitable for a single place of test object. However, only two-dimensional information can be obtained, and the reliability of navigation needs to be improved.

Oscar et al. [42] designed an orchard automatic navigation system. The noise of the laser scanner was eliminated by the autoregressive method. The Hough transform was used to identify the tree line. According to the information of the tree line on both sides, the position of the robot between the rows was obtained, and the central route in Figure1 (a) was fitted. The navigation parameters such as lateral deviation and heading deviation of the robot were obtained for navigation. The experimental results show that the lateral error and heading error of the system are 0.11 m and 1.5 °, respectively. Santosh et al. [43] proposed a navigation algorithm based on particle filter to estimate the position of the robot in the corn field, and fitted the center line between the trips according to the distribution density of the corn stalks on both sides to navigate. The experimental results show that the root mean square errors of the heading deviation and lateral deviation of the system are 2.4 ° and 0.04 m, respectively. Bayar et al. [44] used a low-cost laser scanner to navigate in the apple orchard. Through the laser point information, the straight line equation was used to fit the tree line to obtain the center line between the lines. The encoder was used to calculate the track to obtain the position of the robot, and the straight line walking between the lines and the turning of the ground were completed. The reliability of the system was verified by experiments. Pieter et al. [45] compared the navigation accuracy and robustness of two laser positioning algorithms, particle filter (PF) and Kalman filter (KF), in navigation robots. In the PF case, the lateral deviation of the robot is evenly distributed on both sides of the optimal navigation line, while in the KF case, the robot

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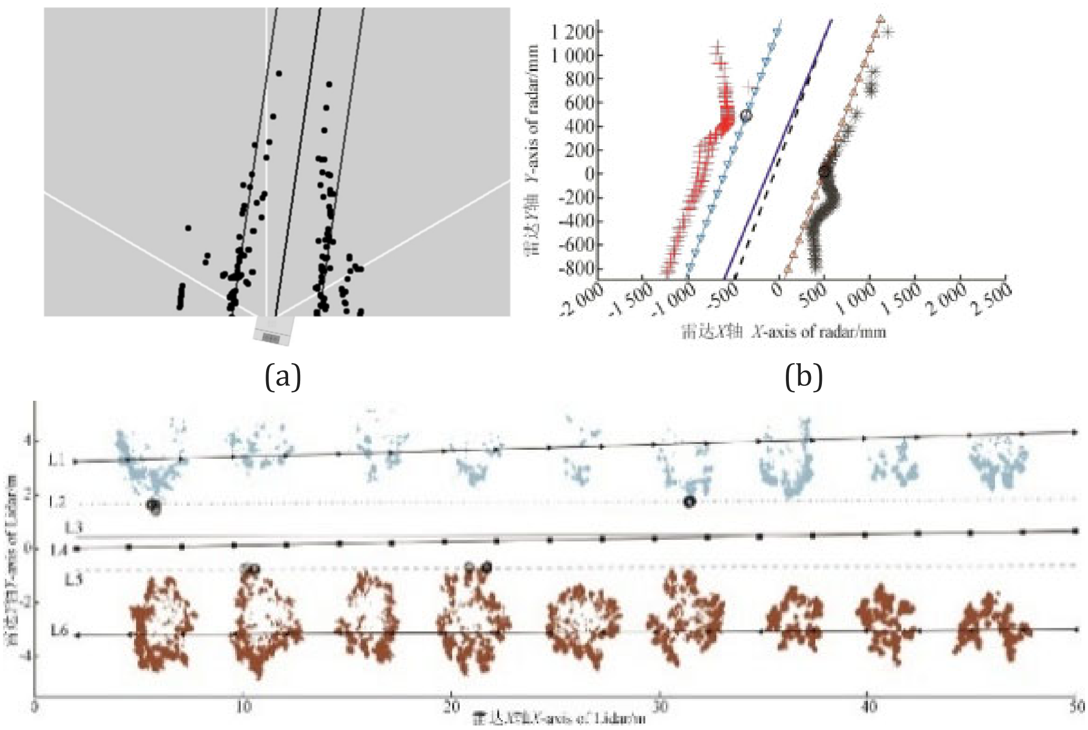
tends to navigate left. The results show that the positioning algorithm using PF is superior to the KF algorithm in the row navigation of autonomous orchard robots.

Chen et al. [46] scanned the fruit tree trunk by laser, filtered the position of other fruit trees by standardizing the orchard row spacing, and finally extracted the position information of the fruit tree trunks on both sides of the robot. According to the proposed curve navigation path fitting algorithm, a fuzzy controller with lateral deviation and heading deviation as output was constructed to realize the automatic navigation of the robot in the orchard curve path. The robot walks along the sine curve at a speed of 0.54 m / s, with a maximum lateral deviation of 0.40 m and an average deviation of 0.12 m. Jia et al. [47] proposed a navigation method for greenhouse robots. The laser range finder was used to detect the edge of the road and generate the expected heading of the robot. The average lateral deviation of the navigation test was 0.0127 mm, and the mean square error was 0.0268 m. Ai et al. [48] used Kalman filter combined with SVM algorithm to process laser radar data to obtain the positioning of the robot and fit the operation navigation line in Figure1 (c). The navigation line fitted by this method meets the requirements of vineyard plant protection robot operation. Li Qiujie et al. [49] proposed an inter-row path extraction method based on laser radar. The two-dimensional laser radar was used to measure the orchard trunk data, extract adjacent tree rows, and use the least square method to fit the tree line and extract the center line of the tree line. Experiments show that the absolute lateral deviation of the vehicle is less than 0.14 m during autonomous navigation. Liu Xingxing et al. [50] obtained the polar coordinate position of the trunk and transformed it into the Cartesian coordinate system based on the two-dimensional laser radar scanning trunk information. The tree row was fitted by the least square method, and the center line between the rows of the orchard was predicted by the SVM algorithm. As a reference navigation line in Figure 1 (c), it was tested in peach orchards, citrus orchards and pine forests. The maximum lateral deviation of the navigation algorithm is 107.7 mm, and the absolute average value of the lateral deviation does not exceed 17.8 mm.



(c)

Figure 1. Navigation line extraction of two-dimensional laser point cloud

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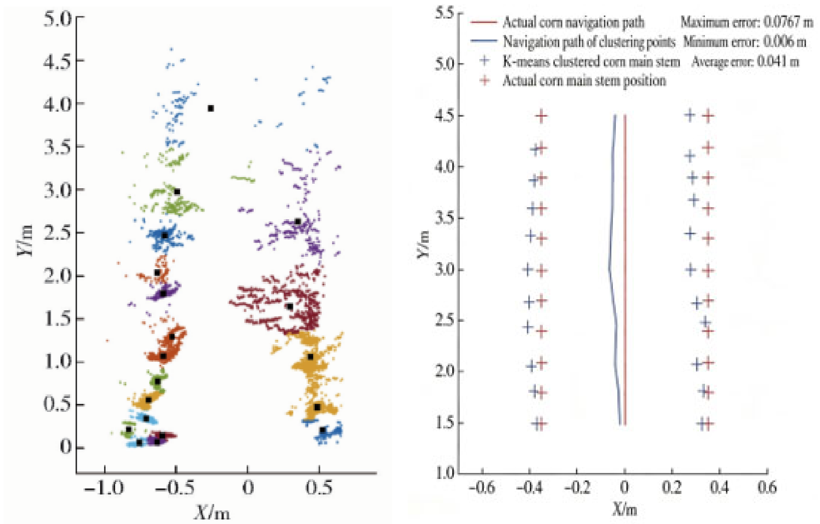
3.2. Three-dimensional laser radar research

In recent years, with the continuous development of laser radar technology, the application of three-dimensional laser radar is more and more. The advantage of three-dimensional laser is to obtain the three-dimensional information of the environment and realize the accurate perception of the target. However, there are also problems such as large amount of data and time-consuming processing of data.

Tuan [51] et al.proposed a three-dimensional laser radar positioning mapping method for large farms. This method separates the data collected by the 16-line lidar into ground points and non-ground points, and the ground points are used as plane features. The non-ground points are divided into different clusters, and then the edge features are extracted by the target clustering method. Then the extracted features are used for pose matching, the position information of the robot is estimated, and the environment map is established according to the point cloud information. This method is suitable for agricultural structured environment, but requires strong computational support.

Liu et al. [52] proposed a method based on 16-line lidar to extract the passable area between crop rows in the middle and late stages of maize. In this method, the spatial point cloud information is projected onto the ground, and the corn trunk position is obtained by clustering according to the K-means algorithm in Figure 2 (a). Finally, the navigation line of the corn crop row center in the high occlusion environment is analyzed in Figure 2 (b). The maximum error of the forward-looking distance of the sensing system is 0.0355 m, which basically meets the normal driving of the mobile robot between the rows of 0.8 m width. Liu Weihong et al. [53] proposed an orchard inter-row navigation method based on 3D laser radar. This method performs Euclidean clustering on point cloud data to obtain the trunk position in Figure 3 (a). According to the optimal parallelism of the left and right tree rows, the random sampling consistency algorithm and the least square method are complementary and fused to find the center line to obtain the navigation line in Figure 3 (b). Experiments show that the system tracks the tree row at a speed of 1.35 m / s, and the absolute lateral deviation does not exceed 0.221 m.



(a) (b)

Figure 2. Extraction of navigation information between maize rows

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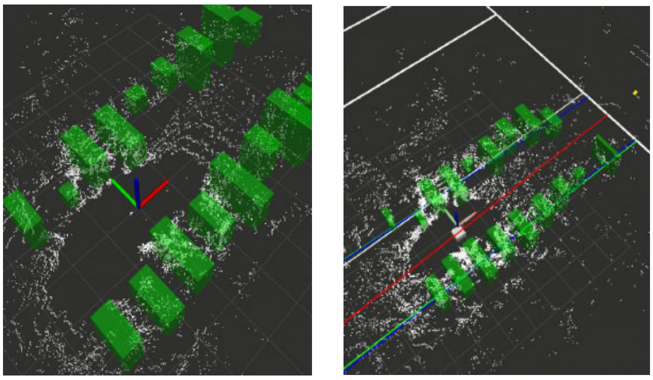

(a) (b)

Figure 3. Extraction of navigation information between orchard rows

At present, the two-dimensional lidar can well adapt to the agricultural scene with obvious trunk features and simple environment. However, for the complex environment of dense canopy, occlusion of trunk features and branches, it is difficult to obtain environmental features, extract navigation information, and the detection data is easily disturbed by the environment. [54] With the development of technology and the reduction of cost, 3D lidar is more and more used in the research of agricultural machinery navigation. Although the cost of 3D laser radar is high, due to its rich data information, the reliability of navigation is greatly improved, and the adaptability to the agricultural environment is also stronger. However, the huge amount of data, the requirements for the processor are gradually increasing, and the cost of navigation will also increase.

4. RESEARCH ON THE INTEGRATION OF THE TWO IN AGRICULTURAL MACHINERY NAVIGATION

At present, in the research of agricultural machinery navigation, the fusion of vision and laser data is mostly used in the target detection link in the navigation process, and most of them are the combination of monocular vision and two-dimensional laser radar to reduce the research cost and difficulty. Monocular vision can easily obtain the shape, size and color information of the target, and lidar can perceive the position information of the target in the environment. The fusion of the two can obtain richer environmental target information.

Auat et al. [55] proposed a method for sensing trunk information based on camera and laser scanner respectively. The camera is used to estimate the orientation of the olive trunk, and the distance information associated with the trunk is detected by a laser scanner to extract the position information of the trunk (Fig.a), which is used to establish a map of the forest for navigation. Nagham et al. [56] proposed an orchard trunk detection method based on data fusion of camera and laser scanner. The laser scanner detects edge points, determines the width of the trunk and non-tree objects, and the camera recognizes the color and parallel edges of the trunk and non-tree objects (Figure b). The test results show that the detection accuracy of the algorithm reaches 96.64 % in sunny and cloudy weather. This method provides a basis for the extraction of navigation lines. Xue Jinlin et al. [57] proposed an obstacle detection method for agricultural machinery navigation based on the fusion of camera and laser radar. This method detects the saliency of the monocular camera based on the Ft algorithm. At the same time, the laser radar data is clustered. The image is segmented by the cluster points generated by the clustering, and the regional information of the obstacle is finally obtained. Abdelkrim et al. [58] proposed a joint calibration method of monocular vision and two-dimensional lidar, which was applied to the target detection of strawberry greenhouse robot. This method can estimate the homography matrix by calibrating the edge laser points and visual images of the plate. The

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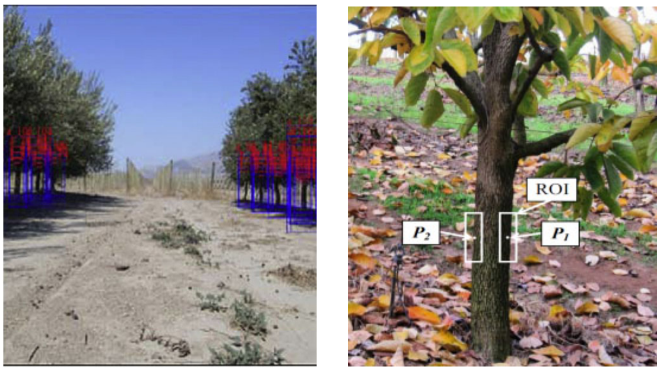
matrix can project the laser points into the visual image and extract the size, shape and depth information of the target.



(a) (b)

Figure 4. The detection results of sensor fusion

5. EXISTING PROBLEMS

Farmland environment variability and unstructured interference on precision navigation. Because the farmland environment is mostly unstructured and variable, it will have a certain impact on the information collection of the sensor. For example, the influence of illumination on the visual sensor is relatively large, which easily leads to the failure of the visual algorithm and the inability to complete the navigation work. The weeds and stones in the environment will also affect the detection of lidar. The algorithm cannot eliminate all the interference and is easy to lose the target at work. In the future, how to solve the interference problem through target detection and recognition technology is extremely important.

Improve navigation accuracy based on low-cost sensor multi-source fusion mode. The use of high-precision sensors in agricultural machinery navigation is bound to increase the cost of agricultural production. At the same time, the reliability of low-cost sensors currently used is relatively low, so the fusion of low-cost sensors has become a new direction, but the fusion method is still in its infancy. The fusion algorithm is relatively simple and can only identify targets with fixed features. The accuracy of the extracted information still needs to be improved. In the future, it is necessary to conduct in-depth research on the fusion algorithm to obtain richer environmental information for navigation.

6. FUTURE TRENDS

Application of sensor technology upgrade optimization. Research new technical methods to optimize the shortcomings of different sensors, such as hardware or software updates for the sensitivity of visual sensors to light intensity, and gradually enhance the adaptability to light. With the wide application of lidar sensors, the technology will be constantly updated and the manufacturing cost will be reduced, so that it can be applied to the navigation development of agricultural machinery.

Multi-source sensor fusion technology development. Multi-sensor fusion navigation technology has been studied more and more widely in recent years. Each sensor can make up for each other 's disadvantages and improve the stability of the navigation system. The fusion of different sensors is not only a simple combination, but also needs to strengthen the efficiency of information fusion and obtain accurate navigation information. The research of fusion technology needs to be further strengthened.

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Develop a new mode of following navigation. The sensor collects information fusion in a more complex agricultural environment, but it has high reliability for the detection of specific specified targets, such as detecting the guider or the guide machine driven by the human. The guidance characteristics of these targets are relatively clear, which can improve the accuracy of navigation information, which will greatly improve the stability of the system.

REFERENCES

[1] Zhou Jun, He Yongqiang. Advances in Research on Navigation Path Planning of Agricultural Machinery [J]. Journal of Agricultural Machinery, 2021, 52 (09) : 1-14

[2] Wang Baoliang, Shen Wenlong, Zhang Baoyu. Development status and trend analysis of environmental perception technology for agricultural unmanned vehicles [J].Chinese Journal of Agricultural Machinery Chemistry, 2021,42 (11) : 214-221

[3] Hu Jingtao, Gao Lei, Bai Xiaoping, etc. Advances in Automatic Navigation Technology of Agricultural Machinery [J]. ACTA AGRICULTURAL ENGINEERING, 2015,31 (10) : 1-10

[4] Zhang Man, Ji Yuhan, Li Shichao, etc. Advances in Navigation Technology of Agricultural Machinery [J]. Journal of Agricultural Machinery, 2020,51 (04) : 1-18

[5] Yang Tao, Li Xiaoxiao. Research progress of machine vision technology in modern agricultural production [J]. Chinese Journal of Agricultural Machinery Chemistry, 2021, 42 (03) : 171-181

[6] Otsu N. A Threshold Selection Method from Gray-Level Histograms[J]. IEEE Transactions on Systems, Man, and Cybernetics,1979,9(1)

[7] Woebbecke D M, Meyer G E, Bargen K V, et al. Color Indices for Weed Identification Under Various Soil, Residue, and Lighting Conditions[J]. Transactions of the Asae,1995,38(1):259-269

[8] Soggaard H, Olsen H J. Determination of crop rows by image analysis without segmentation[J]. Computers & Electronics in Agriculture,2003,38(2):141-158

[9] M. Montalvo, G. Pajares, J.M. Guerrero, et al. Automatic detection of crop rows in maize fields with high weeds pressure[J]. Expert Systems with Applications,2012,39(15)2012:11889-11897

[10] Zhang Wei, Du Shangfeng. Recognition of positioning datum line in farmland by machine vision [J]. Journal of China Agricultural University, 2006 (04) : 75-77 + 88

[11] Chen Jiao, Jiang Guoquan, Du Shangfeng, etc. Visual navigation multi-ridge line recognition based on ridge line parallel feature [J]. ACTA AGRICULTURAL ENGINEERING, 2009,25 (12) : 107-113

[12] Diao Zhihua, Zhao Mingzhen, Song Yinmao, etc. Crop row recognition algorithm and system implementation of corn precision application system based on machine vision [J].ACTA AGRICULTURAL ENGINEERING SCIENCE, 2015,31 (07) : 47-52

[13] Zhang Tiemin, Zhuang Xiaolin. Field path recognition and navigation system of high clearance car based on DM642 [J].ACTA AGRICULTURAL ENGINEERING SINICA, 2015,31 (04) : 160-167

[14] Guan Zhuohuai, Chen Keyin, Ding Youchun, etc. Visual navigation path extraction method for rice harvesting [J].Journal of Agricultural Machinery, 2020,51 (01) : 19-28

[15] Jiang Guoquan, Ke Xing, Du Shangfeng, et al. Crop row detection based on machine vision [J]. Journal of Optics, 2009,29 (04) : 1015-1020

[16] Meng Qingkuan, He Jie, Qiu Ruicheng, etc. Crop row recognition and navigation line extraction in natural environment based on machine vision [J].Journal of Optics, 2014,34 (07) : 180-186

[17] Gao Guoqin, Li Ming. Greenhouse mobile robot navigation path recognition based on K-means algorithm [J]. ACTA AGRICULTURAL ENGINEERING, 2014,30 (07) : 25-33

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202604_12(4).0007

[18] Li Yunwu, Xu Junjie, Wang Mingfeng, et al. Development of self-driving transfer vehicle and its visual navigation system for field roads in hilly and mountainous areas [J].ACTA AGRICULTURAL ENGINEERING SINICA, 2019, 35 (01) : 52-61

[19] Kim W, Lee D, Kim Y, et al. Path detection for autonomous traveling in orchards using patch-based CNN[J]. Computers and Electronics in Agriculture, 2020, 175:105620

[20] Yang Yang, Zhang Yalan, Miao Wei, et al. Research on accurate identification and location of maize rhizomes based on convolutional neural network [J]. Journal of Agricultural Machinery, 2018,49 (10) : 46-53

[21] Wang Yi, Liu Bo, Xiong Longye, et al. Research on orchard road navigation line generation algorithm based on deep learning [J].Journal of Hunan Agricultural University (Natural Science Edition), 2019,45 (06) : 674-678

[22] Han Zhenhao, Li Jia, Yuan Yanwei, et al. Orchard visual navigation path recognition method based on U-Net network [J].Journal of Agricultural Machinery, 2021,52 (01) : 30-39

[23] Bison, Wang Yuhao. Orchard robot vision navigation inter-row pose estimation and fruit tree target positioning method [J]. Journal of Agricultural Machinery, 2021,52 (08) : 16-26 + 39

[24] Rao Honghui, Ji Changying. Detection of early crop row centerline using Hough transform based on label information [J].ACTA AGRICULTURAL ENGINEERING SCIENCE, 2007 (03) : 146-150

[25] Zhang Zhibin, Luo Xiwen, Li Qing, etc. Visual navigation parameter extraction algorithm for agricultural machinery based on well-ordered set and ridge structure [J].ACTA AGRICULTURAL ENGINEERING SCIENCE, 2007 (07) : 122-126

[26] Feng Juan, Liu Gang, Si Yongsheng, et al. Orchard visual navigation baseline generation algorithm [J].Journal of Agricultural Machinery, 2012,43 (07) : 185-189 + 184

[27] Diao Zhihua, Wang Huidan, Song Yinmao. Research on farmland mechanical navigation line extraction algorithm based on machine vision [J].Research on agricultural mechanization, 2015,37 (02) : 35-39 + 45

[28] Zhang Q, Chen M.S, Li B. A visual navigation algorithm for paddy field weeding robot based on image understanding[J]. Computers and Electronics in Agriculture, 2017,143:66-78

[29] Peng Shunzheng, Kan Za, Li Jingbin. Visual navigation path extraction for harvesting operation in dwarf and close planting jujube orchard [J].According to Journal of Agricultural Engineering, 2017,33 (09) : 45-52

[30] Guo Xiangyu, Xue Xinyu. Navigation line extraction method for rice seed production field based on machine vision [J]. Chinese Journal of Agricultural Machinery Chemistry, 2021, 42 (05) : 197-201

[31] B Astrand, Baerveldt A J. A vision based row-following system for agricultural field machinery[J]. Mechatronics, 2006, 15(2):251-269

[32] Zhang Zhibin, Luo Xiwen, Zhou Xuecheng, et al. Ridge recognition algorithm based on Hough transform and Fisher criterion [J].Chinese Journal of Image and Graphics, 2007 (12) : 2164-2168

[33] Wu Gang, Tan Yu, Zheng Yongjun, et al. Linear detection of walking target for harvesting robot based on improved Hough transform [J].Journal of Agricultural Machinery, 2010,41 (02) : 176-179

[34] Si Yongsheng, Jiang Guoquan, Liu Gang, et al. Early crop row centerline detection method based on least square method [J].Journal of Agricultural Machinery, 2010,41 (07) : 163-167 + 185

[35] Song Yu, Liu Yongbo, Liu Lu, et al. Extraction method of maize rhizome navigation baseline based on machine vision [J].ACTA AGRICULTURAL MACHINERY, 2017,48 (02) : 38-44

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202604_12(4).0007

[36] Ma Chi, Dong Ziyang, Chen Zhijun, etc. Study on the generation method of inter-row navigation lines in kiwifruit orchards based on root point substitution [J].Agriculture research in arid areas, 2021,39 (05) : 222-230

[37] Jiang G Q, Wang Z H, Liu H M. Automatic detection of crop rows based on multi-ROIs [J]. Expert Systems With Applications, 2015,42 (5) : 2429-2441

[38] Kneip J, Fleischmann P, Berns K. Crop edge detection based on stereo vision[J]. Robotics and Autonomous Systems, 2020,123:103323

[39] Zhang Zhengan, Li Shichao, Li Chenyang, et al. Navigation path extraction method of banana garden inspection robot based on binocular vision [J].ACTA AGRICULTURAL ENGINEERING SCIENCE, 2021, 37 (21) : 9-15

[40] Gai J Y, Xiang L R, Tang Lie. Using a depth camera for crop row detection and mapping for under-canopy navigation of agricultural robotic vehicle[J]. Computers and Electronics in Agriculture,2021,188:106301

[41] Xue Jinlin, Zhang Shunshun. Research on navigation control of agricultural robot based on laser radar [J].Journal of Agricultural Machinery, 2014,45 (09) : 55-60

[42] Oscar C, Mizushima A, Ishii K, et al. Development of an autonomous navigation system using a two-dimensional laser scanner in an orchard application[J]. Biosystems Engineering,2007,96(2):139-149

[43] Santosh A. Hiremath et al. Laser range finder model for autonomous navigation of a robot in a maize field using a particle filter[J]. Computers and Electronics in Agriculture,2014,100:41-50

[44] Bayar G, Bergerman M, Koku A B, et al. Localization and control of an autonomous orchard vehicle[J]. Computers and Electronics in Agriculture,2015,115:118-128

[45] Pieter M. Blok, Koen van Boheemen, Frits K. van Evert, et al. Robot navigation in orchards with localization based on Particle filter and Kalman filter[J]. Computers and Electronics in Agriculture,2019,157:261-269

[46] Chen Jun, Jiang Haoran, Liu Pei, et al. Curved path navigation control of orchard mobile robot [J].Journal of Agricultural Machinery, 2012,43 (04) : 179-182 + 187

[47] Jia Shiwei, Li Junmin, Qiu Quan, etc. Road edge detection and path navigation of greenhouse robot based on laser range finder [J]. ACTA AGRICULTURAL ENGINEERING, 2015,31 (13) : 39-45

[48] Ai Changsheng, Lin Hongchuan, Wu Delin, et al. Path planning algorithm for vineyard plant protection robot [J]. Journal of Agricultural Engineering, 2018,34 (13) : 77-85

[49] Li Qiujie, Ding Xudong, Deng Xian. Laser radar-based inter-row path extraction and navigation in orchards [J].Journal of Agricultural Machinery, 2020,51 (S2) : 344-350

[50] Liu Xingxing, Zhang Chao, Zhang Hao, etc. Autonomous navigation method between fruit rows based on least square method and SVM [J].ACTA AGRICULTURAL ENGINEERING SCIENCE, 2021, 37 (09) : 157-164

[51] Tuan Le, Jon Glenn Omholt Gjevestad, Pål Johan From. Online 3D Mapping and Localization System for Agricultural Robots[J]. IFAC PapersOnLine,2019,52(30)

[52] Liu Lu, Pan Yanjuan, Chen Zhijian, etc. Research on inter-row navigation of maize plant protection robot in high occlusion environment [J]. Agricultural Machinery Journal, 2020,51 (10) : 11-17

[53] Liu Weihong, He Xiongkui, Liu Yajia, et al. Orchard inter-row 3D LiDAR navigation method [J].Journal of Agricultural Engineering, 2021, 37 (09) : 165-174

[54] Zhang J, Chambers A, Maeta S, et al. 3D perception for accurate row following: Methodology and results[C]. IEEE International Conference on Intelligent Robots and Systems,2013

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202604_12(4).0007

[55] F. Auat Cheein, G. Steiner, G. Perez Paina, R. Carelli. Optimized EIF-SLAM algorithm for precision agriculture mapping based on stems detection[J]. Computers and Electronics in Agriculture, 2011, 78(2): 195-207

[56] Nagham S, Tobias L, Cheryl M, et al. Orchard mapping and mobile robot localisation using on-board camera and laser scanner data fusion – Part A: Tree detection[J]. Computers and Electronics in Agriculture,2015,119:254-266

[57] Xue Jinlin, Dong Shuxian, et al. Obstacle detection method for agricultural autonomous vehicles based on information fusion [J]. Agricultural Machinery Journal, 2018,49 (S1) : 29-34

[58] Abdelkrim A, Lhoussaine M, Mohamed E A. A calibration method of 2D LIDAR-Visual sensors embedded on an agricultural robot[J]. Optik, 2022, 249:168254