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Research Article

Research on Door-Opening Strategy Design of Mobile Manipulators Based on Visual Information and Azimuth

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At present, the manipulator has become an important auxiliary tool in the production and processing operations, so new requirements are put forward for the control strategy of the manipulator. In production, because traditional manipulators can only perform tasks according to the set procedures and cannot fully realize the intelligence and collaboration of control, how to improve the operating efficiency of manipulators has become an urgent problem to be solved. The autonomous door-opening control of robots is a challenging research topic in the field of automation. In the robot movement, target recognition and positioning and the coordinated control of manipulators and mobile platforms are difficult points in the research of autonomous door-opening control. Through the research on autonomous door-opening control, the robot has a broader working space, which greatly improves the robot's ability to serve humans and has important theoretical value and practical significance.

1. Introduction

With the rapid development of mechanical automation, industrial robots have been widely used. As one of the main equipment, the mechanical arm can be regarded as a complex system composed of hands, arms, wrists, bases, and other structures. The control system of the robotic arm is generally a computer that can perform human-computer interaction, through which it sends instructions to the robotic arm to control the motion of the robotic arm's joints and linkages and finally make the end effector reach the target position. The end effector of the robotic arm is selected according to the specific working environment and work tasks, and the positioning and orientation of the end effector are completed by the cooperation of the arm and wrist of the robotic arm. With the development of the manufacturing industry, the requirements for precise operations of the robotic arm are getting higher and higher, requiring it to have the characteristics of flexibility, reliability, and stability. The premise of the robotic arm to complete the task is a reliable control strategy of the robotic arm. The manual teaching method is the most widely used method for the control strategy of the robot arm. It first obtains a position of the robot arm that is most suitable for the operation. This step is mostly derived by the engineer based on his own experience, and then, the robot arm control system is manually operated. Operate, make the robot arm reach the designated position, and finally input all the operations into the host computer as a teaching program, so that the robot arm will automatically repeat the teaching program to complete the production task. In this method, the robotic arm only performs repetitive activities and cannot cope with emergencies. The teaching program is generally adapted to the fixed tasks it corresponds to, and its reusability is poor. Therefore, a new control strategy is needed to improve the accuracy, speed, flexibility, smoothness of motion, system stability, etc., of the robotic arm, so as to improve the efficiency of the robotic arm [1–9].

The hardware construction of the door-opening control system includes the construction and debugging of the movable platform; the selection of sensors; the integration of sensors; and the acquisition of sensor data information. The positioning of the door handle is to determine the positional relationship between the door handle and the robot, so as to give the control system the ability to "observe." The positioning of the door handle is a prerequisite to ensure that the robot completes the task of opening the door. In a three-dimensional environment, positioning the door handle based on visual information has the advantages of simplicity and efficiency. Therefore, the use of visual information is the most commonly used method in the study of the door-opening control systems. Robotic arm motion planning is to plan and execute the motion trajectory of the robot arm for the specific door handle. By controlling the rotation of each joint of the multidegree-of-freedom robot arm, the door handle is operated to complete the door-opening action. The movement trajectory designed in the plan is generally only valid for a specific door handle type [10–15]. The mobile manipulator is shown in Figure 1.

Figure 1: Mobile manipulator.

The motion control of the mobile body of the robot is to plan the motion trajectory of the mobile body of the robot. Due to the limited operating range of the manipulator itself, controlling the robot to reach the area where the door handle can be operated is a very important research content [16–19].

Andreopoulos and Tsotsos have designed a wheelchair for the disabled. The wheelchair is controlled by a computer. The door can be positioned and opened by using an active vision technology combined with a robotic arm. Kragic et al. modeled the door handle in the image space and positioned the door handle on the image plane. Kim et al. used a stereo camera to guide the robotic arm to a position where the door handle can be grasped. Chung et al. used a voting algorithm to estimate the shape of the door handle, using a monocular camera to identify the approximate position of the spherical door handle and then using the end effector to repeatedly touch the door handle. Saleh et al. adopted the modular and reconfigurable robot (MRR), using the characteristics of its multiple working modes and by switching its selected joints to work in the active mode when opening the door, thereby simplifying the steps of opening the door. Rusu et al. proposed a method of using 3D point cloud data to locate doors and handles by detecting geometric structure and ground reflectivity. Klingbeil et al. used vision-based learning algorithms to detect and locate door handles and elevator buttons before and after the robot navigates to the door and determine the direction of rotation of the door handle based on vision. Petrovskaya et al. determined the position and direction of the door handle based on Bayesian posterior estimation based on force measurement and proposed a method to detect the position and direction of the door handle [20–28].

Sachin et al. used a graph-based representation method to overcome the high-dimensionality of the planning problem. This representation method requires a small amount of information but includes effective door-opening motion planning. Experiments on the PR2 robot verify its effectiveness. Advait et al. adopted a behavioral model of sensory feedback, ignoring a large number of door-related factors, such as color or door handle geometry, so that the robot can open multiple types of doors without additional programming and learning. In the next study, they introduced the balance point into the door-opening method, thus completing the task of opening the door within 2 minutes. Wim et al. proposed a comprehensive door-opening system that uses a reaction controller to coordinate the movement of the arm and the robot body with the door, but it is only limited to the behavior of pushing the door open. Lars et al. combined the online estimation of the door model with the hybrid system model and applied it to the door-opening experiment. Andrei et al. used PCA and SVM algorithms to analyze feature points and identify door handles in a single scene. Dragomir et al. established a probabilistic framework to capture the shape, color, and motion characteristics of doors and walls. After the probabilistic model is optimized by a highly expected algorithm, the obtained environmental information is divided into two different objects, doors and walls, and it analyzed their respective characteristics. Niemeyer et al. estimated the speed of the end effector on the premise that the door handle has been held and applied a force in the direction of the estimated speed. Ott et al. introduced the concept of impedance controller to a flexible joint robot under the premise of knowing the direction of the door handle screwing, thereby guiding the robotic arm to complete the task of opening the door. Schmid et al. designed a static mechanical arm to complete the task of opening drawers and cabinet doors under the assumption that the door handle does not need to be rotated. Natale and others applied sensitive tactile sensors and flexible actuators to the robot platform and demonstrated that the tactile feedback generated by contact contains the invisible information of the grasping object, shape, which is very useful for robot learning. Morales et al. proposed a humanoid robotic arm grasping model for grasping objects in a kitchen environment. An offline grasping analysis system was established by establishing a model database and combined with a stereo camera vision system to obtain real-time object positioning information to complete the grasping task [29–33].

Therefore, through the research on autonomous door-opening control, the robot has a broader working space which greatly improves the robot's ability to serve humans and has important theoretical value and practical significance.

2. Door-Opening Judgment Process Based on Depth Image Information

Figure 2 is the flow chart of the door-opening judgment method based on depth image information proposed in this article. The door-opening judgment method based on depth image information proposed in this paper includes six parts:

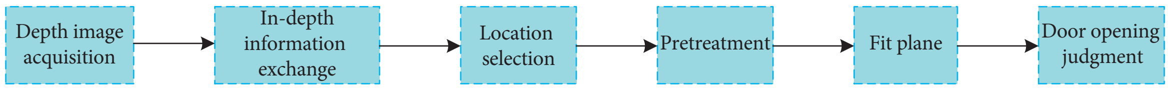


Figure 2: Flow chart of the door-opening judgment method.

depth image acquisition, registration, position selection, preprocessing, fitting plane, and door-opening judgment. The acquisition of depth information uses optical coding technology. Its working principle is to use an infrared transmitter to emit infrared rays. When the infrared rays hit the uneven medium, speckles will be formed and then the speckle information will be read by the infrared CMOS camera and transmitted to the PS1080 system level. The chip decodes and calculates it to generate an image that represents depth information. The schematic diagram of Kinect depth information acquisition is shown in Figure 3.

In summary, the current research on the robot door-opening control system focuses on the recognition and operation of the door handle, such as judging the type of door handle and judging the direction of rotation when the door handle is operated. In order to obtain the precise depth information of Kinect, the Kinect depth sensor needs to be calibrated. The depth camera returns an 11-digit number, which can be further processed to extract the true depth information. According to the calibration procedure of MIT, the original data of a point P in the three-dimensional environment is defined as follows:

$$d = K\ \tan\left(Hd_{\text{raw}} + L\right) - O, \tag{1}$$

where d is the depth value of point P, $H = 3.5 \times 10\ -4$ rad, $K = 12.36$ cm, $L = 1.18$ rad, and $O = 3.7$ cm.

Once the depth information is obtained by the above method, the complete coordinate vector of the point P in the Kinect camera frame can be obtained. If the distance between the target to be measured and Kinect changes, the resolution of the target to be measured will also change, that is, the longer the distance, the lower the resolution of the target; the smaller the distance, the higher the resolution of the target. Based on the above reasons, each pixel in the depth image has a nonlinear relationship with its corresponding point in the actual space. Khoshelham et al. gave the point coordinate equation in real space from the pixel point coordinates and scale of the depth image:

$$\begin{cases} x = \dfrac{\left(i - c_x - \delta_x\right)d}{f_x}, \\[2ex] y = \dfrac{\left(j - c_y + \delta_y\right)d}{f_y}, \\[2ex] z = \sqrt{d^2 - \left(x^2 + y^2\right)}. \end{cases} \tag{2}$$

Among them, (c_x, c_y) is the image center point, (δ_x, δ_y) is the distortion of Kinect, f_x and f_y are scale parameters, and d is the actual distance from the space point to Kinect. Since the depth camera and the RGB camera are located at different positions, the depth image of Kinect does not match the RGB image, so the two need to be registered. Considering that the RGB image is the projection of the points in the three-dimensional coordinate system on the two-dimensional plane, only the affine transformation of rotation and translation is required. The coordinate transformation formula of depth camera and RGB camera is as follows:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = R * \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} + T. \tag{3}$$

Among them, (x, y, z) are the coordinates of the midpoint of the RGB camera coordinate system, R is the rotation matrix, (X, Y, Z) are the coordinates of the midpoint of the depth camera coordinate system, and T is the translation matrix. The point coordinates of the RGB image are

$$\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} f_x * \dfrac{x}{z} \\[2ex] f_y * \dfrac{y}{z} \end{bmatrix} + \begin{bmatrix} c_x \\ c_y \end{bmatrix}, \tag{4}$$

where (u, v) is the point coordinates of the RGB image, f_x and f_y are the scale parameters corresponding to the RGB image, and (c_x, c_y) is the center point of the RGB image.

The preconditions of the research are mostly completed when the robot is already in front of the door or the robot arm does not need to operate the door handle. The focus of the above research is less related to the motion control of the mobile body, so it is slightly lacking in the requirements of the actual application environment. In the actual use process, the depth image obtained by Kinect is easily affected by external factors such as illumination, resulting in noise and image holes in the depth image and insufficient accuracy and stability of the information obtained from the depth image. Therefore, before acquiring the depth information, it is necessary to preprocess the acquired depth image to eliminate the noise in the depth image. The preprocessing includes two parts: Poisson equation noise filtering and median filtering. Among them, the Poisson equation noise filtering is done autonomously by the Kinect hardware, but because its filtering effect cannot completely remove the noise, this article still adds median filtering on the basis of the Kinect autonomous filtering to improve the filtering effect.

The resolution size of the depth image acquired by Kinect is 640 × 480. The reason for the lower resolution is the limited hardware capabilities of Kinect. Therefore, Kinect uses algorithms such as Poisson equation to improve the quality of depth images. This method can be used to determine whether some feature points on the surface of the

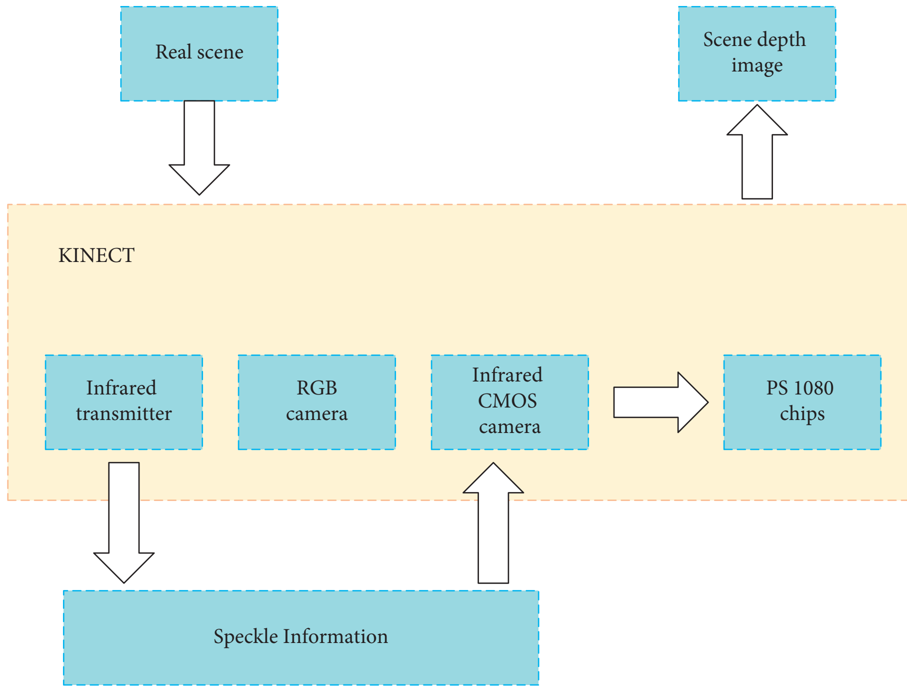


FIGURE 3: The schematic diagram of Kinect depth information acquisition.

human body are noise. The specific principle is as follows: first, extract the orientation and angle of the feature point on the surface of the object, and determine the possible position of the point in space; at the same time, according to the orientation judgment, a virtual distance field is formed around the feature point with the help of the Poisson equation; then, according to the judged position of the sampling feature point, the influence on the surroundings and the distance field of the surrounding surface are estimated on average. If there is a hole on the surface of the human body, its influence can spread to the surroundings, so that a smooth shape can be obtained. Since the final state and characteristics of each feature point depend not only on itself but also on many other points around it, that is, if there is a convex point on the sampling surface, the points around that point are in the direction of characteristic. If there is no bulging trend in the position, the point is judged to be noise and filtered out; otherwise, it is kept. However, because the sampling accuracy of Kinect is not high enough when the surface feature information of the object is relatively subtle, it is likely to be judged as noise. Therefore, it is necessary to further filter the image after the Poisson equation filtering. The sampling is shown in Figure 4. Therefore, this article combines the motion of the mobile body with the door opening of the robot arm to move the door-opening control system of the robot arm platform as the main research direction.

After the Poisson equation noise is filtered, the depth image obtained by Kinect will still have some noise, so it is necessary to select an appropriate noise filtering method. This paper still uses median filtering to remove noise from the depth image. Median filtering is a kind of nonlinear signal processing technology based on sorting statistics theory that can effectively suppress noise. The basic principle is to set a size template in a digital image or digital sequence, take the values that the size template can cover near the target point, sort these values, and select the middle value as the filtered point at the same time; let the pixel value of the pixel near the target point approach the true value, so that the noise point is isolated and filtered out. The specific method is to use a two-dimensional sliding template with a specific structure to sort the pixels in the template according to the size of the pixel value and then generate a monotonous two-dimensional data sequence. The output formula of the two-dimensional median filter is

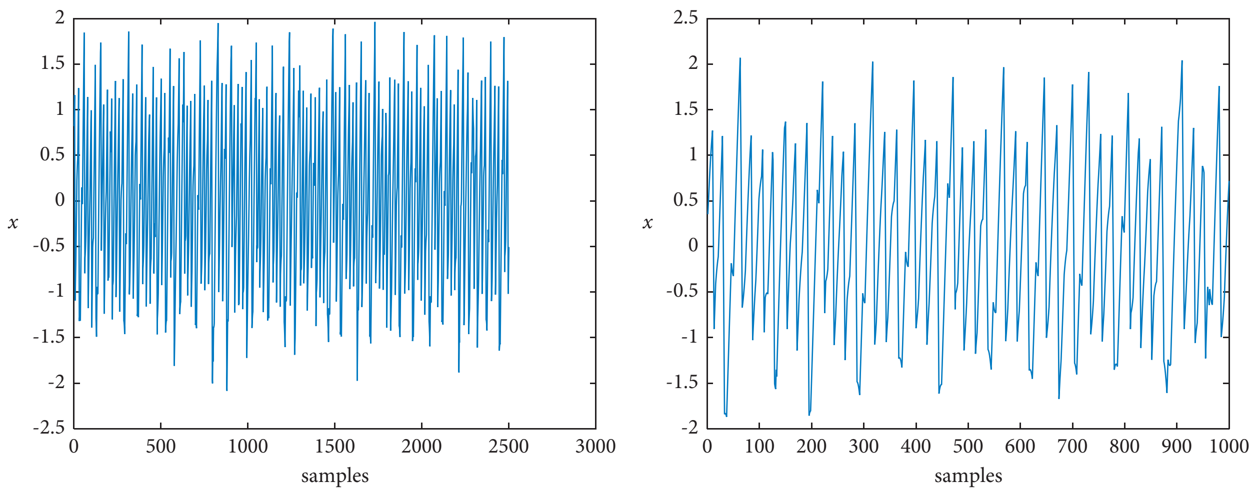
$$g(x, y) = \text{med}\{f(x - k, y - l), (k, l \in W)\}. \quad (5)$$

Among them, $g(x, y)$ is the filtered image, $(f x, y)$ is the original image, and W is the two-dimensional template, which has generally an area of 3×3 or 5×5.

The image resolution of the somatosensory sensor Kinect used in this article is small, only 640×480, and the filtering operation will have an adverse effect on the clarity of the image, so this article selects a smaller template when filtering to reduce these factors that affect clarity. In summary, the pixel of the filter template used in this study for depth image filtering is 3×3. Because of the principle of Kinect depth imaging, it is known that the noise points of depth images are generally zero points. Therefore, the specific steps of the filtering algorithm in this article are as follows.

Step 1. Select the filter template for the depth image. This algorithm uses a template with a size of 3×3 pixels.

Step 2. Roam the filter template in the image, and overlap the center point of the template with a certain pixel.



(a) (b)

Figure 4: Sampling.

Step 3. Determine whether the depth value of the center point of the window coincident with the template is a value of 0; if it is a value of 0, it means that the point is a noise point and delete it; if it is not a value of 0, it means that the point is not a noise point and keep its depth value.

Step 4. Perform median filtering on noise points. First, delete the noise points with a depth of 0 in the template and then take the median of the remaining pixels in the window to assign values to the pixels. The FFT distribution is shown in Figure 5.

Robot technologies such as indoor positioning and navigation have been developed quite in an advanced way. Based on these technologies, robots can move autonomously in indoor environments. Therefore, how to expand the working space of robots is an important research direction at present. The preprocessed depth data are the coordinate value in the real coordinate system of Kinect. The coordinate value of each individual point can be fitted to a plane by mathematical fitting methods, and the plane equation can be obtained. The plane equation can further calculate the plane normal vector, so that the included angle in the plane can be calculated and the door opening can be judged. Fitting refers to knowing several discrete function values of a certain function, and by adjusting several undetermined coefficients in the function, the difference between the function and the known point set (least squares meaning) is minimized. If the undetermined function is linear, it is called linear fitting or linear regression (mainly in statistics); otherwise, it is called nonlinear fitting or nonlinear regression. The expression can also be a piecewise function, in which case it is called spline fitting. Plane fitting is to describe the discrete point cloud data in a three-dimensional space as a plane through mathematical methods. There are many methods of plane fitting, among which the most commonly used are the least square method and the eigenvalue method.

Suppose the expression of the plane equation is as follows:

$$Ax + By + Cz + D = 0. \tag{6}$$

Let

$$a_0 = -\frac{A}{C},$$
$$a_1 = -\frac{B}{C}, \tag{7}$$
$$a_2 = -\frac{D}{C}.$$

Then, the fitted plane is

$$z = a_0 + a_1 y + a_2. \tag{8}$$

Also, suppose the expression of the plane equation is

$$ax + by + cz + d = 0, \tag{9}$$

where a, b, and c are unit normal vectors and

$$a^2 + b^2 + c^2 = 1. \tag{10}$$

After a series of transformations,

$$|A - \lambda I| = 0. \tag{11}$$

Since the real symmetric matrix A is of order 3, it has at most 3 real eigenvalues and the smallest real eigenvalue is λmin. Substitute it into the corresponding homogeneous linear equation system:

$$\left|A - \lambda I_{\min}\right| = 0. \tag{12}$$

The nonzero solution obtained by formula (12) is the eigenvector corresponding to λmin, that is, a, b, and c in formula (9).

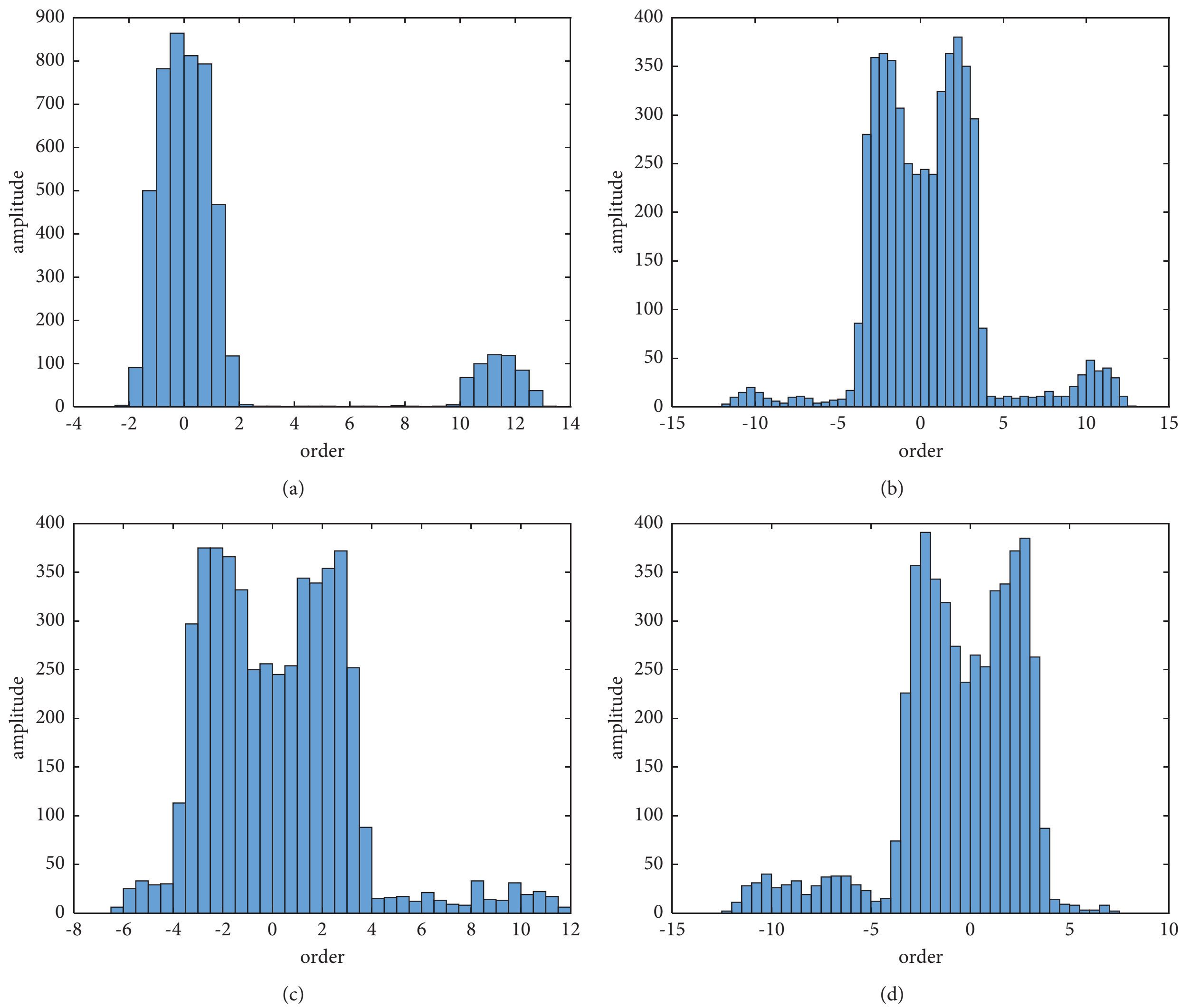


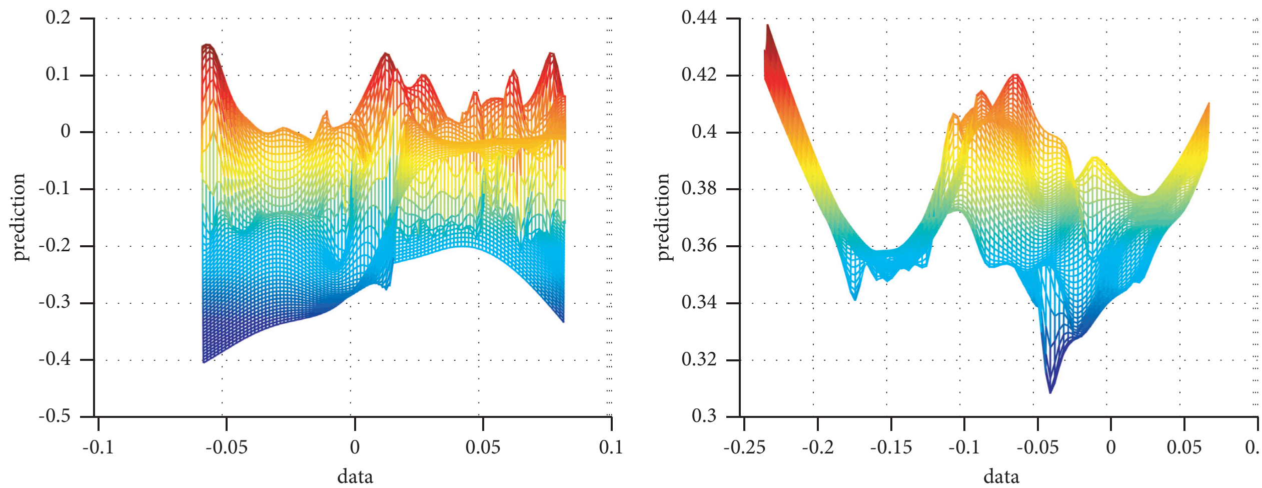
Figure 5: Fourier distribution.

3. Door-Opening Control System of Mobile Manipulators Based on Visual Information and Azimuth

In an indoor environment, opening a door, which is a very simple and natural behavior for humans, is a considerable challenge for robots. The research on the door-opening control system includes the construction of door-opening control system hardware, the positioning of door handles, the motion planning of manipulators, and the motion control of the mobile body of the robot. If only the distance between the somatosensory sensor and the door handle is controlled and the deviation of the azimuth angle of the mobile robot arm platform is not corrected, as the starting distance increases, the door-opening success rate will decrease, therefore improving the mobile machinery. The key to the success rate of arm platform door opening is whether the platform can reach the best opening position in front of the door, so that the end effector of the robotic arm can operate the effective depression area on the door handle. Based on the research idea of azimuth angle control, this study uses the digital compass LP3300 to measure the azimuth angle of the platform during movement. The predicted data are shown in Figure 6.

During the movement of the platform, the angle between the north line of the origin of the movement coordinate system and the x_m axis in the clockwise direction is the azimuth angle defined in this article, expressed as α. The schematic diagram of platform door opening with the introduction of azimuth angle control is shown in Figure 7.

As shown in Figure 7, in the experiment designed in this paper, the motion coordinate system of the platform is xoy, the x-axis is the forward motion direction, and the y-axis is the right motion direction. When the distance between the platform and the door handle is increased, the x-axis still points to the middle of the door handle and the y-axis remains parallel to the door which is a key factor to ensure the successful opening of the platform. Due to the fact that the diameter of the left and right wheels of the platform is not exactly the same and the left and right wheels are driven independently, this will cause the x-axis to not point to the middle of the door handle when the platform reaches the



(a) (b)

Figure 6: Predicted data.

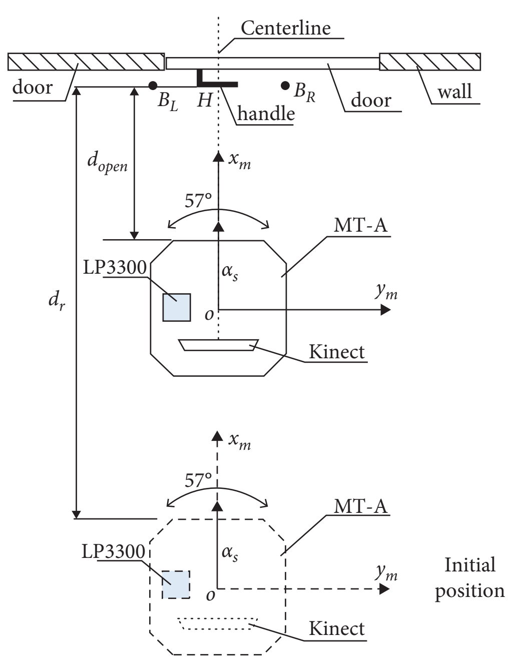


Figure 7: The schematic diagram of platform door opening.

front of the door handle, but to a certain point on the left side of the door handle (LB point) or a point on the right (RB point). At this time, the distance between the center line of the door handle and the x-axis of the platform (LB H or RB H) is the offset distance of the platform. The offset distance will cause the robot arm to shift the operation target (handle), thereby affecting the success rate of the door opening. The offset distance is caused by the deflection of the movement direction during the advancement of the platform. Introducing the digital compass into the movement process of the platform, through real-time detection and control of the azimuth angle of the platform, this offset distance can be reduced, which is helpful in improving the success rate of the door opening. However, due to the hardware structure of the instrument itself, as the running time increases, the dead reckoning extrapolation algorithm will cause the drift error to become larger and larger, which is not suitable for the requirements of precise positioning. In comparison, absolute positioning and relative positioning have their own advantages and disadvantages.

The door-opening control process of the platform that introduces the azimuth angle is described as follows: navigation is one of the key technologies of mobile robots, and it is also a hot issue in robot control. There are various navigation methods for mobile robots, which can be divided into navigation based on environmental maps, navigation based on road signs, visual navigation, and navigation based on other sensors. The mobile robot navigation problem is mainly to solve the three problems raised by Leonard and Durrent Whyte: (1) Where am I now? (2) Where will I go? (3) How can I get to that place? Therefore, the navigation is mainly used to solve the above three problems.

Question 1: where am I now?

The problem is how to obtain the current position and posture of the robot in space, that is, to locate the robot.

Question 2: where will I go?

The problem is how to analyze and understand the information obtained by the robot, build a model of the surrounding environment, and obtain the destination position of the robot. In this article, the platform reaches the door-opening position in front of the door.

Question 3: how can I get to that place?

The problem is how to plan the path of the robot from the starting point to the target point. In this article, it is planned to reach the door-opening position from any starting position.

3.1. Location Problem. Robot positioning is to determine the position and posture of a mobile robot in a two-dimensional working environment, which is the most basic link in robot navigation. The robot positioning method depends on the type of sensor used. The sensors currently used in mobile robots usually include odometers, mono-binocular cameras, laser sensors, ultrasonic sensors, infrared sensors, gyroscopes, speed meters or accelerometers, and tactile sensors. Positioning technology mainly includes two kinds of positioning: absolute positioning and relative positioning. Absolute positioning is the use of navigation beacons, active and passive markings, map matching, or global positioning system (GPS) for positioning. The calculation methods used usually include three-line-of-sight method, three-view method, and model matching algorithm. Relative positioning is to determine the current position of the robot by measuring the distance and direction of the robot relative to the initial position. It is also called the dead reckoning algorithm. The main sensors used are odometer, gyroscope, accelerometer, etc. The dead reckoning algorithm is used to calculate the current pose of the robot, so there is no need to perceive the external environment, so the external interference is minimal. Figure 8 shows the trajectory diagram of the starting position in the area D.

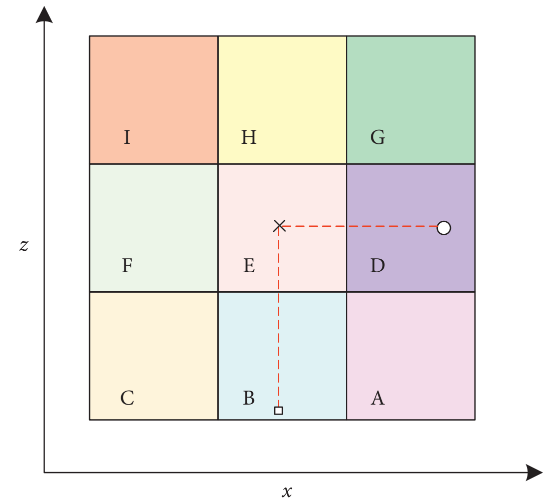


Figure 8: The trajectory diagram of the starting position in the area D.

In this article, the sensors used are the somatosensory sensor Kinect and the digital compass LP3300, so it is planned to use the information obtained using these two sensors for positioning. The idea of the initial positioning method: first, control the platform to rotate, and use the LP3300 to control the platform to rotate to the position where the x-axis of its motion coordinate system is perpendicular to the door and the azimuth angle needs to be set. After obtaining the coordinates of the door handle in the Kinect real coordinate system through Kinect, the relative distance and position between the platform and the door handle can be determined.

The advantage of using this method of positioning is that it is more convenient and has good real-time performance. The disadvantage is that MT-A cannot be too far away from the door when it is located at any initial position. When it is rotated to the initial positioning state shown in Figure 9, Kinect can observe the door handle, otherwise; the initial positioning of MT-A will fail.

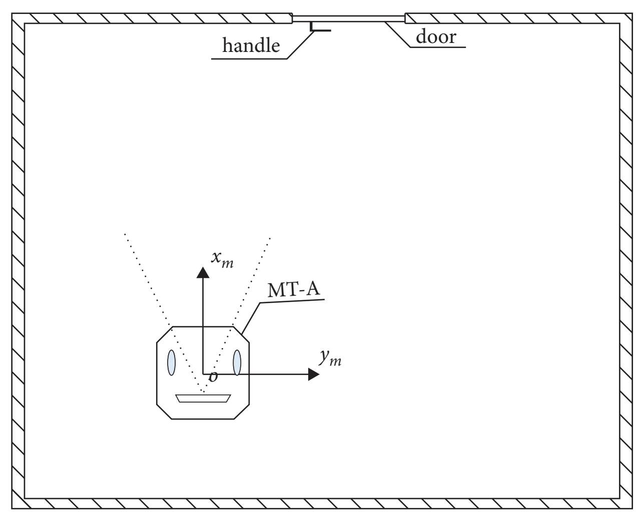


Figure 9: Initial positioning state.

3.2. The Problem of Environmental Model Establishment. The establishment of the environment model is to use sensors to map the surrounding environment. The method of map construction varies according to the different sensors used. The local map is constructed by detecting the surrounding environment and perceiving environmental information and matching it with the complete map stored in advance. There are generally two ways to establish an environmental model:

(1) It is established directly through a precise distance measuring device, such as a laser distance meter. The disadvantage of this method is the high cost.

(2) Based on the human visual system principle, two or more cameras or image sequences are used to model the environment. Some researchers place a mirror directly above the camera and use the camera to shoot directly above to obtain the surrounding panoramic image information. Some researchers use a multiscale visual navigation method of omnidirectional spatiotemporal images. By using visual sensors and processing methods of different temporal and spatial scales, they can look around at a large-scale omnidirectional space, with multiscale binocular gaze and large-scale time domain. The combination of time and space farsightedness comprehensively completes the understanding of environmental images.

The representation methods of environmental models mainly include raster maps, geometric maps, topological maps, and hybrid maps, each of which has advantages and disadvantages. The main representation method of the grid map is to divide the entire environment into several grids of the same size and assign a probability value to each grid, indicating the possibility that the grid is occupied by obstacles and is impassable. For example, a grid that is not passable is represented as 1 and a grid that is passable is

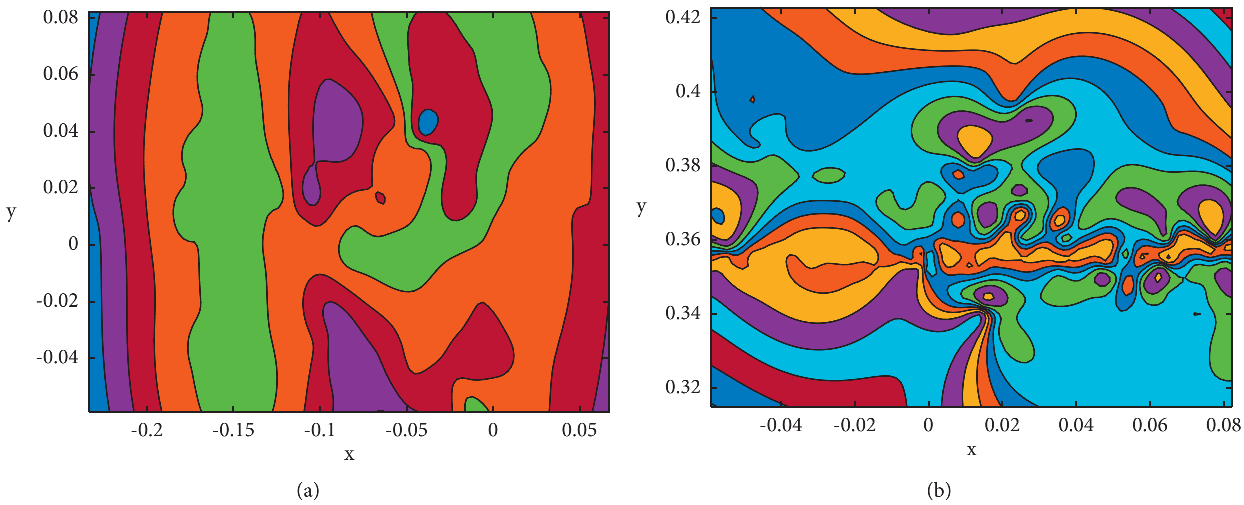


Figure 10: Position variation.

represented as 0. Morvaes and Elefs first proposed the establishment of this environmental model. The advantages of the grid map representation method are it is easy to create and easy to maintain. The information in the grid directly corresponds to the area in the environment, and it is convenient for the robot to self-locate and plan the path. The disadvantage is that when the scale of the environment is relatively large, or when the grid is required to be small in a more complex environment, the memory and CPU computing time for map maintenance will increase dramatically, affecting the real-time performance of the entire system. The position variation is shown in Figure 10.

The main representation method of the geometric map is to extract more abstract geometric features, such as line segments or curves, from the external information obtained by the mobile robot. The advantage of the geometric map representation method is that the positioning is accurate and its mathematical model is easier to be described and represented by the computer. The parameterized features are also suitable for path planning and trajectory control and are conducive to estimating the current position and identifying the target. However, due to this, the representation method is very dependent on the extracted geometric features, so additional data preprocessing is required, because it is very sensitive to the noise of the data acquired by the sensor.

4. Conclusion

The conclusion is summarized as follows:

(1) This paper takes the mobile robot arm platform as the object, combines the operation of the door handle by the robot arm and the motion control of the mobile platform, and uses visual information and azimuth as the information acquisition method of the mobile robot arm to study the realization of the door-opening control system.

(2) The door-opening control strategy of the mobile manipulator is designed, and the task of opening the door of the mobile manipulator at any starting position in the room is completed.

(3) The research results show that a door-opening judgment method that combines azimuth control, eigenvalue method, and depth data is proposed in this paper and realizes a control strategy that combines mobile platform motion control with manipulator door-opening operation.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors' Contributions

All authors contributed equally to this article.

Acknowledgments

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