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Article

Robot navigation algorithm based on real-time ranging and map matrix

Linwei Cui, Jianwei Cui *, Zizheng Huang, Xiang Li, Yucheng Shang and Liyan Tong

Institute of Instrument Science and Engineering, Southeast University, Nanjing 210096, China; 220203464@seu.edu.cn (L.C.); 220213616@seu.edu.cn (Z.H.); 220213755@seu.edu (X.L.); 220223282@seu.edu.cn (Y.S.); 220223279@seu.edu.cn (L.T.);
* Correspondence: cjw@seu.edu.cn

Abstract: By constructing a static map, the library robot can navigate and access documents autonomously, which greatly improves efficiency; however, for libraries where shelves can be moved, map changes do not allow for direct navigation, and also sensors such as radar and camera are relatively expensive, so we propose a low-cost navigation algorithm based on real-time ranging data and map matrices, and designed a mobile archive access robot. In order to obtain real-time distance data, nine near/long range sensors were mounted on the chassis and a composite digital filtering algorithm was designed based on different moving area characteristics; then the access task matrix and map matrix were designed based on the archive access task and the location characteristics of the archive shelf placement, the robot can rely on the range data to update the map matrix during the moving process, complete its own positioning, and use the task matrix The robot can use the task matrix to complete autonomous navigation and access to multiple files. Experiments show that the filtered positioning accuracy can reach 1cm, while the robot can move to the target shelf autonomously, which is more practical and less costly.

Keywords: Intelligent archive repository; archive access robot; complex digital filtering; map matrix; navigational mobility

1. Introduction

In recent years, with the rapid increase in the volume of corporate archives and the use of smart archives repositories, there has been an increasing need to seek intelligent robots to replace human involvement in archives management. Robots can be used for inventorying and accessing archives, which is more efficient than human labour and can further provide a level of intelligence in archives repositories. Access robots with autonomous navigation capabilities that can move autonomously to target archival shelves and complete access to archives, thus eliminating the need for manual manipulation of the robot, are a hot research topic in archival robotics.

At present, the more widely used robot navigation methods include orbital navigation [1-3], inertial navigation [4-5], radar and visual navigation [6-8], etc. Most intelligent management robots of archives and books use orbits, markers and radar for navigation, such as laying tracks on the bottom of archival shelves, and the robot moves to the target archival shelf with the help of the tracks [9]; He Junjie et al. studied a combination of vision and inertial navigation based on two-dimensional raster maps and inertial guidance combination of vision and inertial navigation to move by recognising QR codes in the storage room [10]; Hao Chen et al. developed an intelligent book management robot that moves according to ground signs and marker lines, using sensors such as laser ranging and ultrasonic waves to achieve obstacle avoidance and line patrol [11-12]; Yan Chehai et al. designed a book management robot whose path is identified by The recognition of the path of the library management robot designed by Yan Chehai et al. is electromagnetically guided by pre-laying tracks on the ground and marked by installing RFID electronic tags

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at the locations of path nodes along the path [13]; in addition, the navigation of the robot can also be achieved by using cameras to detect landmarks [14].

Most of the aforementioned navigation methods are aimed at navigating archival shelves in a fixed placement, and once the archival shelves in an archival repository change position, a new track needs to be laid on the ground or a map needs to be constructed, making it difficult for the robot to return to the preset track independently once it is off the track. In addition, in terms of navigation technology research, Xuyan Hou proposed an interactive navigation method for mobile robots based on hand-drawn path recognition, using a pen, paper and camera as the interface between the user and the mobile robot [15], and Chi Li proposed a deep learning-based method for locating mobile robots using 2D lasers and inertial measurement devices to improve positioning accuracy [16].

The paper proposes a navigation method for archive access robots based on accurate ranging and map matrix matching, which combines the features of pathfinding navigation and map navigation and enables robot positioning and real-time updating of archive shelf positions without changing the archive environment or requiring external auxiliary signs, etc., with higher reliability and robustness.

2. System Overview

2.1. Archival Access Robot Design

The archive access robot developed by the group is shown on the left in Fig. 1, including autonomous navigation chassis, robot arm, robot hand, archive bin and other devices, the robot main controller is STM32F407, relying on the chassis to achieve autonomous navigation in the dynamic environment of the warehouse, relying on 48V 20A lithium battery to provide power, moving speed of 1.5m/s. During the robot's autonomous movement, the main control drives sensors for In the process of autonomous movement, the main control drives sensors for distance measurement and updates the map matrix to position itself and the archive shelf, and then moves to the target archive shelf.

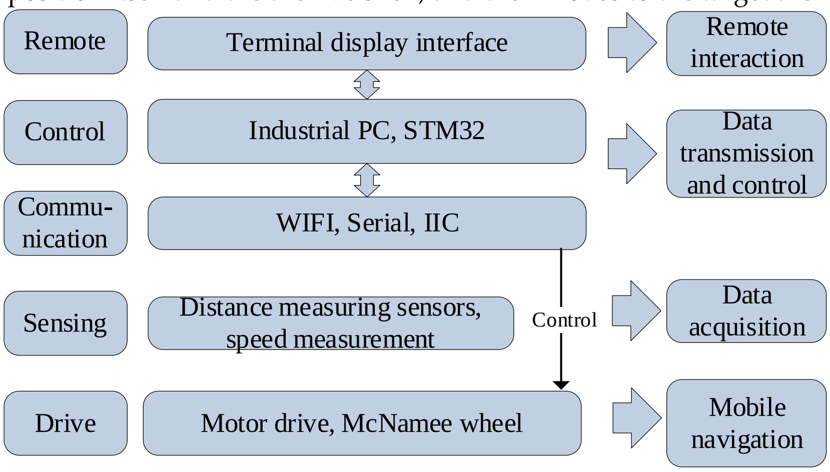


Figure 1. Schematic diagram of the archive access robot

2.2. Mobile Robot Chassis Design

The robot relies on a mobile chassis, which consists of a drive system, a controller and range sensors, to complete the overall movement. The drive system consists of four hollow cup motors driving four McNamee wheels, which enable the robot to move omnidirectionally within the archive. The STM32F407 main controller receives the range data collected by the nine laser range sensor modules via the serial port, calculates the robot position and the real-time position of the archive shelves and drives the robot's overall movement.

The layout of the range sensors in the mobile chassis is shown in Fig. 2, where the markers 1, 2, 3, 4, 5, 6, 7 and 8 are FS010 dynamic high-precision close-range laser rangefinders with a range of 0.15m to 10m and a measurement frequency of up to 14.28kHz, and the marker 0 is a long-range laser rangefinder FS100 with a range of 0.5m to 100m and a measurement frequency of up to 4kHz. collecting the range data from these sensors and processing it, we can obtain real-time information about the robot's position in the archive.

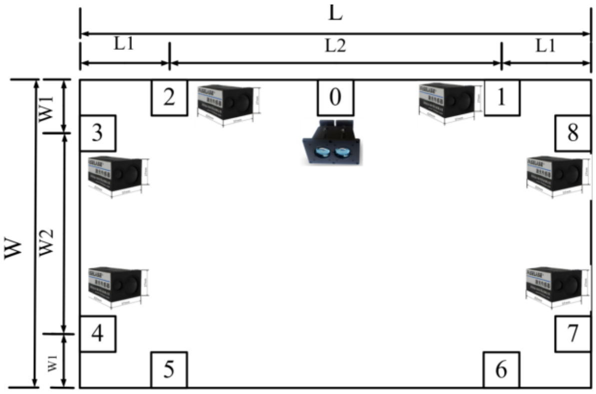


Figure 2. Layout of the laser distance measuring sensor

2.3. Composite Digital Filtering Algorithm

When the archive robot moves in the storage room, there are errors in the laser ranging data collected by the following factors: (1) errors exist when measuring the walls of the archive storage room or the archive shelves with strong mirror reflections; (2) jitter is generated during the robot's movement, so digital filtering of the ranging data is needed to ensure the accuracy and stability of the robot's navigation. Digital filtering methods can be divided into digital filtering method to overcome large pulse interference, mean filtering method to suppress small amplitude high frequency noise and compound filtering method [17-19]. Considering that the archive access robot mainly operates in the aisles and inside the archive shelves, where the map environment, robot travel speed and navigation distance are different, the article designs a compound digital filtering algorithm to process the data.

The archive access robot walks in the aisle, and each time it walks to a place with a gap, the FS010 sensor reads a distance that exceeds the range and displays 0. In order not to confuse it with the normal distance measurement of 0, it is suitable to use the median value averaging filtering method, i.e. median value filtering with arithmetic average filtering, to filter out bad distance measurement data by continuous sampling, and the filtering formula is as in equation (1). The laser sensor used in the article has a range frequency of up to 1.43 KHz. Even if the number of samples in the filtering algorithm is set to 10, the filtered data acquisition frequency is still 143Hz, which can meet the needs of the robot walking at high speed.

$$\bar{x} = (x_1 + x_1 + \ldots + x_{N-2}) / (N-2) \quad (1)$$

In the above equation, the data collected at one time is $\{x_1, x_2, \ldots, x_N\}$, the maximum and minimum values are removed, and the remaining data is averaged, where N=10.

When the file access robot moves within the shelf, it needs to identify the files to be stored and retrieved. At this time, the walking speed is relatively slow, the data change amplitude is not large, and the phenomenon that the sensor reading data exceeds the range will not occur, so it is suitable for using the limit recursive average filtering method, the filtering algorithm can play a good role in suppressing the sensor measurement error caused by sharp pulse interference or periodic interference, and it is suitable for the slow change signal The filtering formula is equation (2), after collecting a batch of data, the first amplitude limiting process, and then the recursive averaging filtering process.

$$x_i - x_{i-1} > k_1, x_{i+1} = x_i$$
$$x_i - x_{i-1} > k_2, x_{i+1} = (x_{i+1} + x_i)/2 \quad (2)$$
$$\bar{x} = (x_{i-(N-1)} + x_{i-(N-2)} + ... + x_i)/N$$

where N = 10 and is the filter window; and are the current and previous range values respectively; and are the limit thresholds, where $k_1 = 2cm, k_2 = 1cm$. After obtaining, it is stored at the end of the sampling sequence and the beginning of the sequence is removed, and the mean value of the sequence is taken as the filtered data.

3. Navigation algorithm for archive robot

3.1. Map of the Archive Repository

The archives are stored in a smart archive vault. Fig. 3 shows a schematic diagram of the archival shelf arrangement, with four areas divided into two columns, A and B, each with M and N archival shelves. The four areas include archival shelves 0-M/2, 0-N/2, M/2-M and N/2-N respectively. In the diagram M=16, N=16, shelves 8 and 9 are not movable and there is a larger aisle in between.

In a smart archive, the shelves are normally closed and the corresponding shelves can be opened manually when storing or retrieving files. However, the robot needs to determine the position of the target shelf and whether the target shelf is open enough for the robot to enter and exit based on the dynamic opening and closing of multiple shelves. The paper therefore designs a navigation algorithm based on real-time ranging, an access task matrix and a dynamically updated map matrix. The robot first obtains the task matrix based on the archive access task, then dynamically updates the map matrix based on the ranging data during the robot's movement, and calculates the actual position of the target archive shelf, and then completes the storage and retrieval of the target archive when it reaches the target shelf in combination with the incoming and outgoing archive shelf navigation algorithm.

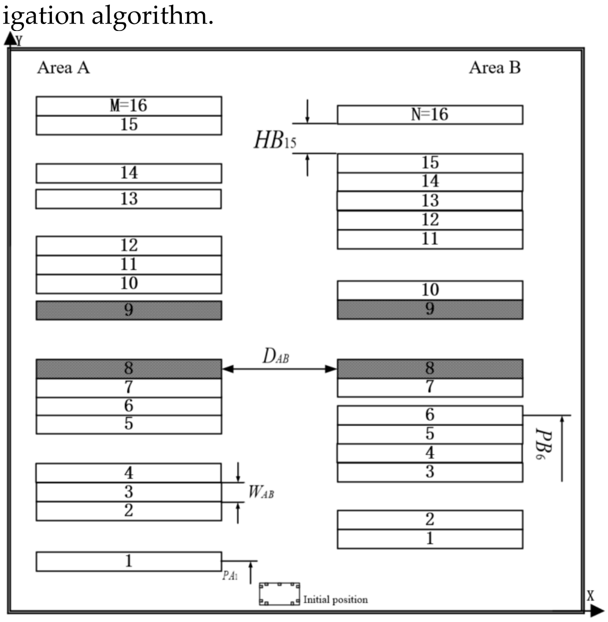


Figure 3. Diagram of the distribution of archive shelves in the archival repository

3.2. Map Matrix and Access Task Matrix Design

To enable the robot to move autonomously to the location of the archive shelf where the archives are to be stored or picked up, the article designs a map matrix and an access task matrix. Before the navigation task is carried out, the archive access task is resolved according to the instructions given by the client. The robot updates the map matrix of the archive shelf based on the distance measurement data while moving, and moves to the target archive shelf in conjunction with the task matrix, updating the task matrix upon completion and finally accessing multiple archives.

Firstly, the map matrix is designed according to the archive shelf position distribution in Fig. 3 and defined as follows:

① Define the archive shelf width matrices: WA and WB, the error between the actual and nominal values of the width is noted as ΔW: WA=[WA1 WA2 ... WAM]; WB=[WB1 WB2 ... WBN], M=N=16;

② The initial position of each archival shelf is represented by the position of the archival shelf parallel to the centre line of the x-axis. Define the archival shelf position matrix PA and PB: PA = [PA1 PA2 ... PAM] represents the position of shelf M in area A; PB = [PB1 PB2 ... PBN] represents the position of shelf N in area B, for example, shelf 6 in area B in Fig. 3 the initial position of the archive shelf is PB6.

③ Define the distance matrices HA and HB of adjacent archival shelves to determine whether the opening width of the archival shelves meets the shelf spacing necessary for robot access to the shelves: HA = [HA1 HA2 ... HAM-1] is the distance matrix of the A zone; HB = [HB1 HB2 ... HBN-1] is the distance matrix of the B zone, where HAn and HBn denote the distance between shelf n and shelf n+1.

④ Define 2M+1 bit archival shelf map matrices MA and MB: MA=[0111111110111 1111111000000000000000000], MB=[0111111110111111111111110000000000000000000], where 0 indicates a gap and 1 indicates an archival shelf. For example, 101 means that there is a gap between two archival shelves. The MA, MB matrix in the above equation is the initial state and represents the case where the archival shelves are all together. The zeros at the end of the matrix are artificially added and do not represent the number of spaces.

⑤ Define the maximum measurement error of the robot for all shelf spacings as ΔL, denoting by L the shelf spacing necessary to enable the robot to enter the aisle, and define an error variable ER, the number of tasks the robot can perform at one time as TM.

Define the task matrix according to the tasks sent by the remote client:

① define the mobile task commands Ai, Bi(i=1, 2,...,16) sent by the remote terminal, A and B denote the area where the archive shelf is located and i denotes the number of the archive shelf;

② define the task column matrix TA, TB, which denote the sequence of tasks for the left and right archive shelf respectively, and the elements in the matrix represent the location of the work area. For example, TA=[1 4 4 3 2], which means that the storage and retrieval tasks need to be executed sequentially in work areas 1, 4, 4, 3 and 2 of the archive shelves in area A, where work area k (k=1,2,...,15) is located between file shelves k and k+1;

③ define matrices TN1 and TN2 to indicate the number of tasks, and use TN1[m] to indicate the number of TA[m], and use TN2[n] to indicate the number of TB[n];

④ define the SD×4 matrix TE, column 1 indicates the task to be performed, indicated by the work area number; column 2 indicates the number of tasks; column 3 indicates the location of the work area and column 4 indicates the A and B areas of the work, with 0 indicating area A and 1 indicating area B.

The specific process of accessing the task matrix is shown in the following example: first the remote sends task instructions [A1, B2, A4, B6, A9, B10, B10, B10, A12, A12, A4, A4, B15, B15, A13, A14, A14, A14, A14, B15, B15, A12, A12, A12, A12, A12, A12, A12, A12 A12, A12, B2, B2, B2, B2, B2, B2, B2, B2]; then the robot translates the move task instructions Ai, Bi into TA, TB and TN1, TN2, merges the tasks in the same work area in the matrix and arranges them in ascending order by number, so that TA = [1 4 9 12 13 14], TN1 = [1 3 1 10 1 4], TB = [2 6 10 15] ; TN2 = [8 1 3 4], where TN1[0] = 1, indicating that there is 1 task in file shelf 1 in area A; finally the TE matrix is obtained by processing and the robot performs the work tasks according to the TE matrix.

$$TE = \begin{bmatrix} 1 & 1 & HA_1 & 0 \\ 4 & 3 & HA_4 & 0 \\ 9 & 1 & HA_9 & 0 \\ 12 & 10 & HA_{12} & 0 \\ 13 & 1 & HA_{13} & 0 \\ 14 & 4 & HA_{14} & 0 \\ 2 & 8 & HB_2 & 1 \\ 6 & 1 & HB_6 & 1 \\ 10 & 3 & HB_{10} & 1 \\ 15 & 4 & HB_{15} & 1 \end{bmatrix} \quad (3)$$

Using the work task matrix TE described above, while the robot dynamically updates the MA and MB matrices as it moves, in order to calculate the actual position of the target archive shelf, the robot is then able to move to the target shelf and perform archive access.

3.3. Aisle movement navigation algorithm

In Fig. 3, the robot is in the initial position and needs to move from the initial position in the aisle to the target archive shelf when performing a task according to the job task matrix. The article uses the TE matrix to obtain the zone number and number of the target archive shelf, and updates the MA and MB matrices in conjunction with the nine range sensors around the robot, determining whether to move to the target archive shelf in the process of updating. The aisle navigation movement algorithm consists of (1) file shelf detection in zones A and B and (2) updating the MA and MB matrices.

As shown in Fig. 3, the robot starts from the initial position, detects the archive shelf on the A side using the range sensors, and calculates the HA matrix for the archive shelf opening distance and the PA matrix for the archive shelf position, where Xn represents the range values of the sensors numbered n (n=0,1,2,...,8). The robot moves forward in the order of the flowchart until m=M. The B-side detection flow is identical to the A-side.

When the m parameter is updated, the MA matrix is updated internally by the robot simultaneously: in the matrix MA it detects whether the mth 1 is followed by a zero, and if it is not a zero, as the left archive shelf is already detected as open at this point, a 0 is inserted after this 1, while the last 0 in MA is deleted to ensure that the number of MA bits remains unchanged. Table 1 shows the update of the MA and MB matrices during the robot's movement according to Fig. 4 in the case of an open archive shelf, with 0 representing the middle aisle after the archive shelf has been opened.

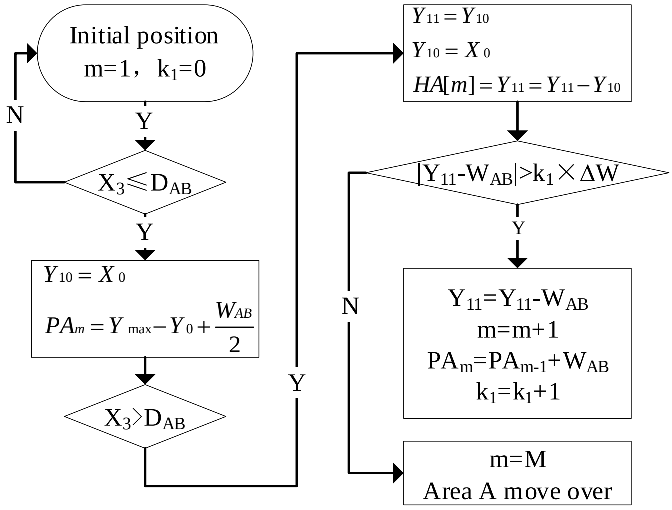


Figure 4. Flow of inspection of file shelf position and opening width

Table 1. Matrix MA、MB changes.

Matrix M_A change	Matrix M_B change
011111111101111111110000000000000（initial）	011111111101111111110000000000000（initial）
010111111101111111110000000000000	-
-	011011111101111111110000000000000
010111011110111111111000000000000	-
-	011011101101111111110000000000000
010111011110101111111000000000000	-
-	011011101101101111110000000000000
010111011110101110111100000000000	-
010111011110101110101110000000000	-
010111011110101110101011000000000	-
-	011011101101101111101000000000000
010111011110101110101011000000000（finally）	010111011110101110101011000000000（finally）

As the robot moves through the aisles, it completes the update of the MA and MB matrices from the ranging data. During the update process, it determines whether to enter the archive shelves to access the archives based on the task data in the task matrix. The identification and access of the archives relies on the cameras and robots on the robot. After completing the archive access task, the robot rolls out the archive shelf and continues to update the map matrix and task matrix and completes all tasks.

4. Robot navigation experiment

4.1. Archive Robot and the experimental environment

In the article, robot navigation experiments were conducted in a smart archive storage room. Fig. 5(a) shows a physical view of the archive storage aisle and the archive access robot. Fig. 5(b) shows a physical view of the open archives shelves with six levels, each 40cm apart, with a maximum height of 240cm and a width of 80cm between shelves.

(a) (b)

Figure 5. Archival robot and experimental environment

4.2. Sensor filtering experiment

In the archive room, the robot is about 140cm from each side of the archive shelf when walking along the middle of the aisle, about 50cm from its side when walking along one side of the aisle, and about 20cm from the side to be accessed when walking in the shelf. therefore, three typical distances of 20cm, 50cm and 140cm were selected and sensor filtering experiments were conducted in the actual archive room. filtering experiments.

The sensor measurement frequency was set to 1.43 kHz. 13 consecutive samples were taken in the aisle, i.e. at distances of 50 cm and 140 cm, for median average filtering, i.e. an actual frequency of 110 Hz; within the shelves, i.e. at a distance of 20 cm, for limit average filtering, the queue length was taken to be 13. The sampled data is shown in Fig. 6.

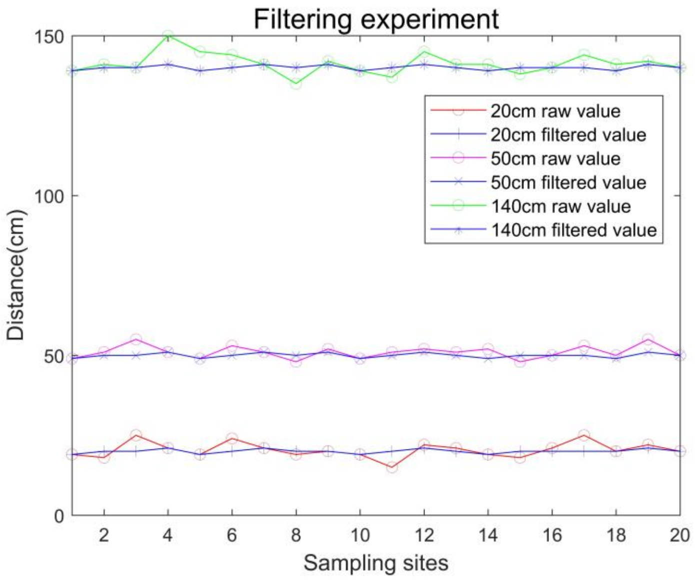
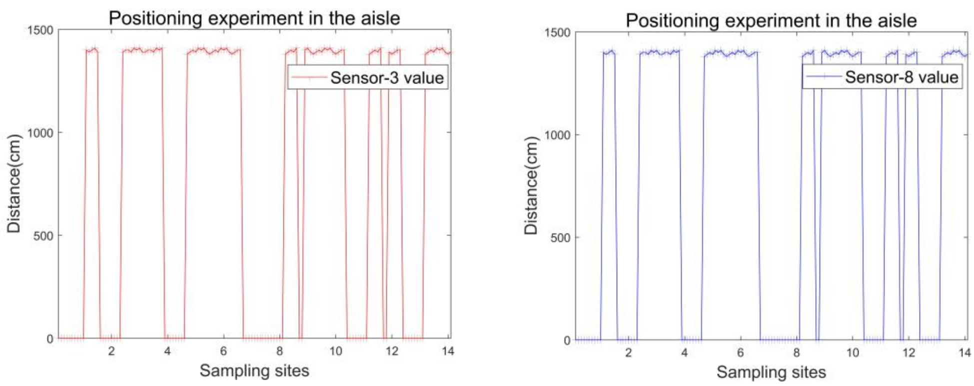


Figure 6. Sensor filtering experiment

4.3. Navigation Experiment

The sensor travels along the middle of the aisle at a distance of 1400mm from the archive shelves on both sides, when the archive shelves are detected to be open, at which point the sensor data is the distance from the warehouse wall, which exceeds the sensor range and reads 0. Fig. 7(a), (b) and (c) show the readings of sensors 3, 8 and 0 respectively when the robot is navigating and walking in the aisle. Where sensors 3 and 8 are the range filtered values of the FS010 sensor and sensor 0 is the filtered value of the range measured by the FS100 laser rangefinder. The data in Fig. 7(a) and Fig. 7(b) allow the distance of the robot from the archive shelves on both sides to be calculated and used to detect whether the archive shelves are open, and the data in Fig. 7(c) allow the distance of the robot from the wall in the positive direction of the y-axis of the archive room to be calculated, which in combination enables the robot to be precisely positioned and, according to the filtered data, to achieve a positioning error of 1 cm in the archive room.

The actual readings and filtered values show that sensor data filtering in the aisle and within the frame can achieve good results, and can also play a good role in suppressing the fluctuating interference signals caused by accidental factors; and the error after filtering is reduced to 1cm ± 0.5cm, meeting the high accuracy requirements of mobile navigation.



(a) (b)

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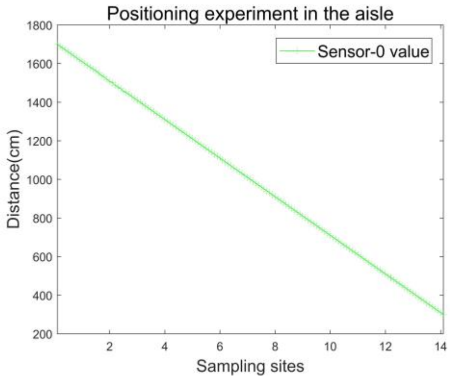

(c)

Figure 7. Experiment on navigation in the aisle

The experimental results show that the navigation flow algorithm designed in the article is safe and reliable, and that the robot is capable of completing archive access operations in confined spaces.

(a) (b)

Figure 8. Diagram of the archive access robot moving through the storage room. (a) Aisle (b) Inside the shelf

5. Conclusions

The article investigates the navigation algorithm of the archive access robot under the change of the map of the repository due to the movement of the archive shelves. It mainly introduces the robot system design, the complex digital filtering algorithm of the ranging data and the navigation algorithm combining the access task matrix, the map matrix and the ranging data, and designs the navigation algorithm for the robot moving in the aisle. The robot was tested in the smart archive repository of the maintenance branch of the State Grid Jiangsu Province Electric Power Company, and all of them were able to meet the usage requirements. The navigation algorithm designed in the article can solve the problem of autonomous movement of the robot under dynamic changes in the map of the repository, and the efficiency and accuracy of the robot in completing access tasks need to be considered in the next research.

Author Contributions: J.C.: funding acquisition, paper revision work and overall project proposal design. L.C.: archive robot movement control and navigation algorithm design, draft preparation and writing. Z.H.: archive robot hardware structure construction and debugging. X.L. and Y.S.: sensor, MCU software development and debugging. L.T.: assisted with the experiments of the wheelchair in the archive storage room. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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