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Robotics-based residential fire protection system design

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Abstract Traditional residential firefighting methods have problems such as high labor intensity and harsh operating environment, which are difficult to meet the high standard requirements of modern residential firefighting system construction. The application of robotics in the field of firefighting provides a new way to solve these problems. Firefighting robots are equipped with functions such as autonomous navigation, fire source identification and fire extinguishing, which can perform firefighting tasks in dangerous environments and effectively reduce the safety risks of firefighters. In this paper, we propose a design scheme for a residential firefighting system based on robotics, which adopts SLAM technology that fuses LiDAR and RGB-D cameras to realize robot localization and mapping, and combines thermal imaging technology and artificial intelligence algorithms to complete fire source identification and autonomous fire extinguishing. In terms of methodology, the system fuses LiDAR and RGB-D camera to construct the environment map, applies rtabmap algorithm for data fusion processing, adopts the maximum interclass variance method to identify the fire source, and realizes the precise location of the fire source through the alignment of the point cloud and thermal imaging image. The experimental results show that the obstacle recognition rate of the fused SLAM composition technology reaches 95.9%, the absolute position error is reduced by 51.6%, the fire source recognition accuracy reaches 100%, and the maximum error of fire source orientation is 3°. The system was able to effectively recognize the fire source within a distance of 35 meters, and the recognized temperature range was between 262 and 349°C. The conclusion shows that the residential fire fighting system based on robotics technology performs well in terms of orientation accuracy, fire source recognition and autonomous fire fighting, and provides an effective technical solution for the construction of intelligent fire fighting system, which has good practical value and application prospects.

Index Terms robotics, SLAM, fire source identification, autonomous fire extinguishing, LiDAR, RGB-D camera

I. Introduction

In today's society, the human and property losses caused by fire are increasing, and the importance of fire protection system is becoming more and more obvious [1]. At the same time, with the diversification of the housing industry, the development of urban buildings is becoming increasingly high-rise and dense, which brings difficulties to the fire fighting work [2]. There are more and more cases of both high-rise and multi-story buildings in a building area, and the previous fire trucks, fire ladders and other fire fighting facilities can not adapt to the new requirements [3], [4]. It is urgent to solve the current problems in fire fighting.

Family members in modern society are aiming for diversified information and safe, comfortable and convenient living environment brought by community and home intelligence, thus community and residential intelligence is the key development direction of the country in the future [5]-[8]. An intelligent fire protection system also plays an increasing role in intelligent residential communities. Residential fire protection system based on robotics is an economic design program that meets the requirements of the fire code and the use of the single building under the conditions of functionality, and gives full consideration to the whole area of the fire water supply system [9]-[11]. Based on the advanced management and control platform, it can transmit the fire fighting situation of the residence to the staff, so that they can understand the structure of the residence building and the surrounding fire fighting facilities in the shortest possible time when a fire occurs [12]-[14]. In addition, the residential fire protection system based on robotics has good scalability and upgradability, and is able to continuously expand its scale and function with the progress of technology and society [15]-[17]. Therefore, it is of great significance to explore the scientific and efficient residential firefighting system, which is an important guarantee for firefighters to carry out the work of firefighting and rescuing people in distress.

In modern society, the number of residential buildings continues to grow, fire safety issues are becoming increasingly prominent, the traditional manual firefighting mode faces many challenges. Manual firefighting operations are not only labor-intensive, but also in the high temperature, smoke and other harsh environments, there are greater safety risks, firefighters' life safety is difficult to be effectively protected. At the same time, the traditional firefighting method in the fire source positioning, firefighting efficiency and other aspects of the obvious shortcomings, often can not quickly and accurately identify the location of the fire source, resulting in inefficient firefighting operations, resulting in greater property losses. In addition, the complex internal structure of residential buildings, narrow passages and dense obstacles further increase the difficulty of manual firefighting operations. Against this background, the development of intelligent firefighting technology has become an inevitable trend. Robotics, as an emerging intelligent solution, shows great potential for application in the firefighting field. Firefighting robots are able to replace manual firefighting tasks in hazardous environments, which can not only effectively reduce the safety risk of firefighters, but also improve the accuracy and efficiency of fire source identification and fire extinguishing through precise sensor systems and intelligent algorithms.

In this study, a complete residential firefighting system based on robotics is constructed, which mainly includes the design and realization of three core modules. First, the design of the localization and mapping module adopts the SLAM technology that fuses LIDAR and RGB-D cameras to enable the firefighting robot to realize autonomous navigation and environment map construction in unknown environments, providing accurate location information for the subsequent search of fire sources. Secondly, the fire source identification and localization module is developed, combining thermal imaging camera and LiDAR, using image processing algorithms and point cloud fusion technology to achieve accurate identification and 3D spatial localization of the fire source. Finally, the autonomous fire extinguishing module is constructed to realize the autonomous fire extinguishing function of the robot through the fire water cannon control system and intelligent decision-making algorithm. The design of the whole system focuses on the coordination between the modules to ensure that the firefighting robot can efficiently and safely complete the residential firefighting tasks.

II. Design of residential fire protection system from the viewpoint of robot technology

II. A. Robotics

Traditional residential firefighting methods have problems such as high labor intensity, harsh operating environment, etc., which are difficult to meet the high standard requirements of modern residential firefighting system construction. With the rapid development of robotics technology, its application in residential firefighting system is increasingly broad prospects, robotics automation technology with its high efficiency, precision, safety features, effectively solving the traditional residential firefighting in the many problems. In the future, with the development of intelligence, integration and standardization, robots will play a greater role in the field of residential firefighting, providing more powerful technical support for safeguarding people's lives and property. This subsection centers on robot selection and configuration, robot vision and navigation technology, robotics and artificial intelligence integration applications, to start the depth of the analysis of robotics. Specific details are shown below:

II. A. 1) Robot selection and configuration

In the design of residential fire protection systems, robot selection and configuration is the cornerstone of automation technology. Considering the complexity of the installation environment of the residential fire protection system, such as narrow space, high temperature and high humidity conditions and potentially toxic gases, it is necessary to choose the robot with explosion-proof, waterproof, high temperature characteristics, specific selection, based on the residential fire fighting tasks (such as pipeline laying, installation of sprinkler heads, deployment of fire detectors) to accurately calculate the load capacity, endurance time and operational accuracy and other parameters.

II. A. 2) Robot vision and navigation technologies

Robot vision and navigation technology is the core of the automation of residential fire protection systems. Using stereo vision and deep learning algorithms, the robot is able to accurately identify the obstacles, fire piping layout and installation location on the site, use SLAM (real-time localization and map construction) technology, combined with LIDAR scanning and inertial navigation system, to realize autonomous navigation in indoor GPS-free environment, and in the complex environment, the use of infrared thermal imaging with the assistance of the active light source, to enhance the ability of visual recognition [18], [19]. The navigation algorithms need to optimize the path planning to ensure that the navigation is not a simple one. The navigation algorithm needs to optimize the path planning to ensure that the robot efficiently traverses the firefighting area while avoiding collisions and reducing firefighting mission delays.

II. A. 3) Integrated Robotics and Artificial Intelligence Applications

The deep integration of robotics and artificial intelligence has brought an unprecedented direction of intelligent development for residential fire protection systems. AI algorithms are used to analyze residential firefighting site data in real time, predict potential firefighting risks, and optimize the firefighting construction process. For example, by analyzing historical data and environmental parameters, the AI system is able to identify difficult points in residential firefighting projects in advance, and automatically adjust the robot's operating strategy. In the quality control segment, AI image recognition technology is used to detect the installation quality of fire protection equipment, such as the installation angle of sprinkler heads and the sealing of pipelines, to reduce human error. Meanwhile, the integrated predictive maintenance function is able to predict residential fire protection risks based on robot sensor data and AI models, arrange maintenance plans in advance, and guarantee the long-term stable operation of residential fire protection systems.

II. B.Design of Firefighting Robot Localization Composition Module

This subsection proposes a SLAM fusion approach, using RGB-D and LiDAR combined with SLAM technology, this fusion mapping function can be applied in intelligent monitoring firefighting robots on the basis of rtabmap algorithm, which is able to realize the firefighting robot's functions of ranging, localization, autonomous mapping, and navigation, which provides a reference firefighting environment topography for the residential firefighting operation, and greatly improves the firefighting The efficiency of firefighting is greatly improved.

II. B. 1) SLAM Overview

SLAM is an acronym for simultaneous localization and map building, which is mainly used for continuous localization and map building of firefighting robots in unknown areas [20], [21]. The most common is the application of LiDAR SLAM in 2D map building, and vision SLAM has become a more popular research direction nowadays, so the research on the fusion technology of the two is more of an inevitable orientation. The robot in this paper is equipped with a variety of sensors such as LiDAR, RGB-D camera, encoder, odometer, etc., which can realize the accuracy of ranging and can be applied in SLAM. From the SLAM basic problem description model, it can be concluded that the state of the robot at this moment is closely related to the state of the previous moment and the control inputs to this moment.

If the control input at moment k is U_k, this control quantity consists of the velocity data of the robot at moment k:

$$U_k = \begin{pmatrix} v_k \\ \omega_k \end{pmatrix} \tag{1}$$

where v_k is the robot as a predetermined desired linear velocity and w_k is the predetermined angular velocity.

The state of the robot at k is denoted as X_k, then the state at the previous moment is X_{k-1}. At this point the state space is composed of the robot's pose as well as its position:

$$X_k = \begin{pmatrix} x_k \\ y_k \\ \theta_k \end{pmatrix} \tag{2}$$

According to the above, it can be seen that, considering the current robot control input, state space and error information as a whole, the motion model of the robot at the current control input of U_k is:

$$X_{k+1} = \begin{pmatrix} x_{k+1} \\ y_{k+1} \\ \theta_{k+1} \end{pmatrix} = \begin{pmatrix} x_k \\ y_k \\ \theta_k \end{pmatrix} + \begin{pmatrix} x_{k+1}\Delta t\cos\theta_k \\ y_{k+1}\Delta t\sin\theta_k \\ \theta_{k+1}\Delta t \end{pmatrix} + Q_k \tag{3}$$

where Q_k denotes the error information of the robot during the moving process.

II. B. 2) Lidar SLAM building maps

(1) Lidar SLAM working principle

Lidar is through the emission of pulsed laser, hitting the surrounding obstacles, scattering on the surface of the obstacles, some of the reflected light will be transmitted back to the detection end of the sensor, using the principle of laser triangulation to calculate, you can get the distance from the Lidar to the target object. Laser transmitter and camera position is determined, the length H and angle A is known, the camera through image processing to identify the laser point, and then according to the principle of small hole imaging can be calculated to get the angle B, and then according to the simple principle of triangulation can be calculated from the distance D. Through the continuous collection of information, you can get the information of the surrounding obstacles data, and then converted into image data, and finally generate a map.

(2) Lidar map building process

RVIZ is a three-dimensional visualization technology development tools, can be well compatible with the robot platform under the ROS software architecture, by running the launch file to start and control the program, can complete the corresponding functions. In RVIZ, it is possible to use graphical methods to instantly display various signals from the robot sensors, as well as the robot's movement status and environmental changes. It is also possible to assist the user in the graphical display of detectable information, which improves the convenience of human-computer interaction to an extremely high degree.

Before running the graph building node, the launch file of the graph building node is opened to view the contents, and it can be seen that the graph is built using the gmapping algorithm. First, the wireless communication between the operator and the robot, ssh login, and then input the radar laser mapping command: roslaunch turn_on_wheeltec_robot mapping.launch. After running without any error, another terminal window is opened and input the RVZI, and after running, the mapping screen appears. Now you need to control the robot to move by turning on the keyboard node, and build the map during the moving process. No matter what kind of way to build the map, you need to collect data continuously during the movement of the robot to complete the command of building the map.

II. B. 3) RGB-D Visual SLAM Building Maps

(1) Imaging Principle

RGB-D camera can create a “point cloud” of the surrounding environment, point cloud data information combined with the environment image of the RBG signal can be a realistic scene restoration. In this project, this function can be utilized to build firefighting environment scenes, which can greatly restore the real sense of the scene. The binocular RGB-D camera used in the experiment is a binocular structured light mode, i.e., one infrared emitter and two infrared receivers. By comparing the difference of the images captured by these cameras at the same moment and using an algorithm to calculate the depth information, multi-angle 3D imaging can be performed.

(2) Working principle of vision SLAM

Most vision SLAM systems work by taking successive camera frames, tracking and setting keypoints, localizing their 3D position with a triangulation algorithm, and using this signal to approach or predict the camera's own position. In short, the goal of this operation is to map the environment in relation to its own position. And unlike other types of SLAM techniques, vision SLAM only requires a 3D vision camera to accomplish this. In contrast to LIDAR SLAM, in vision SLAM a loopback detection is performed, i.e., the ability of the robot to recognize a scene it has reached before. Under the condition of successful detection, the cumulative error may be significantly reduced. Loopback detection is essentially an algorithm for detecting the similarity of observations. Visual SLAM adopts bag-of-words pattern detection method more often, using the bag-of-words model to cluster the visual features in the image to form a classification “dictionary”, and then find out the “words” contained in each image.

(3) Introduction of Rtabmap

Rtabmap is an incremental closed-loop detector based on RGB-D and LiDAR SLAM approach, and a Graph-Based SLAM algorithm based on RGB-D and LiDAR.

(4) Pure visual map building

In this experiment, we use the gridded map for the mapping experiment, after the wireless communication between the operator terminal and the robot, we make the communication connection and log in, input the pure visual mapping instruction on the terminal: roslaunch turn_on_wheeltec_robot pure3d_mapping.launch, and then open the RVIZ software under the Ubuntu system After that, you can open the RVIZ software under Ubuntu system, and then input the command of the keyboard node, and control the robot's movement through the keyboard, and then you can use the RGB-D camera to build 3D maps during the continuous movement.

II. B. 4) LIDAR and RGB-D fusion SLAM map building

The LiDAR and RGB-D camera are built with different map data types, and the data information from the two parts is fused under the rtabmap algorithm tool. Firstly, the rtabmap build node is inputted, which provides the startup file base parameters and default values, next are the inputs of several topics, the first part is the topic inputs required to run the RGB-D camera, so that the inputs of the published topics are used as inputs for the RGB-D camera part of the build, which includes the color RGB maps, the RGB depth maps, and the RGB calibration files. The second part is first in the setup, using the RGB-D image input, which should set subscribe_depth to false and subscribe_rgbd to true. Fusion 2D LIDAR build map, enter the LIDAR and RGB-D camera fusion build map command, and then open another terminal window to turn on the keyboard control node to control the robot to run and complete the map building.

II. C. Autonomous firefighting module for firefighting robots

II. C. 1) Firefighting robot autonomous firefighting program design

The autonomous firefighting process of the firefighting robot includes fire water cannon control as well as fire source identification and localization. In the autonomous inspection phase, the robot carries out inspection tasks along the pre-set navigation target points, and uses thermal imaging cameras and other sensors to detect potential fire sources in a timely manner. When the fire robot accepts the fire alarm signal, the robot will use image recognition technology to accurately identify and locate the fire source. Next, the robot automatically adjusts the fire water cannon and turntable to determine whether the fire source is in the right position, if the fire source is in the middle of the image, then the fire fighting action.

II. C. 2) Control of water cannons and turntables

The autonomous fire extinguishing function of the firefighting robot is mainly realized by the fire source identification and localization sensor installed on the fire water cannon and the fire water cannon itself. In the process of identifying and localizing the fire source, the sensor is closely integrated with the fire water cannon to ensure that the direction of the two is the same, and the fire source is identified and localized by rotating left and right to cover a larger area. Therefore, the precise control of the direction of the fire water cannon is crucial in the whole process of autonomous fire extinguishing.

(1) Fire water cannon automatic control process

In this paper, when the fire robot arrives at the fire source area, the fire water cannon will start to unfold the arm until the arm is completely unfolded. Since the fire source point is relatively fixed, the tracking performance requirements for the fire water cannon are low, so the rotation of the fire water cannon in this paper adopts the uniform motion model.

After receiving the fire source alarm signal, the fire water cannon control system will perform the following steps:

First, the distance of the fire source area is accurately measured using LiDAR, which is the first step to locate the position of the fire source. Using this distance information and a coordinate transformation algorithm, the exact position of the fire source with respect to the center of the rear axis of the firefighting robot is calculated. The firefighting robot then further identifies and localizes the fire source through the rotation angle of the rotary table. After the thermal imaging camera finds the fire source, the system records the rotation angle of the turntable and the pitch angle of the fire water cannon. Next, the system evaluates whether the current position of the fire water cannon is within the optimal firing range and determines whether the fire source is located in the effective firing area. If the fire source is not in the optimal firing area, the system will adjust the pitch angle of the first, second and third arms of the firefighting robot to ensure that the water cannon can accurately target the fire source. Once the fire source is within the effective range of the water cannon and the position is correct, the fire-fighting robot will start the fire-fighting operation.

(2) Fire water cannon and turntable steering control protocol design

First of all, define the specific structure of the data packets sent and received on the CAN bus. The fire water cannon assembled with this fire-fighting robot adopts CAN bus for data transmission and complies with the CANopen communication protocol, and its baud rate is set at 280kbps, in which CAN SendID is 0x1B9, which is used to identify the unique identification of the data packet, and the data field contains 4 bytes. The data exchange through CAN bus should be real-time in order to respond quickly to the changes of the fire source, so the water cannon sends the robot status information periodically with a cycle of 100 milliseconds.

II. D. Fire source identification and localization

The algorithm first makes a temperature judgment based on the highest temperature region on the thermal imaging image, sets the temperature region threshold, and when the temperature is greater than the set temperature threshold, the image segmentation module processes the different temperatures to obtain a high temperature target region. Then the processed thermal imaging image is fused with the laser point cloud for localization, and finally the fused information is output.

(1) Thermal imaging image imaging principle

Thermal imaging image grayscaling is the process of converting thermal imaging images, which originally represent different temperatures in different colors, into grayscale images. In a grayscale image, different temperature regions will be represented by different grayscale levels rather than by colors. This conversion helps to simplify the image processing and analysis process in some applications, especially when color information is not necessary. The image grayscaling method is shown in equation (4):

$$Gray(i,j)=\omega_1 * R(i,j)+\omega_2 * G(i,j)+\omega_3 * B(i,j) \tag{4}$$

where (i,j) is any point in the image, $Gray(i,j)$ is the gray value of the point, $R(i,j),G(i,j),B(i,j)$ is the RGB value of the point, and $\omega_1,\omega_2,\omega_3$ are the corresponding weights, in this paper, $\omega_1=0.3,\omega_2=0.6,\omega_3=0.1$.

(2) Fire source identification based on maximum inter-class variance method

The maximum inter-class variance method (OTSU) is an adaptive thresholding image segmentation algorithm, the core idea of this method is to maintain the overall information of the image while minimizing the probability of misclassification, making the segmentation results more accurate.

The core of OTSU algorithm is assuming the existence of threshold T_{th}, dividing all the pixels of the thermal imaging image into two classes, namely c_1 (grayscale is less than T_{th}) and c_2 (grayscale is greater than T_{th}), and the global mean of the whole image is m_G. The interclass variance σ^2 is given below:

$$p_1\times m_1+p_2\times m_2=m_g \tag{5}$$

$$p_1+p_2=1 \tag{6}$$

$$\sigma^2=p_1(m_1-m_G)^2+p_2(m_2-m_G)^2 \tag{7}$$

where p_1,p_2 is the probability that a pixel is categorized into the class c_1,c_2, and m_1,m_2 is the mean of the pixels in the two classes.

Substituting (5) into (7) gives:

$$\sigma^2=p_1p_2(m_1-m_2)^2 \tag{8}$$

(3) Point cloud and thermal imaging image alignment

In order to obtain the 3D spatial position of the fire source, it is necessary to align the point cloud with the thermal imaging image, i.e., to complete the internal parameter calibration of the thermal imaging camera and the external parameter calibration between the thermal imaging camera and the LiDAR.

In order to correspond the thermal imaging pixel point $P^c[u,v,1]^T$ to the LIDAR point cloud point $P^{'}[X_t,Y_t,Z_t]^T$, it is necessary to jointly calibrate the thermal imaging camera with the solid-state LIDAR by solving the camera by the following equation The external parameter between the thermal imaging camera and the solid-state lidar, where R,t is the external parameter to be solved, which is denoted as T_l^c, and the point $P^{'}[X^{'},Y^{'},Z^{'}]^T$ is the coordinate transformed to the camera coordinate system. I.e.:

$$P^{'}=\begin{pmatrix}X^{'}\\Y^{'}\\Z^{'}\end{pmatrix}=R\begin{pmatrix}X_l\\Y_l\\Z_l\end{pmatrix}+t=RP^l+t \tag{9}$$

Bringing Eq. (5) into Eq. (9) and writing it in the form of chi-square coordinates then we have:

$$P^{ltc}=\begin{pmatrix}u^{'}\\v^{'}\\1\end{pmatrix}=\frac{1}{Z}\begin{pmatrix}f_x&0&c_x\\0&f_y&c_y\\0&0&1\end{pmatrix}\begin{pmatrix}R&t\\0&1\end{pmatrix}\begin{pmatrix}X_l\\Y_l\\Z_l\\1\end{pmatrix}=\frac{1}{Z}KT_l^cP^l \tag{10}$$

Eq. (10) converts the chi-square coordinates to non-chi-square coordinates, where P^{ltc} is the coordinates converted to the camera pixel coordinate system through the camera's external reference to the LiDAR and the camera's internal reference, K is a 3×3 matrix, and $T_i^cP_i$ is a 4×1 matrix, so it is necessary to take $T_l^cP_l$ in the first three dimensions taken out into 3×1 non-chiral coordinates.

By solving the least squares problem, the solution of the external parametric error equation between the camera and LIDAR is completed as shown in Eq. (11), and the result of the external parameter T_l^c is shown in Eq. (12). Namely:

$$e=argmin\frac{1}{T_i^{ò}}\sum_{n}^{n}\|P_i^c-\frac{1}{Z}KT_i^cP_i^l\|^2=argmin\frac{1}{n}\sum_{i=1}^{n}\|P_i^c-P_i^{ltc}\|^2 \tag{11}$$

$$T_l^c = \begin{pmatrix} -0.002 & -0.993 & -0.014 & 0.066 \\ -0.009 & 0.014 & -0.998 & 0.006 \\ 1 & 1 & 1 & -0.005 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{12}$$

(4) Fire source localization algorithm by fusion of point cloud and thermal imaging

Firstly, the fire-fighting robot performs a fire source identification at the position A, and obtains the point cloud coordinates $F_A(X_A, Y_A, Z_A)$ at the position A through coordinate conversion, and then the fire-fighting robot travels to the position B, and similarly, obtains the point cloud coordinates $F_B(X_B, Y_B, Z_B)$, and the center coordinates of the fire source $F_F(X_F, Y_F, Z_F)$ can be obtained by triangular positioning, and the center coordinates of the fire source $F_R(X_R, Y_R, Z_R)$ can be obtained by fusion positioning in B, and finally the weighted fusion according to the point cloud coordinates of the two is carried out to obtain more accurate center coordinates of the fire source.

III. Residential Fire Protection System Testing and Analysis

III. A. Positioning Composition Module Analysis

III. A. 1) Experimental platform architecture

To verify the feasibility of fusion of LiDAR and RGB-D camera for map construction. The main sensors used in the firefighting robot are Rplidir C1 LIDAR and AOBI Zoomlite's RGB-D camera.The main parameters of the Rplidir C1 LIDAR are: measuring radius 12m, sampling frequency 16Hz, scanning frequency 30Hz, angular resolution 0.855°, power supply voltage 10V, ranging resolution <0.6% of the actual distance (distance <10m), Ranging accuracy: 0.62% of actual distance (<1.6m). The main parameters of AOBI Zoomlite RGB-D camera: depth resolution 2560x512@7FPS, color resolution 256x512@40FPS, measuring range 0.53-8.71m, depth FOVH57.20-V43.20, etc.

III. A. 2) RGB-D Camera Mapping

The experimental platform builds maps for traditional RGB-D cameras in Ubuntu version 16.04, and the maps constructed after extracting the feature points are sparse, which can only be used for localization and cannot be directly used for the navigation of firefighting robots. The experimental results are shown in Fig. 1, where the tiny points represent the sparse point cloud, blue color indicates the navigation path of firefighting robot, while orange color indicates the obstacles. The dense point cloud map is constructed using the RGB-D camera and compared with the sparse point cloud map before improvement, and then the point cloud data is utilized to convert and output the octree map, and finally the octree is converted into a raster map after projection. In the raster map, the orange part indicates that there are obstacles and occupied, and the gray part indicates unoccupied, and the experimental results are shown in Fig. 2.

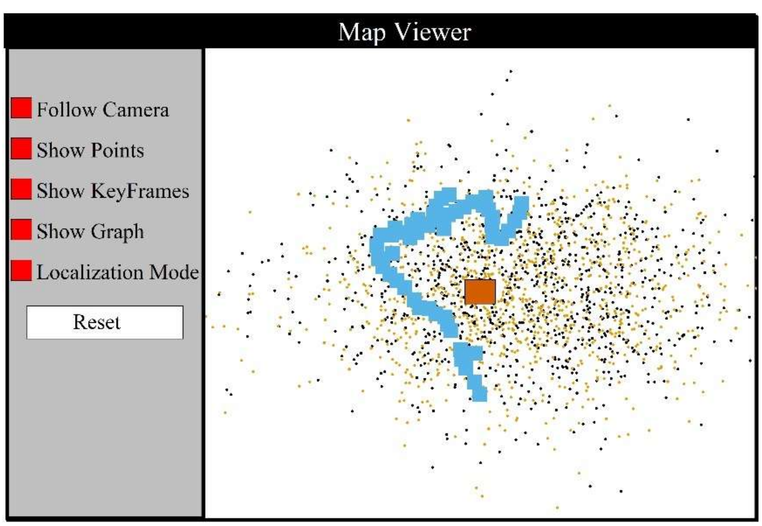

Figure 1: RGB-D camera mapping

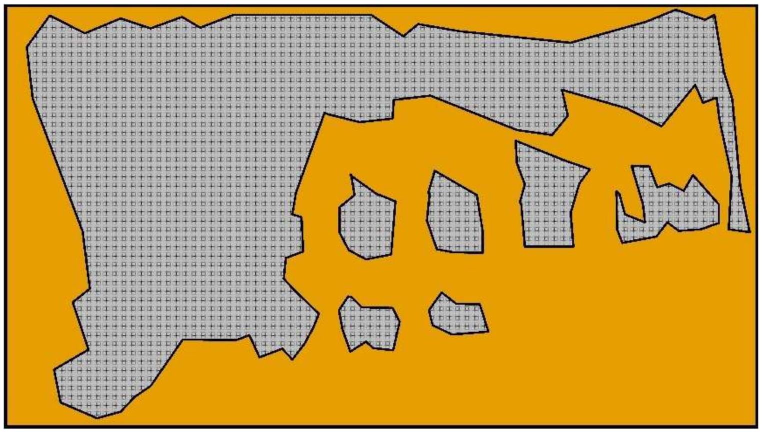

Figure 2: Improved RGB-D camera mapping

III. A. 3) LIDAR and fusion mapping

The environment of the experiment is a medium-sized residential building, and the 2D raster map is constructed using LIDAR SLAM. When the mobile firefighting robot turns on the radar, it starts to scan the surrounding environment and continuously updates the point cloud and position information in the two-dimensional space, and continues to control the firefighting robot to move, and finally obtains the two-dimensional raster map as in Figure 3. Utilizing the improved fusion algorithm, after many experimental comparisons and processing of some cumulative errors and relative position, the fused raster map in Figure 4 is finally obtained. As can be seen from the synthesis of Fig. 3 and Fig. 4, the contour description is not clear when a single LiDAR builds the map, and the scanning information for small obstacles is not complete. The map constructed using the fusion of RGB-D camera and LiDAR compensates for this shortcoming, and the fused SLAM mapping technique provides a clearer characterization of the obstacles and a more complete scan of some smaller obstacles. A comparison of the single sensor's composition time and obstacle detection rate is shown in Table 1, and a comparison of all the statistical metrics of absolute error is shown in Table 2. For the accuracy of localization, the absolute position error index is used for comparison, and the smaller the absolute error, the higher the localization accuracy of the constructed map. As can be seen from Table 2, both the average error and the median error are better after fusion than before fusion, which shows that the absolute positional error of the fused constructed map is smaller and the global consistency is higher. In summary, it can be seen that the recognition rate of obstacles in the fused SLAM in the process of mapping reaches 95.9%, and the absolute position error is reduced by 51.6%, which indicates that the trajectory error between the real position and the estimated position of the fused SLAM mapping of LiDAR and RGB-D is smaller, and the accuracy of localization and the recognition rate of obstacles are higher, which verifies the effectiveness of the localization mapping module of the residential fire fighting system in this paper.

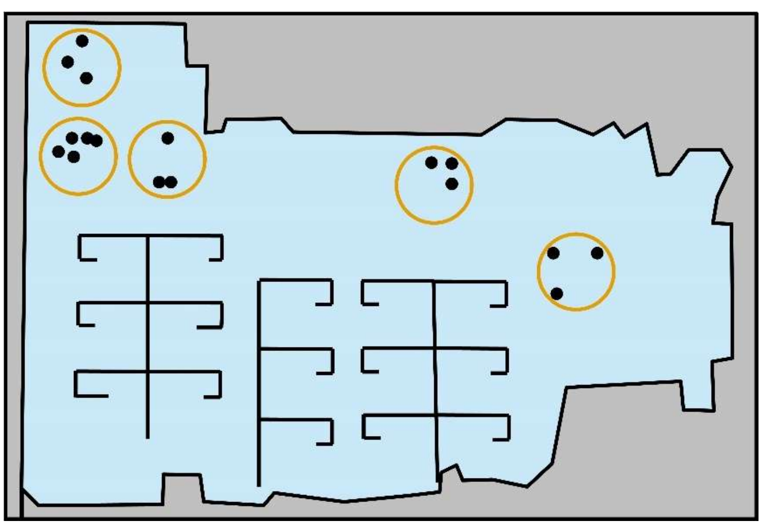

Figure 3: Lidar SLAM mapping

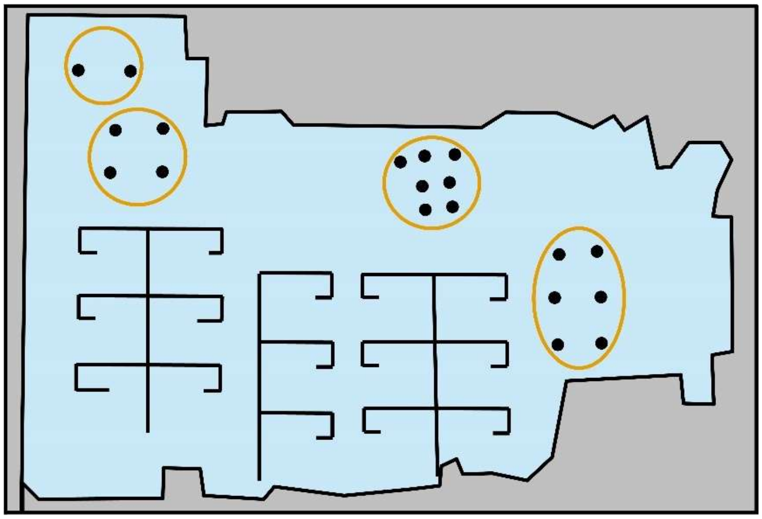

Figure 4: Lidar and RGB-D fusion SLAM mapping

Table 1: Comparison of map construction data

Mapping plan	Mapping time/s	Obstacle detection rate/%
Lidar	179	88.7
RGB-D camera	256	77.8
Fusion mapping	208	95.9

Table 2: Comparison of all statistical indicators of absolute error

Type	Min/m	Max/m	Average error	Median error	Variance/m^2	Standard deviation/m
Before integration	0.0006	0.0686	0.0116	0.0084	0.136	9.0069
After fusion	0.0004	0.0326	0.0085	0.0066	0.067	89.0046

III. B. Analysis of Autonomous Fire Extinguishing Modules

III. B. 1) Fire source identification and orientation experiments

In the fire source identification and orientation experiments, burning waste wood and cardboard to form a fire source, set up in front of the fire robot about 35m position, waiting for its full combustion to the fire source is not less than 0.23m × 0.23m, through the control of the water cannon in front of the 180 ° range of left and right reciprocating swing so that the fire source detection sensor fire source identification, swing speed of about 0.23rad / s, identification of the source of fire after After recognizing the fire source, the water cannon barrel autonomously corrects the direction so that it points to the fire source to complete the orientation, and the experimental data of fire source recognition is shown in Table 3. In 10 experiments, the firefighting robot was able to effectively recognize the experimental fire source during the first swing of the fire source detection sensor over the fire source, and the recognition accuracy rate reached 100%, which was higher than the set target of 90%. According to the experimental data, the firefighting robot to the experimental fire source recognition of the temperature between about 262 ~ 349 ℃, the general wood combustion temperature of 450 ℃ or more, usually in the 640 ℃ or so, taking into account that the heat radiation will be reduced with the increase in distance, the experimental data within a reasonable range. At the same time, in the experiment, the maximum error of fire robot fire source orientation in 3 °, also less than the required performance indicators. In summary, in the case of fire source size to meet the requirements, the firefighting robot can effectively identify the fire source, and can realize the orientation of the fire water cannon to the fire source, reducing the manual intervention in the fire extinguishing, proving the identification and orientation function of the residential firefighting system in this paper.

Table 3: Experimental data for fire source identification

Experiment Number	Whether the recognition was successful or not	Temperature/℃	Number of pixels	Fire source orientation error /°
1	Yes	340	19994	1.5
2	Yes	272	20123	-2.5
3	Yes	262	17150	1.5

4	Yes	273	18148	-2.0
5	Yes	349	21119	1.5
6	Yes	308	17454	2.0
7	Yes	325	21960	2.0
8	Yes	308	19287	2.0
9	Yes	293	16208	-2.0
10	Yes	309	19299	-2.0

III. B. 2) Autonomous Fire Fighting Experiment Based on Unknown Map

In the firefighting robot's autonomous firefighting experiment based on an unknown map, the fire source is recognized and oriented and the distance is estimated to cooperate with the firefighters to complete the firefighting work. A fire source is set up in the open area of the park, the size of the fire source is not less than 0.23m×0.23m, the operator releases a navigation target that can be visible to the fire source, the firefighting robot navigates to the target and identifies the fire source, the firefighting robot recognizes the fire source and the operator releases a second navigation target, the firefighting robot navigates to the target to identify the fire source again, and the location of the fire source is outputted after the fire source is recognized. Relative to the robot's current position of the estimated distance, repeat the experiment five times to record the experimental data as shown in Table 4 (mainly to obtain the distance estimation error of the fire source), and in the last experiment to complete the whole process of the autonomous fire-fighting program, i.e., the operator according to the estimated distance of the fire source to determine whether the source of fire is in the range of the fire cannon, when the source of the fire into the range of the cannon, the firefighters for the robot to connect to the fire hoses by adjusting the pressure of the water pump to control the water cannon shot. When the fire source enters the water cannon range, the firefighter connects the fire hose to the robot and controls the range of the water cannon by adjusting the pressure of the water pump to complete the fire fighting work. From the experimental data, it can be seen that in five experiments, the fire robot on the fire source distance estimation error of the maximum value of about 2.22 m. Through this distance estimation data and take into account the error to determine the position of the water cannon firefighting, in order to prevent the fire source is too far away from the fire robot to exceed the range of the water cannon, and the actual range of the cannon can be adjusted through the control of the water pump water pressure size. The maximum range of the water cannon carried by the firefighting robot is about 35m, and it is innovative and valuable to determine whether the fire source is too far away from the firefighting robot and thus beyond the range of the water cannon, while the actual range of the water cannon can be adjusted by controlling the water pressure of the water pump. In summary, the experiment verifies the feasibility of this paper's method for estimating the distance to the fire source and the autonomous fire extinguishing program of the firefighting robot, and at the same time confirms the effectiveness of the application of the residential firefighting system based on the robot technology.

Table 4: Autonomous fire extinguishing experiment data

Experiment Number	The actual distance between the fire source and the fire extinguishing point is m	Estimated distance between the fire source and the fire extinguishing point /m	Distance estimation error
1	18.39	20.27	1.88
2	19.56	18.29	-1.27
3	18.22	20.44	2.22
4	18.69	20.81	2.12
5	18.32	18.61	0.29

IV. Conclusion

Through the design and experimental validation of a residential firefighting system based on robotics, the system excels in several key performance indicators. The SLAM composition technology of LIDAR and RGB-D camera fusion significantly improves the system's environment sensing ability, and the obstacle recognition rate reaches 95.9%, which is a significant improvement compared with the single-sensor scheme. In terms of positioning accuracy, the absolute position error after fusion is reduced by 51.6%, verifying the effectiveness of multi-sensor fusion technology in improving positioning accuracy. The fire source recognition module shows excellent performance, with 100% recognition accuracy in 10 experiments, and the recognition temperature range covers 262 to 349°C, which meets the requirements of practical firefighting applications. The maximum error of the fire source orientation function is controlled within 3°, which ensures the accuracy of fire-fighting operations.

The system integrates advanced SLAM technology, thermal imaging recognition technology and intelligent control algorithms to realize the autonomous navigation, fire source recognition and fire extinguishing functions of the firefighting robot. The experimental results prove the adaptability and reliability of the system in complex residential environments, providing a technical reference for the development of intelligent firefighting equipment. The system can not only effectively reduce the safety risk of firefighters in dangerous environments, but also enhance the efficiency and success rate of firefighting operations through precise sensing and control technology, which is of great significance in promoting the intelligent transformation of the firefighting industry.

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