Design of Intelligent Robot Platform based on Multi-sensor Fusion

Ya Dajin¹, Lei Xiaochun², Li Yue¹, Chen Junyan¹,³, Huang Rongcun¹, Lan Lin¹

¹School of computer and information security, Guilin University of Electronic Technology, Guilin 541004, China;
²Guangxi Colleges and Universities Key Laboratory of Intelligent Processing of Computer Images and Graphics, Guilin 541004, China;
³Guangxi Cooperative Innovation Center of cloud computing and Big Data, Guilin University of Electronic Technology, Guilin 541004, China)

*Corresponding author’s e-mail: glleixiaochun@qq.com

Abstract: The mobile robot adapts to the more complicated indoor and outdoor environments, and can expand its scope of application. In order to reduce the influence of the cumulative error caused by navigation in complex environments, the indoor mobile robot that combines Inertial Measurement Unit (IMU) and encoder fusion is designed and implemented. In view of the limitations of the traditional single lidar scheme, a Multi-sensor Fusion scheme is proposed to achieve indoor map construction, path planning, multi-point navigation and other functions, and a MSIF KartoSLAM (Multi-sensor Information Fusion) algorithm is proposed, which combines the KartoSLAM algorithm and Multi-sensor information to achieve map construction in complex environments. Through comprehensive testing in the indoor environment, the results show that the Multi-sensor Fusion scheme is superior to the traditional single lidar scheme, and can achieve higher accuracy in mapping and navigation. At the same time, the robot platform can also be combined with the Internet of Things technology and integrated into intelligent housing system.

1. Introduction
There are some problems in the indoor positioning and autonomous movement of existing robots, such as low precision, inaccurate map building and so on. With the promotion of artificial intelligence technology, the research of indoor positioning is gradually developing towards the direction of intelligence. The autonomous navigation system of robot based on the technology of simultaneous localization and mapping (SLAM) has become the main trend of robot research and development.

In order to adapt the needs of domestic use robots, an intelligent robot platform of multi-sensor information fusion (MSIF) is designed in this paper by using the open-source robot framework ROS (robot operating system). The platform realizes autonomous cruise of robot, uses app designed by RosJava framework to communicate data with robot, and voice broadcast environment data of robot to meet various requirements of domestic robot.

Common SLAM schemes can be divided into laser SLAM and visual SLAM. In dynamic environment, the information collected by visual SLAM has texture and performs better.
However, in the static indoor environment, the characteristics of laser SLAM are more prominent, its single point and single measurement are more accurate.

In terms of computing requirements, the performance of laser SLAM is far lower than that of visual SLAM. Therefore, the indoor mobile robot designed in this paper uses laser SLAM technology, combined with KartoSLAM algorithm and multi-sensor information fusion to achieve complex environment mapping and navigation.

2. Hardware architecture design of indoor mobile robot

The hardware architecture of the robot designed in this paper is shown in figure 1. The robots use the crawler-type motorized structure, which can walk in the complex ground environment. The acceleration and angle of the object in the carrier coordinate system can be obtained by the IMU sensor MPU9250. The linear velocity of the robot is obtained by the decelerating photoelectric encoder motor with photoelectric encoder. According to the angular velocity, acceleration and linear velocity in three-dimensional space, the gesture of robot can be defined.

The acceleration and angle of the object in the carrier coordinate system can be obtained by the IMU sensor MPU9250. The linear velocity of the robot is obtained by the decelerating photoelectric encoder motor with photoelectric encoder. According to the angular velocity, acceleration and linear velocity in three-dimensional space, the gesture of the robot can be defined.

The essence of positioning and navigation of IMU is dead reckoning, because the error of previous positioning results will accumulate in the current results, and due to the zero deviation characteristic of IMU, the final performance is that the positioning error will accumulate with time. The encoder can only be used for odometer acquisition. Due to various environmental interference factors, the navigation error increases with the accumulation of time, and the measurement of the two sensors will produce data offset with the passage of time. Therefore, two sensors and lidar are used to fuse and correct the data, so as to make the mapping and navigation perform better.

3. Indoor Navigation Algorithm based on multi-sensor information fusion

3.1. ROS node distribution

The robot is equipped with ROS system, which makes full use of the distributed framework, and establishes SLAM mapping node, path planning node, lidar node, odometer node, basic control node and IMU node. Each node is shown in figure 2.
The robot uses STM32F103 controller as the driving unit to decode the encoder data and collect the data of IMU module. The IMU node obtains the robot's three-dimensional space gesture \(^5\); the odometer node is used to receive the gesture information and publish the odometer message topic to the SLAM node and the navigation node. LiDAR Lidar publishes the laser data to the SLAM node, which is used to build the map. Through the rviz, which is a visual chemical tool under the ROS system, you can view the map building and operate the robot to complete the map building. The path planning node relies on the Topic of the SLAM node, receives the odometer data, uses the three-dimensional gesture information to find the optimal path in the generated cost graph, and the navigation node also publishes messages to the hardware layer to control the robot's movement.

### 3.2. MSIF KartoSLAM algorithm

The SLAM algorithm used in this system is KartoSLAM algorithm. Karto algorithm is based on the method of graph optimization (g2o) \(^{10}\), which uses highly optimized and non-iterative Cholesky matrix to decouple the sparse system as its solution. The mean value of the graph is used to represent the map. Each node represents the sensor measurement data set of the robot's motion track. The arrow pointing connection represents the motion trend of the path points of the continuous robot's position. When each new node is added to the map, the node arrow data in the space will be calculated and updated according to the given constraint term \(^1\). This paper improves the KartoSLAM mapping scheme, and designs the mapping algorithm scheme of multi fusion sensors (MSIF KartoSLAM). The algorithm framework of MSIF kartoslam algorithm is shown in figure 3. The \(\psi_t\) is the pose covariance at the current time, \(X_{(t-1)}\) is the gesture of the previous moment, and \(\Delta\) is the difference. After the sensor inputs data, it calculates the initial gesture and compares it with the last gesture. If the difference \(\Delta\) is greater than 0, it means the gesture has changed; if it is less than or equal to zero, the gesture remains unchanged.
LIDAR data

Start

Last_position+Odometer_Data → Initial_position

$\psi_{t-1} + \Delta$?

Return

Integrate: IMU,Odometer,Pose_data

Odometer_data

IMU_data

Return: Node position, covariance

Add: side and vertex

Loopback?

NO

Return

YES

Global optimization

Return

Fig. 3 MSIF KartoSLAM algorithm framework

MSIF kartoslam algorithm is a multi-sensor gesture fusion method proposed in this paper. This method is based on the time stamp down alignment data, through the help of auxiliary sensors such as IMU and odometer to provide more accurate position and gesture estimation of rotation and displacement included in the next moment, which belongs to the position and gesture incremental. Compared with lidar, the data acquisition rate of IMU and Odom odometer sensors is higher than that of lidar.

In view of the errors of IMU and Odom odometer over time, this paper performs some update initialization operations to eliminate the accumulated errors when estimated the gesture. When estimate the gesture rotation, with the IMU data absenced, the speed can be simulated by odometer or current gesture data, which maintains the stability of pose data to a certain extent. The specific scheme process is shown in figure 4.

This method uses the data structure of double end queue to cache data, which is convenient to update and delete data. The algorithm continuously polls gesture data, IMU data and odometer data. During acquiring the latest estimated pose and processing two kinds of sensor data of IMU and odometer, the change of gesture is divided into three tracker (pose_Tracker、IMU_Tracker、Odom_Tracker) indicates that the IMU data is updated to the three trackers, and finally the fusion completed pose is provided to the scan matcher as the initial value.

Tracker calculation and update

Is have IMU data?

NO

Is have Odom data?

NO

NO

YES

Calculate the pose increment based on IMU data

Calculate the pose increment based on Odom data

Calculate the pose increment from the angular velocity calculated from the pose

Output

(a) Calculation and update of posture incremental tracker
The first step of scanning and matching is to generate a subgraph (reference model). Because the slam map is a 2D grid, the subgraph can be understood as a small part of the map around the robot. Secondly, a look-up table is generated. Compared with the violence matching method, the laser data information of the same angle and different position is indexed only once, without recalculating each laser data information every time, so the complexity of the program algorithm is reduced. The odometer can estimate the attitude angle and calculate a look-up table with $n$ angles under a certain resolution and offset value. The formula is shown as follows:

$$n = \frac{\theta}{\tau} + 1 \quad (1)$$

The $\theta$ is the angle offset and $\tau$ is the resolution. The pose state of a mobile robot contains $(x, y, \theta)$ information. The problem of angle can be solved quickly by looking up the table.

A search area is set up with the odometer as the location center, which is searched discretely and traversed with the lookup table. A certain displacement in the table is put into the subgraph, and the laser data is processed by Gaussian blur. Suppose that there are $m$ hit points, each hit point has a different response function value (caused by Gaussian blur), and then the value $r$ of the maximum probability is the current position. The traversal algorithm is shown in figure 5:

**Fig.5 response ergodic description**

Response function $[9]$ is calculated as follows:

$$R = \frac{\sum_{i=0}^{m} G_i}{G_{\text{max}}} \quad (2)$$

The $G$ is the target point. And the $G_{\text{max}}$ is the maximum value.

When the robot moves to the original environment that has been explored, it is necessary to judge whether it is loopback detection. Because KartoSLAM is an algorithm based on graph optimization, it can use the internal topology map to carry out active closed-loop detection, modify the original
position and attitude topology map, and modify the closed-loop map, so as to achieve more reliable environment mapping. The robot optimization algorithm uses the LM (Levenberg-Marquardt) algorithm to optimize the feedback data and get the optimal solution.

3.3. Path Planning and Positioning Navigation
When the mobile robot is positioning and navigation, the first step is robot positioning. This system uses ACML (Adaptive Monte Carlo localization) positioning scheme, also known as Adaptive Monte Carlo positioning [3]. The navigation algorithm adopts Dijkstra algorithm and DWA (dynamic windo-w approach) algorithm [7], among which Dijkstra algorithm is used as the global path planning scheme and DWA algorithm is used as the local planning scheme. The planned local path should obey the global path as much as possible. The flow chart of path planning is shown in figure 6.

The time complexity of the standard Dijkstra algorithm is $O(n^2)$. In order to reduce the complexity of the algorithm, this paper adopts a Dijkstra algorithm based on heap optimization [10], which reduces the complexity to $o(n \log n)$.

4. System Test
In order to test the mapping and navigation of the robot in the room and the effect of MSIF KartoSLAM algorithm, this paper adopts the field test scheme respectively, and sets the multi-point navigation to observe the error after the path planning. Place the robot in a studio for testing, and the effect of the construction drawing is shown in figure 7. The real picture of the studio (area: length: 14.5m * width: 6.9m) is shown in figure 8. There are many equipments in the indoor environment, because the complex environment can better test the robustness of the algorithm. As shown in figure 7, the interior structure of the main body has a good effect, and the four black spots scattered and regular in the figure are the stool feet of the chair, which also belong to one of the obstacles. In general, in the real indoor environment, the robot's drawing effect is more accurate. Based on the map built in the field, this paper tests the multi-point positioning and navigation of the studio.

![Fig.7 Interior construction drawing effect](image-url)
Fig. 8 Actual test environment

In the rviz visualization tool, the target points of the robot are calibrated, and the position coordinates and the orientation and attitude angles are obtained. After the calibration, the robot can move along the calibrated target point for a complete route.

In this experiment, the multi-point navigation contrast test of the two schemes is carried out, and each parameter value in the navigation process is recorded, as described in table 1 and table 2. Table 1 is the data test result of the single lidar scheme, and table 2 is the test result of the sensor fusion scheme proposed in this paper. The positions in the table are expressed in the data format of quaternions. However, in order to compare the data intuitively, the quaternions are transformed into Euler angles in this paper. The transformation formula is as follows:

\[
\begin{bmatrix}
\varphi \\
\theta \\
\psi
\end{bmatrix} = \begin{bmatrix}
\text{atan2}(2(wx + yz), 1 - 2(x^2 + y^2)) \\
\arcsin(2(wy - zx)) \\
\text{atan2}(2(wz + xy), 1 - 2(y^2 + z^2))
\end{bmatrix}
\]

(3)

Since \(x=0\) and \(y=0\) of the quaternion in the data set, the values obtained by \(\varphi\) and \(\theta\) are 0, and only \(\psi\) (course angle, which is called "rotation angle" in this paper) needs to be recorded for the recorded data. Table 3 is the quantitative analysis table. The comparison information includes the average error and root mean square error in X and Y directions, and the average error and root mean square error of rotation angle, which can better evaluate the effect of the scheme. According to table 3, the average error of displacement is reduced by nearly 36%, and the average error of rotation angle is reduced by nearly 57%. In the improved scheme, the dispersion of data is obviously reduced, which indicates that the accuracy is improved. This robot uses RPLiDAR lidar equipment. Its resolution is less than 1% of the actual value which belongs to a dynamic precision. Even in one square meter environment, the single side precision is about 1cm. The error in Table 3 is about 5cm, but for an environment covering an area of about 100m², it is a small error. Similarly, there are some errors in IMU module and encoder. To sum up, the quality effect of multi fusion sensor scheme in navigation and mapping is better than that of single lidar scheme.

| Target point | coordinate /m | gesture (quaternion) | rotation angle |
|--------------|----------------|---------------------|----------------|
| 1            | (5.997,4.018)  | (0.0,0.0,0.38,1.0924)| 44.830°        |
| 2            | (10.998,2.994) | (0.0,0.0,0.9,23.0383)| 134.940°       |
| 3            | (14.008,8.981) | (0.0,0.0,0.9,25.0381)| -135.239°      |
| 4            | (8.011,7.987)  | (0.0,0.0,-0.38,2.0924)| -44.951°       |
| 5            | (1.424,1.536)  | (0.0,0.0,0.257,0.967)| 29.762°        |

Table 1 test results of single lidar scheme data
Table 2 data test results of sensor fusion scheme

| Target point | preset point | measured point |
|--------------|-------------|----------------|
| coordinate /m | (5.998,4.019) | (5.954,3.968) |
| (10.998,2.995) | (10.953,3.037) |
| (14.009,8.992) | (13.962,8.951) |
| (8.011,7.987) | (8.064,7.890) |
| (1.4246,1.537) | (1.480,1.598) |
| gesture (quaternion) | (0.0,0.0,0.381,0.925) | (0.0,0.0,0.916,0.401) |
| (0.0,0.0,0.925,0.381) | (0.0,0.0,0.933,0.359) |
| (0.0,0.0,-0.381,2.924) | (0.0,0.0,-0.360,0.931) |
| (0.0,0.0,0.257,0.967) | (0.0,0.0,0.237,0.972) |
| rotation angle | 44.830° | 42.644° |
| | 134.940° | 132.728° |
| | -135.239° | -137.883° |
| | -44.951° | -42.914° |
| | 29.762° | 27.444° |

Table 3 quantitative analysis of dataset test

| lidar scheme | sensor fusion scheme |
|--------------|----------------------|
| average error in X direction /m | 0.074946 | 0.043346 |
| average error in Y direction /m | 0.07255 | 0.05055 |
| root mean square error in X direction /m | 0.078806248 | 0.043358145 |
| root mean square error in Y direction /m | 0.074360801 | 0.050555957 |
| average error of rotation angle /deg | 5.2782718 | 2.2794202 |
| root mean square error of rotation angle /deg | 5.324616125 | 2.288471804 |

5. Summary
This paper designs a set of intelligent robot platform based on multi-sensor fusion, describes the architecture of the whole system, and focuses on MSIF KartoSLAM algorithm and positioning navigation. The robot uses “IMU + encoder + lidar multi-sensor fusion”, which improves the effect of map building and navigation. The software framework of the robot platform adopts the distributed architecture, which is a software system that node alone designed and combined of nodes. ROS platform provides a wealth of SLAM mapping and positioning solutions, and realizes the basic functions of the robot. Through the test of simulation environment and real environment, the test results are good and the expected functions are basically achieved. At the same time, the contrast experiment of multi-point navigation is set up. Through data analysis, the multi-sensor fusion scheme is better than the traditional single lidar scheme. At the same time, it also integrates popular Internet of things solutions, and the functional interaction evaluation is relatively good, which basically meets the requirements of a set of indoor service robots. In the future work, we will further improve and perfect the positioning and map building algorithm to improve the real-time and robustness of the algorithm.

Acknowledgment
This work is supported by Project to Improve the scientific research basic ability of Middle-aged and Young Teachers (No.2019ky0222, 2020KY05033, Student’s Platform for Innovation and Entrepreneurship Training Program under Grant (No.201910595093, 201910595142)

Reference
[1] Gu Hongming, (2016), Karto_Slam framework and code analysis. https://blog.csdn.net/qq_24893115/article/details/52965410.
[2] Cao, F.P. Fan, Q.Y. (2018). Research on real-time location based on Adaptive Monte Carlo algorithm. J. Computer Engineering, 44(09):28-32+37.
[3] Morning star boy. (2015). The navigation of ROS -- a detailed explanation of the application of AMCL (localization). https://blog.csdn.net/chenxingwangzi/article/details/50038413.

[4] Zhang, L. Shen, P. Ding, J. Song, J. Liu, J. Yi, K. (2015) An improved RGB-D SLAM algorithm based on Kinect sensor. In: IEEE International Conference on Advanced Intelligent Mechatronics (AIM),2015:555-562.

[5] Zhang, L. Liu, Z. Cao, J. Shen, P. Jiang, D. Mei, L.Zhu, G. Miao, Q. (2020) Cartographer algorithm and system implementation based on enhanced pose fusion of sweeping robot. J. Journal of software:1-13.

[6] He,Z.Z. Ding,D.R. (2019) Improved robot navigation method based on D-star and DWA. J. Electronic measurement technology,242(12):122-128.

[7] Edwin, B. Olson. (2009) Real-time correlative scan matching. In: IEEE International Conference on Robotics and Automation.2009:4387-4393.

[8] Jaromir Konecny, Michal Prauzek, Pavel Kromer, et al. Novel Point-to-Point Scan Matching Algorithm Based on Cross-Correlation. Mobile Information Systems, 2016, 2016(2):Article ID 6463945.

[9] Li, S. Jiao, C.Y. (2013) Research on PTN transmission route based on minimum heap optimization. J. Science, technology and Engineering, 13(21):6243-6246+6251.

[10] Liao Shiliang. Research and application of optimization of SLAM backend graph based on G2O. Guangdong University of Technology,2019.