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Research on Sensor Technology in Mobile Robot Navigation

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Abstract. As mobile robots are widely used in daily life, industrial manufacturing and the military, their ability to autonomous navigation in unmanned platforms and a wide range of environments is increasingly demanding. Therefore, the selection of sensors is a necessary process to improve the efficiency of navigation. The paper will introduce the principles and advantages of monocular vision, LIDAR and ultrasonic sensors etc. in detail, and then explore the advantages and disadvantages of various algorithms, and finally conclude optimal fusion of sensor solutions. The comparison results present that for the monocular vision, acquiring an image from a single camera setup, then using a YOLOv5 and mosaic technology to form a single image and finally using the improved RRT and the Frenet coordinate system to model the path is an efficient solution. 3D LIDAR technology can use the SLAM framework of graph optimization to create the map for obstacle avoidance and path planning. At last, this paper provides suggestions and optimizations for mobile robot navigation solutions, which are integrating multiple sensors and combining navigation solutions with machine learning.

Keywords: Mobile robot navigation, monocular vision, LiDAR 3D SLAM.

1. Introduction

As robotics technology continues to advance, mobile robots are becoming more and more common in a variety of industries, including industrial manufacturing, services, and home applications. As a result, they are progressively becoming a part of people's daily lives. As one of the key technologies for mobile robots to realize intelligence, autonomous navigation systems have attracted much attention. A high efficient autonomous navigation system can greatly improve the working efficiency of mobile robots and also allow the robots to autonomously cope with complex and changing working environments, thus making mobile robots become more useful in real life. Realizing effective autonomous navigation in dynamic, complicated situations is still a difficult issue. In order to accurately collect information about the surrounding environment and create an accurate environment model, the perception of the external environment first requires the fusion of numerous sensors. To provide safe and effective navigation decisions based on the environment model and goals, the robot must implement sophisticated path planning and motion control algorithms. To achieve the autonomous operation of mobile robots in

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complicated situations, a high degree of integration is required between these sensing, decision-making, and control components. Studies have suggested using multi-sensor fusion techniques to combine several sensors to provide more accurate and thorough environment monitoring. Nonetheless, there are still certain issues with the perception of dynamic environments. For instance, how to quickly and appropriately navigate by precisely perceiving and predicting changes in the dynamic environment. Furthermore, sensor data are quickly altered and disturbed in complicated situations.

This article is particularly meaningful for the research on sensors for mobile robots. Highly accurate sensor system can make the automatic navigation become more accurate, which is the basis for realizing the work of autonomous mobile robots in complex environments. The improvement of the autonomous navigation ability of the mobile robot can make its work efficiency and safety improved, which in turn meets the needs of the current work scene and also lays the technical foundation for future mobile robots. This article will analyze different sensor solutions to find the advantages, disadvantages and limitations of different sensors to perform and improve the fusion of sensors. Then the automatic navigation technique will be upgraded by machine learning to carry out and thus optimize and improve the mobile robot.

2. Mobile robot navigation solution

2.1. Monocular vision solution

The whole monocular vision scheme can be divided into 4 different parts. The first is acquiring an image from a single camera setup. Then a high-precision target detection framework with YOLOv5 as the core is used to realize the fast recognition and classification of obstacles in images. YOLOv5s model are mainly made by Input, Backbone, Neck and Output. The input image is processed on the YOLOv5s input side using adaptive anchor frames, mosaic data augmentation, and adaptive image filling. Using image processing techniques including cropping, scaling, and other adjustments, mosaic technology combines four or more photos into a single image while adding a thin black border to the source item to decrease the amount of computation and increase the speed of calculation [1]. In order to map the relationship between the monocular image features and the actual physical distance, the machine learning regression model is used. At the same time, by combining the fusion of on-board odometer, IMU and other sensor data, the accuracy of distance estimation can be further improved. The extended Kalman filter is used to eliminate the distance noise and jitter in a single-frame image. The extended Kalman filter can efficiently combine the input from various sensors and produce consistent and trustworthy filtering results, so as to obtain smooth and continuous obstacle distance information. Using the improved Rapidly-exploring Random Tree (RRT) path planning algorithm which incorporates the concept of artificial potential field based on the standard RRT algorithm to better control the distance between the generated path points and obstacles. This helps to make the planned obstacle avoidance path safer and more efficient. Specifically, by utilizing the distance information of different types of obstacles provided by the monocular camera, the algorithm can adapt the potential field ranges accordingly. This allows the system to cope with a variety of complex obstacle scenes more effectively. After that, simplified modelling of the road using the Frenet coordinate system is used to accurately represent the position and attitude information of the vehicle on the road. Finally, the Robot Operating System (ROS) platform is used to integrate the sensing and planning modules into the intelligent simulation cart for experimental validation [2].

This monocular vision solution has two main advantages. The first point is that the scheme uses an improved RRT path planning algorithm based on an artificial potential field which can plan a safer and more efficient obstacle avoidance trajectory and adapt to the complex and changing road environment. The algorithm may be a superior option overall because it performs well in terms of avoiding obstacles, average sampling, and average amount of samples [1]. The second point is that the program uses the Frenet coordinate system to simplify roadway modelling. This method can better characterize the position and attitude information of the vehicle on the road, thereby solving the problem of avoiding obstacles in curves.

However, they are limited in their efficiency, particularly in large-scale or constantly changing situations, and they face the difficulty of high dimensional space and time complexity. Furthermore, these algorithms exhibit poor performance when dealing with dynamic barriers, and in real-world applications, the pathways they generate could seem unduly idealized [1]. Moreover, the deep learning-based perception algorithm and the improved RRT path planning algorithm have high requirements on computational performance, so it requires careful hardware resource allocation. The medium and long-range performance of the target detection algorithm is good. However, because of the viewing angle and other factors, it still has issues at close range. Furthermore, range algorithms perform worse against barriers that are not directly in front than they do when they are.

2.2. 3D LiDAR SLAM solution

3D LIDAR SLAM technology is based on multi-line LIDAR, and it can be applied to solve the problem of positioning and mapping of large-scale scenes in the field of unmanned driving by following and developing the SLAM algorithm framework based on graph optimization, acquiring more precise environmental information. In the process of mapping, the SLAM framework of graph optimization mainly consists of scan matching, closed-loop detection, back-end optimization, and point cloud map storage representation [3]. The scan matching and closed-loop detection, as the front-end part of the SLAM, obtain the relative pose and map through the sensor and check the pose. Then the local errors are eliminated in the process of back-end optimization, and finally can create the octree map According to the barriers, imaging lidar is mainly divided into spaceborne scanning imaging lidar, airborne scanning imaging lidar, vehicle-mounted imaging lidar and so on. airborne scanning imaging lidar is mainly used for space rendezvous, navigation and imaging of spaceborne earth [4]. It has the merits of long detection distance, a relatively mature system, and high precision reading. At the same time, it is also accompanied by strict constraints on system volume, quality and other characteristics, high requirements for system power, and high costs. Furthermore, airborne scanning imaging lidar is mainly used in terrain mapping, power line patrol and other fields. It possesses a relatively wide and mature application at home and abroad. Its maximum ranging range is 3km ~6km, and the ranging accuracy is high. Finally, the main application of the direction of vehicle-mounted imaging lidar is automotive autonomous driving. Thus, its detection range is relatively low. In comparison, it is more likely to meet the market demand, acquiring good business prospects in response to the low cost [5].

3. Sensors in mobile robot navigation

3.1. Monocular camera

Monocular sensors are heavily used to sense the surrounding environment. In order to create crisp images of the surrounding environment, a camera operates by detecting light emissions from the environment on a photosensitive surface via a camera lens that is placed in front of the sensor [6].

The monocular camera requires only one imaging sensor, so the cost is lower than other sensors, and it has strong compatibility with some mature image processing algorithms to generate clear images.

However, it also has some limitations and challenges in the real situations. Because they don't have native depth information, traditional RGB monocular cameras are inherently more limited than stereo cameras [6]. Monocular camera navigation and image analysis systems are both greatly affected by the environment, with too much or too little light affecting sensor performance.

3.2. Lidar

Lidar is a kind of active detection technology which can acquire 3D spatial information of target efficiently. It uses the laser as the carrier and obtains the range information by measuring the time difference between the transmitted and the echo signals reflected by the object.

There are lots of methods of laser ranging, in addition to directly using the timing circuit to measure the flight time of the pulse, it can also be modulated by the amplitude, frequency, and phase of the emitted laser signal, harvesting the distance information of the target indirectly. At present, the

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commonly used laser ranging technology can be roughly separated into three kinds: direct pulse time-of-flight detection, amplitude-modulated continuous wave detection and frequency-modulated continuous wave detection. Direct pulse time-of-flight detection is to directly measure the round-trip time of the laser pulse from the emission to the scattering of the target back to the radar. In addition, direct pulse ranging technology can be subdivided into linear detection and photon counting detection. The merits of direct pulse time-of-flight detection are long-range and short detection time. Especially with the development and maturity of photon counting detectors, radar systems can realize the measurement of hundreds or even thousands kilometers. Its main drawback is its relatively low-ranging accuracy. The amplitude modulation continuous wave (AMCM) range is measured by detecting the phase difference between the echo and transmitted signals. Different from direct pulse measurement technology, AMCM has a higher accuracy but lower detection time and relatively limited detection distance [5].

3.3. Infrared sensor

Infrared (IR) sensors are devices that detect infrared radiation, which is a type of electromagnetic radiation with wavelengths longer than visible light but shorter than microwaves. It is used in various applications, including temperature sensing, distance measurement, and movement detection. Infrared Sensors and primarily classified into two categories: active and passive infrared sensors. Active IR sensors emit infrared radiation and then detect the radiation that is reflected back by an object. Applications of the active IR sensor could be in proximity sensors, which are in devices like smartphones to detect when it is close to an object, such as a user's face; in obstacle detection, which is widely used in robotics and automation to detect and avoid obstacles; in distance measurement, which is common in various range-finding applications, including industrial and automotive sectors. Particularly in controlled environments, active IR sensors can provide high precision and high accuracy distance measurements compared to other sensors. Nevertheless, it is susceptible to interference, in which other sources of infrared radiation, such as sunlight or heat sources, can interfere with the operation. Passive IR sensors detect infrared radiation naturally emitted by objects. passive IR sensors work better in motion detection, which could be used in security systems, lighting control, or automatic doors to detect the presence or movement of people [7]. However, one drawback of passive IR sensors is that it is limited to movement detection and cannot provide the measurement of distance for stationary objects. To conclude, through the comparison of the two different IR sensors, the active IR sensor would best fit in the idea of a mobile robot navigation system.

3.4. Ultrasonic distance sensor

The ultrasonic distance sensor measures the distance to an object using ultrasonic sound waves. This highlight of distance sensing could be applied in numerous places. The ultrasonic sensor provides a non-contact measurement, which could make it suitable for use with delicate or hazardous materials or conditions. Out of the numerous benefits of the sensor, it is relatively robust and can work well in harsh conditions. Unlike optical sensors, the operation of ultrasonic sensors is not affected by daylight, any changes in lighting, or black material. It offers wonderful non-contact detection with high accuracy associated stable readings in an easy-to-use package from two cm to four hundred cm. However, there are indeed some shortcomings in this sensor. For instance, temperature, humidity, and noises would affect the accuracy of the detection of the distance. Since the ultrasonic sensor works best on hard and flat surfaces, irregular or soft surfaces might scatter the sound waves and also reduce accuracy. Moreover, the effective range of ultrasonic sensors is typically limited to a few meters, which makes them less suitable compared to other more effective devices for long-distance measurements which a robot would require for navigation.

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4. Mobile robot navigation solution optimization and suggestions

4.1. Sensor optimization in the navigation solution

In optimizing mobile robot navigation solutions, enhancing sensor performance is crucial to achieving reliable and efficient autonomous navigation in complex environments. For the monocular vision solution, optimization can focus on improving the accuracy of depth estimation and obstacle detection. This can be achieved by integrating more advanced machine learning models, such as deep convolutional neural networks (CNNs), to better interpret visual data and reduce errors caused by environmental factors like lighting variations. Additionally, enhancing the processing power and speed through hardware acceleration, such as using GPUs or dedicated AI processors, can mitigate the high computational demands of deep learning algorithms, which can ensure real-time performance.

LIDAR optimization involves refining the SLAM algorithms to enhance mapping accuracy and reduce latency. For instance, improving the integration of GPS data with the LIO-SAM algorithm can enhance long-term mapping reliability and navigation precision in dynamic environments. Meanwhile, advancements in LiDAR sensor technology, such as increasing the range and resolution while reducing power consumption and cost, can further improve obstacle detection and environment mapping, making LiDAR more accessible for a broader range of applications.

For ultrasonic sensors, optimization should address the limitations in range and accuracy, particularly on irregular surfaces. Incorporating advanced signal processing techniques and adaptive filtering can enhance the sensor's ability to handle diverse surface textures and environmental conditions. Furthermore, integrating ultrasonic sensors with other types of sensors, like infrared or LiDAR, can provide complementary data and can improve overall obstacle detection and distance measurement capabilities.

4.2. Navigation solution combined with machine learning

The navigation solution can be improved by using deep reinforcement learning. First, as a model for the decision-making process, a deep neural network is created using a vast quantity of driving trajectory data. The model is trained and optimized using the deep Q-network and additional techniques, enabling the car to figure out the best navigation option. In order to enhance the generalization capacity, transfer learning and online learning techniques are used to optimize the model continuously. The reason why navigation solutions can be combined with machine learning is there is a significant nonlinear link between the numerous complicated components that go into intelligent trolley path planning, including vehicle dynamics, and sensing of the environment. Machine learning algorithms are highly adept at extracting such hidden patterns and regularities from data, whereas traditional rule-based algorithms struggle to capture such intricate nonlinear patterns. The intelligent vehicle's perception, decision-making, and control abilities in complicated situations are greatly improved by this machine learning-based method, which also increases the performance of autonomous navigation [8].

5. Conclusion

The application of mobile robots is more and more close to people’s life, like the transport robots that transport supplies on the military battlefield, driverless vehicles in the community, and vacuum cleaners in homes. Therefore, the robots’ requirements for the ability of sensors in different environments directly correspond to their self-navigation ability. At the same time, with the development of science and technology, how to integrate sensors and algorithms to improve the efficiency of robot navigation has become a challenge. This paper is based on monocular vision, laser radar, ultrasonic radar and other sensors to conduct in-depth research. The monocular visual ranging solution has the advantage of having a more efficient obstacle avoidance trajectory and adapting the complex environment, but it also maintains the drawback of limited efficiency in the algorithm. Aiming at the LIDAR scheme, this paper proposes to apply the 3D LIDAR SLAM algorithm, facilitating the distance measurement and the forming of image which improves obstacle avoidance path planning. However, this solution also has the open-source problem of the algorithm and the cost problem. Subsequently, this paper introduces the

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principles and advantages of monocular vision, laser radar and ultrasonic radar. Specifically, the cost of monocular vision is low, and it has a strong compatibility with some mature image processing algorithms to generate clear images. The characteristics of small size, high precision and fast response speed facilitates the wide application of laser radar in many fields. For the ultrasonic radar, it is relatively robust and can work well in harsh conditions. Lastly, after combining all the above information and in-depth research, this paper puts forward two optimizations and suggestions for mobile robot navigation schemes, merging multiple sensors and combining them with machine learning.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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