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Core Technologies and Applications of Robotic Navigation Systems

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Abstract. In recent years, robotics navigation has become a core component of autonomous navigation, enabling robots to sense their environments, localise themselves, and plan safe and efficient paths autonomously. This paper explores the core and fundamental technologies, including LiDAR, computer vision, infrared sensors, Simultaneous Localisation and Mapping (SLAM), GPS with RTK, path planning algorithms, vehicle-to-everything communication, and Direct Memory Access (DMA). It also introduces some typical applications of robotics navigation and its core technologies. Despite the widespread use of robotics navigation and its significant improvement, numerous challenges and difficulties are faced. These include the difficulty of navigation, especially in unknown or dynamic environments. The heavy load of dealing with multiple data streams from sensors is also a problem that should be overcome. Moreover, the social and ethical considerations, such as safety and trust in a human-shared area, remain unsolved. The future development of robotics navigation will focus on Artificial Intelligence combined with 6G communication and edge-cloud computing. Establishing ethical standards will also be essential for the future development of robotics navigation.

Keywords: Robotics Navigation, Core Technologies, Autonomous Systems, Path Planning Algorithms, Multi-Sensor Fusion

1. Introduction

Many areas, including mining, construction, agriculture, and air applications, have environments that are often harsh and unstructured. Such environments could also threaten workers' lives. And improve the cost of the labour force. In real life, the growing demand for automation, efficiency, and safety is leading to the unavoidable trend for the widespread use of robots. However, the situations are complex and dynamic, so the robotics navigation system with the core technologies has played an essential role in robotics and reduced the cost for the industries compared to the regular navigation system.

Robotic navigation is a foundational component of modern autonomous systems, enabling mobile robots to perceive their surroundings, localise themselves, and plan efficient paths in dynamic environments. There are numerous core technologies used in the systems, such as environment perception, localisation, mapping, path planning, and motion controllers. The robotics navigation will face multiple challenges that could lead to dangerous and ineffective navigation without these

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core technologies. For example, the environment should be perceived accurately and quickly for robots to avoid obstacles and navigate effectively. However, without advanced sensors and perception algorithms, obstacles cannot be detected in time, especially in dynamic and complicated environments, leading to collisions [1]. The algorithms are as crucial as sensors, too. The traditional navigation approaches often lack the flexibility to adapt to the dynamic environment effectively, which may increase the risk of collisions and cause navigation errors [2]. So, these core technologies not only improve the efficiency of robotics navigation but also reduce the errors during navigation.

The development of robotics navigation has sharply progressed in recent decades. In the 1960s, early robots like Shakey were produced for limited movement and planning [3]. In the 1980s, early navigation was occupied and it was reactive, which involved following the light or a line to reach the goal [4]. The application of the Simultaneous Localisation and Mapping (SLAM) leads to autonomous navigation, which enhances its ability in various areas [5].

This paper will introduce the core technologies applied to robotics navigation, providing definitions and explanations of their functionality. Then, give some example applications for robotics navigation to conclude recent navigation developments, analyse their challenges, and discuss future developments, thereby providing a comprehensive understanding of the field.

2. Core technologies

2.1. LiDAR technology

2.1.1. Definition

LiDAR technology, whose full name is Light Detection and Ranging technology, is a significant technology for robotics navigation.

This advanced remote sensing technology can measure the distances to objects such as obstacles through laser light. Such light could be emitted and then returned to the same position. So the system could calculate the distance between the robot and obstacles through the time that it takes for the pulses to travel to an object and back to the sensor, which is also called 'time-of-flight (ToF) [6].

2.1.2. Function

This technology comprises three main parts, each with a specific function. Firstly, the laser scanning, which is the most essential part of the system, can measure the distance accurately. Then, this system would use the inertial measurement units (IMUs), whose function is to determine the velocity and position through measuring the acceleration, increasing the accuracy of the collected data [7]. Finally, the outputs of the LiDAR technology are in the form of 3D point clouds, which are dense collections of 3D points, revealing a high-detailed scanned environment [4].

So the LiDAR technology plays a pivotal role in robotics navigation to enhance the efficiency and reliability of autonomous systems through these three main functions.

2.2. Camera and computer vision

2.2.1. Definition

Computer vision, a subfield of artificial intelligence, enables computers to interpret and understand visual information, like human vision. The visual data from images or videos captured by cameras can be analysed, and significant elements such as location, object presence, and three-dimensional

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scene layout can be extracted using computer vision algorithms [8]. The primary goal of computer vision is to control systems.

Cameras are a type of equipment that records light from an image to capture visual information. Cameras can also interpret scenes, selecting and emphasising certain elements [8].

2.2.2. Function

The integration of cameras and computer vision significantly contributes to the robotics navigation area, offering numerous benefits.

This technology can reduce the cost of robotics navigation because, compared to laser scanners and other advanced sensors, these cameras are low-cost sensors but provide numerous environmental information [9].

Additionally, since such technology is vision-based, it would have advantages if an indoor environment with weak GPS signals surrounded it. It can provide a more accurate map for robotics navigation than traditional navigation [10].

2.3. Infrared sensors

2.3.1. Definition

Infrared radiation is a kind of electromagnetic radiation whose wavelengths are longer than visible light but shorter than microwaves. The infrared sensors will detect this radiation emitted by objects and measure the temperature, which has a positive linear relationship with the radiation. These sensors can measure data from a distance without physical contact, enabling robots to observe objects that are impossible to reach, rather than relying on traditional navigation methods [11].

2.3.2. Functions

The primary function of the infrared sensors is proximity estimation and obstacle avoidance, which help robots detect and avoid obstacles in real-time, ensuring the security of robots [12].

Besides the simple distance measurement, these sensors play an essential role in locating and mapping, even though their short range requires an incremental mapping approach. However, the line-based maps can be structured through their ability to measure distances based on back-scattered light from objects [13].

The infrared sensors play a significant role in robotics navigation with their obstacle avoidance and fast response times. Combined infrared sensors with other techniques can improve robotics navigation.

2.4. SLAM

2.4.1. Definition

Simultaneous Localisation and Mapping (SLAM) is essential for robotics navigation. Some core sensors are used in the SLAM. The cameras play a crucial role in visual SLAM by capturing images to create a map. The distance can be measured precisely by LiDAR sensors, especially in a poor light environment [14]. The SLAM can identify essential data components and extract valuable data from sensors to build maps and locate themselves through using advanced algorithms [15]. It can also improve the accuracy of maps such as RANSEC and Levenberg-Marquardt [16].

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2.4.2. Functions

The environment can be structured using SLAM, even in an unknown environment. The position of the robot can be located through this function. Environmental sensing is fundamental for autonomous robotics navigation because it allows the robot to understand its environment and interact with it [17].

The SLAM technology can detect obstacles to adjust the dynamic environment to improve robotics navigation [18].

Moreover, the SLAM will be integrated with the sensors to collect and verify data, thereby enhancing accuracy [19].

2.5. GPS with RTK

2.5.1. Definition

The Real-time Kinematic (RTK) GPS can increase the accuracy of robotics navigation by improving the precision of Global Navigation Satellite Systems (GNSS).

The system can correct the wrong data. The data from the base station and rover would be compared during this process to detect the errors. The errors will be amended to improve the accuracy [20].

2.5.2. Functions

RTK GPS provides centimetre-level accuracy. The measurement is essential for accurate positioning. The localisation is significant for the navigation.

The GPS can provide the heading information with RTK. This component is critical for improving the accuracy of navigation. To achieve improved performance, it will be combined with other sensors, such as IMU.

Additionally, RTK GPS can combine with the visual SLAM to improve navigation, especially in indoor navigation that has a weak GPS signal, addressing the limitations of single positioning technologies.

Moreover, due to the techniques employed in the technology, such as asynchronous error correction, it can maintain high-level accuracy despite interruptions in base station data.

2.6. The path planning algorithms

2.6.1. Definition

The planning algorithms can utilise the code and combine sensor data to identify the optimal solution or the approach that meets specific conditions. These solutions can provide a basic platform for robots to reach the final goal.

2.6.2. Functions

The process to get the goal is challenging. Some obstacles should be avoided. The researchers should also consider the efficiency and specific requirements. So, robotics navigation must fulfil these functions. They are fundamental elements for navigation [11].

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Such algorithms can also provide a shorter path by combining with the Dynamic Window Approach (DWA) than without the technique. The path planning algorithms are good at dealing with a static environment. However, the dynamic environment is the weakest for them. The DWA technology, on the other hand, can adjust speed and direction to avoid obstacles in dynamic environments. Because of the advantages and disadvantages, the accuracy can be improved despite the advantages and disadvantages.

Deterministic algorithms can determine the shortest path in a static environment, whereas probabilistic algorithms can adjust to a dynamic environment. The Hybrid approach is significant for robotics navigation. It has better performance than traditional navigation.

2.7. Vehicle-to-everything technology

2.7.1. Definition

The Vehicle-to-everything (V2X) technology is a communication system that is designed to build interactions between vehicles and various components of the transportation infrastructure. Not only vehicles, but also traffic lights, can be connected. This characteristic enables this technology to play a crucial role in ensuring navigation safety and efficiency.

2.7.2. Functions

The communication systems can direct communication between vehicles and share critical data such as speed, direction, and braking behaviour. It can prevent collisions and improve traffic safety.

The middleware and operating systems are also significant for navigation. The Robot Operating System (ROS), for example, is a middleware platform that aims to support numerous services such as path planning, localisation, and perception, which are crucial for robotics navigation. The simulation frameworks can build a realistic virtual environment to provide a test background to reduce the need for real-world testing, which often costs a lot.

The advanced communication technologies, such as 5G networks, can provide the necessary bandwidth and reliability for real-time data exchange to apply to the area of collision avoidance and navigation safety.

2.8. DMA technology

2.8.1. Definition

The Direct Memory Access (DMA) technology is a systems that allow the hardware subsystems within a computer to access the main system memory without relying on the central processing unit (CPU), which is crucial for improving the efficiency and performance of data transfer operations.

2.8.2. Functions

The sensors and other peripherals can transfer data directly to memory without the CPU, which leads to real-time processing for detection and avoidance. This function also allows massive amounts of data from sensors, such as LiDAR or cameras, to be stored in memory, positively influencing the building of maps and localisation.

The tasks for loading data transfer are removed from the CPU, which is offered by DMA, leading to a decrease in computational load on the CPU and allowing it to focus on decision-making

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processes and higher-level navigation algorithms to improve the efficiency and performance of the navigation systems.

Additionally, the integration of various sensors and actuators could be supported by DMA technology through managing data flow between these components and the system memory, which is vital for robots' perception and action modules, leading to smooth and coordinated navigation [1].

3. Applications

3.1.1. Amazon Scout robot delivery

The Amazon Scout robot is designed for autonomous package delivery, and some core technologies of robotics navigation have a significant influence on it.

GPS and SLAM technologies are combined to give a more accurate navigation and localisation than traditional technologies. The GPS can provide precise positioning data for outdoor navigation. The Inertial Navigation Systems (INS) can help navigation when the GPS signal is weak by using accelerometers and gyroscopes to track the robot's movements. However, in dynamic and unknown environments, the GPS and INS cannot provide any help. Still, the SLAM can build maps around robots and provide optimal paths for them to navigate accurately.

Robots may encounter more difficulties and challenges than typical robots because they frequently operate on sidewalks, which feature a greater variety of obstacles, such as garden tools or outdoor toys. However, the advanced computer vision technology and a modest sensor array are used to avoid the barriers in time and ensure proper performance.

Robots are also trained in a digital environment to test their skills. This environment gives more details, and even the individual blades of glass can be designed. The scout team used to add October leaves to a sidewalk, enabling the robots to learn that things have changed compared to April and be guided to another decision.

3.2. Zipline drone medical supply delivery system

Zipline drones play a significant role in medical supply delivery, especially in poor areas such as Africa. It has more advantages than traditional transportation. The drones can easily access hard-to-reach areas and are unaffected by weather conditions.

GPS and INS are used to ensure precise delivery and navigation within a target area of five meters in diameter. This combination is essential to maintaining the accuracy for navigation and delivery, especially in areas with poor road infrastructure.

The AI-driven perception and real-time monitoring also significantly aid in the delivery processing. These two technologies could ensure the reliability and safety of drones; not only can they plan the flight path autonomously, but they can also achieve real-time control of the drone to avoid obstacles and map the surroundings in real-time.

However, most of the paths the drones followed are pre-programmed to ensure accurate navigation for drones in challenging terrains. The 3D satellite maps and a detailed ground survey would reach this goal.

LiDAR and edge computing technologies can provide environmental data to help navigation when GPS does not have signals in a complex environment.

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3.3. Waymo autonomous taxi

Waymo is a company that focuses on developing autonomous taxis, and it launched its commercial autonomous taxi service, which is beneficial for autonomous taxi development.

Several core technologies of robotics navigation are used on the taxi. The sensors would be put on these vehicles to provide accurate data for the environment surrounding the cars to avoid obstacles. The accuracy and safety of autonomous navigation could be improved twice by combining the data from different sensors.

Also, the SLAM technology is used to structure maps for surrounding environments, while localising the vehicles by keeping track of their location without GPS. It benefits significantly in unknown or dynamic environments.

Some advanced path planning algorithms, such as A-star algorithms, are applied to the taxis to plan the best paths to the goal while avoiding obstacle.

The vehicles' speed and directions can be autonomously adjusted to ensure comfortable and safe driving based on the real-time data from sensors and the adaptive control system.

3.4. Otto autonomous Forklift

The Otto autonomous Forklift is a massive progression for material handling technology. It improves efficiency and safety in warehouse settings by eliminating the need for human participation in processing, thereby reducing labour costs and minimising the risk of accidents that can compromise efficiency and security.

Because of the basic requirement for accurate movement, using the advanced control systems, such as PID technology, is the cornerstone of material handling safety and efficiency.

The autonomous loading and unloading, which is an essential movement for the forklift, can enhance its safety and efficiency through the vision sensor-based system.

The IoT technology, similar to the vehicle-to-everything technology, can ease the operations of the forklift and improve its security. This advanced technology empowers forklifts to lift efficiently and transport pallets, as well as load and unload cargo, and convey goods within designated areas with precision and ease.

4. Conclusion

The core technologies of robotics navigation are the most significant elements. These components enable robots to sense their surroundings, construct environmental models, and generate paths for autonomous movements. Their deployment in applications ranging from autonomous delivery to industrial logistics has demonstrated significant improvements in efficiency, safety, and adaptability.

Despite having lots of advantages, robotics navigation still faces numerous challenges. Although the SLAM technique provides a basic way to structure the map for unknown or dynamic environments, it remains challenging to sense complex environments, such as underwater areas, and maintain accuracy and stability for navigation. It also struggles with localisation in environments without GPS signals or feature-sparse areas, where advanced SLAM technologies encounter issues such as drift, uncertainty, and long-term consistency. Moreover, robotics navigation needs to integrate multiple sensors and process their data in real-time, which is computationally intensive and requires efficient algorithms to ensure its reliability. Social and ethical dimensions pose a problem, mainly when robots operate in shared spaces with humans. They must operate within a trustworthy decision-making framework to prevent causing discomfort or accidents.

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However, in the future, as artificial intelligence continues to develop, algorithms based on Artificial Intelligence can further enhance the performance of decision-making, path planning, and perception. It can also combine with machine learning, making it more reliable in complex and dynamic environments. Meanwhile, the development of 6G technique can enhance the ability of real-data exchange, supporting multiple robots' cooperation. The global standards, ethical frameworks, and laws should also be established to ensure the safety, transparency, and social reliability for robotics navigation.

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