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A review of the opportunities and challenges for SLAM application

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Abstract

Simultaneous localization and mapping (SLAM) technology is essential for autonomous navigation and motion control in robotics and computer vision, with applications in autonomous driving, mobile robotics, and augmented reality. Despite its importance, existing studies often focus on specific SLAM aspects, lacking comprehensive reviews of vision-based SLAM applications. This article aims to fill that gap with two major objectives: to use VOSviewer software to analyze SLAM-related keywords, identify current research hotspots, and predict future research trends. The research results indicate the significant potential of SLAM technology in automatic parking and driving trajectory memory, emphasizing the need for continued research to enhance system accuracy and efficiency. Key application areas include parking lot mapping, localization and navigation, object detection, and mission planning. VOSviewer analysis reveals that SLAM is closely

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linked with artificial intelligence, deep learning, and machine learning. The integration of these technologies has advanced SLAM development, especially in augmented reality and object recognition. Future SLAM trends may involve more sophisticated algorithms to address existing challenges and broaden practical applications.

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Keywords: *SLAM, Deep learning, Autonomous navigation, Computer vision, Semantic, Intelligent era.*

1. Introduction

In recent years, there has been a growing interest in simultaneous localization and mapping (SLAM), which is the process of both determining the sensor's own position (localization) and creating a model of the environment (mapping). This involves using various sensors to explore unknown environments, where the system repeatedly observes and checks the map features as the sensors continue to move. By combining the environment map through the intersection calculation of positioning and external environment, the system can gradually construct the indoor map point by point as the map car travels through all the indoor paths.

SLAM technology primarily employs a fusion of robot motion prediction and environmental sensor estimation, with the most commonly used environmental sensor being distance sensors such as ultrasonic and LIDAR scanners. By using a variety of algorithms, calculations, and other sensory data, SLAM software systems allow robots or other vehicles (such as drones or autonomous cars) to map out routes in unfamiliar environments while also identifying their own position in that environment. This self-localization method allows for mapping of areas that may be too small or too dangerous for human exploration. From household vacuum robots to cars, simultaneous localization and mapping technology has been applied to various fields. With this technology becoming cheaper and more research being conducted on the topic, many new practical applications of SLAM are emerging across a wide range of industries.

On the other hand, due to the long development history of SLAM technology, and according to the research by Wang [1], the global SLAM technology market is expected to grow significantly with a compound annual growth rate of 49.41% from 2020 to 2030. One of the main reasons for the rapid growth in the SLAM market is the breakthrough in positioning technology in recent years. It is evident that SLAM will continue to develop rapidly in the future and will be applied to functions such as automatic parking or automatic tracking of driving paths.

Due to the continuous growth of the SLAM market, not all places have ready-made maps available for use in practice. Therefore, this study reviewed relevant literature on the application of SLAM to automatic parking or automatic trajectory memory in driving, and explored how SLAM technology can be used to solve practical problems in actual applications. By understanding the practical applications of SLAM and the problems it can solve, the research results can be provided as a reference for relevant industry units to improve the practical application of SLAM.

Furthermore, this article has two research purposes. The first is to use VOSviewer software to examine keywords related to SLAM technology, aiming to gain insight into current research hotspots. The second is to predict future research trends.

This paper proceeds as follows: the first section introduces the background and purpose of the research. The second section reviews the technologies related to SLAM. The third section describes the methods used in this study. The fourth section analyzes the research results. The final section presents the conclusion and recommendations of this study.

2. Reviews the technologies related to SLAM

In 2016, Cadena et al. proposed a comprehensive three-stage development framework for SLAM, which encompasses a theoretical foundation, algorithmic evaluation, and a focus on advanced robust perception, with particular attention currently directed towards robust perception [2]. They offered an extensive review of the progression of vision-based SLAM algorithms from 2010 to 2016, accompanied by a toolkit designed for novice practitioners. Yousif and Hoseinnezhad [3] delineate the essential framework of Visual Simultaneous Localization and Mapping (VSLAM) and introduce various mathematical challenges aimed at equipping readers with the knowledge necessary for making informed decisions. Bavle et al. [4] provide a synthesis of recent advancements in robotic SLAM technology, emphasizing the growing emphasis on the comprehension of robotic environments. Servieres et al. [5] conduct a review and comparative analysis of prominent SLAM methodologies, including the integration of visual data and inertial measurements, and summarize significant algorithms within this domain.

Azzam et al. [6] undertake a comprehensive investigation of feature-based methodologies, classifying them according to the visual characteristics inherent in the environment, while also proposing potential challenges and solutions for the advancement of SLAM. References [7-8] present and elucidate various SLAM techniques that employ monocular, binocular, RGB-D, and visual-inertial fusion approaches, addressing contemporary challenges and outlining future trajectories. Reference [9] provides an in-depth examination of the opportunities and obstacles associated with Visual SLAM (VSLAM), encompassing topics ranging from geometric considerations to deep learning, and explores the prospective advancements of VSLAM in the context of semantic applications.

In conclusion, the advancement of SSLAM has undergone three distinct phases, each characterized by specific focal points and contemporary challenges. Although the delineation of these phases is not strictly defined, they represent the progressive development of SLAM over time. SLAM is a methodology employed in the fields of robotics and computer vision, facilitating the creation of environmental maps while concurrently tracking the position of a robot within that environment. This technique has found applications across a diverse range of domains, including autonomous vehicles, mobile robotics, and augmented reality, among others. Recent technological advancements have led to the emergence of novel techniques and methodologies aimed at enhancing the efficiency and accuracy of SLAM [9].

One notable approach in this domain is the implementation of deep learning techniques. Deep learning algorithms have demonstrated efficacy in various components of SLAM, including feature extraction, motion estimation, and depth estimation. In the context of feature extraction, deep neural networks are employed to derive high-level features from visual imagery, which subsequently enhances the SLAM system's capacity to interpret the surrounding environment. Regarding motion estimation, deep learning methodologies can augment the precision of pose estimation by integrating data from multiple sensors, including cameras and inertial measurement units. Furthermore, depth estimation represents another significant application of deep learning within SLAM, with methodologies such as monocular and stereo depth estimation yielding promising outcomes [2][10].

Machine learning is another technology that has been used in conjunction with SLAM. Machine learning techniques can be used to optimize the parameters and models of the SLAM system, resulting in a more stable and robust system. In addition, machine learning can be used for dynamic environments, multi-robot cooperative localization, and other areas, expanding the application of SLAM technology in different fields [11].

In the field of navigation, SLAM has been widely used for autonomous movement and control of robots. With the emergence of new sensors and algorithms, SLAM has become more efficient and accurate in navigating robots in indoor and outdoor environments. The use of 3D sensors such as LiDAR and RGB-D cameras has significantly improved the accuracy and efficiency of SLAM for navigation.

Another technology related to SLAM is augmented reality (AR). AR requires the localization and tracking of objects in the real world, which is also a strength of SLAM. SLAM technology is widely used in AR to help achieve the positioning and tracking of virtual objects, thus realizing a more realistic and immersive AR experience.

In conclusion, SLAM technology has been rapidly evolving, with new techniques and approaches emerging to improve the efficiency and accuracy of SLAM. Deep learning, machine learning, navigation, and augmented reality are just a few of the technologies related to SLAM that are contributing to its rapid development. As the field continues to advance, it is expected that SLAM will continue to play a crucial role in various applications and industries.

SLAM technology plays a crucial role in the fields of robotics and computer vision, enabling autonomous navigation and motion control by simultaneously creating a map of the environment and tracking the robot's position within it. However, the applications of SLAM technology are diverse, including autonomous driving, mobile robotics, augmented reality, and more. In these fields, SLAM technology is constantly advancing and evolving, with new techniques and methods emerging, such as deep learning, machine learning, navigation, and augmented reality. Current surveys and studies predominantly concentrate on facets or technologies associated with SLAM, resulting in a deficiency of a holistic review and synthesis of visual-based SLAM applications. Consequently, there is a pressing need for a thorough review and analysis of visual-based SLAM technology, coupled with an examination of prospective research directions. Such an endeavor would facilitate a deeper understanding of this expanding field for researchers and students, enabling them to engage in more extensive and comprehensive investigations.

3. Methodology

3.1 *Literature review*

Conducting a literature review is a fundamental aspect of interdisciplinary academic research. It plays a vital role in refining and validating existing knowledge, ensuring its accuracy and relevance. However, the process also presents significant challenges, as researchers must stay abreast of emerging studies and critically assess an ever-expanding body of literature. s a result, the literature review has assumed greater significance as a methodological approach in research. It entails a systematic framework for the collection and synthesis of prior studies, as described by Baumeister and Leary [12] and Tranfield, Denyer, and Smart [13].

Moreover, a literature review involves evaluating and synthesizing existing literature on a topic. Steps include defining the research question, conducting a comprehensive search, evaluating literature quality, synthesizing findings, and writing up an analysis including a summary of key findings, evaluation of quality, and discussion of implications and future research.

On the other, with the continuous expansion of the SLAM market, existing maps are not applicable to all scenarios. At the same time, the demand for SLAM technology to be applied to automatic parking or driving for automatic trajectory memory is increasing. With the rapid development of self-driving and automatic parking technology, the demand for autonomous navigation and positioning of vehicles is increasing. The use of SLAM technology can achieve autonomous navigation and positioning, allowing vehicles to travel in unknown or partially known environments and remember their trajectories. Therefore, this study uses a document analysis model to obtain an in-depth and comprehensive understanding of SLAM technology.

3.2 *Data Sources*

We conducted a thorough literature search utilizing the ScienceDirect database from 2018 to 2021 to identify relevant papers. We generated the initial search results using the search string “SLAM,” which was then narrowed down by gradually incorporating keywords such as “automatic parking” or “automatically following driving paths.”

3.3 *Keyword Criteria*

The selection of literature from the database using the English keyword "Visual SLAM" was carried out based on the following principles and 5 steps (Figure 1.):

Step 1. In the first stage of screening, the selection was based on the research topic and abstract.

Step 2. In the second stage of screening, the keywords of the research article were checked to confirm if they were relevant to the study.

Step 3. The articles retrieved from the database were screened one by one based on the title and abstract to exclude duplicate literature.

Step 4. The selected literature was downloaded online in full.

Step 5. The articles, topics, and abstracts were checked again.

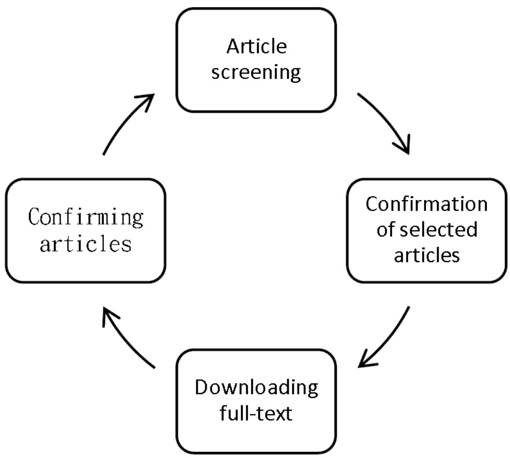

Figure 1

Screening process steps

3.4 *The Literature Classification Results of Visual SLAM*

This study conducted a literature review using the keyword "SLAM" for a duration of 6 years, from 2018 to 2023, and discovered approximately 172 articles. Furthermore, the study conducted a further screening of literature related to specific keywords related to Visual SLAM, resulting in 128 articles. Among them, there were 15 articles in 2018, 15 articles in 2019, 15 articles in 2020, 26 articles in 2021, 38 articles in 2022, and 18 articles in 2023 (as summarized in Table 1).

Table 1

Number of SLAM keyword articles in 2018-2023

Year	Quantity
2018	15
2019	15
2020	16
2021	26
2022	38
2023	18

Due to the fact that this research only focuses on the literature review of indoor parking application related to SLAM keywords, 172 articles were further screened, and finally, about 18 articles were obtained.

3.5 *Data Analysis Software*

Van Eck and Waltman [14] emphasized the flexibility of VOSviewer, a specialized software tool developed for constructing, visualizing, and analyzing bibliometric maps. It is particularly useful for examining diverse types of bibliometric network data.

4. Results Analyze

This section will be divided into three parts. Firstly, it will be clarified that the research focuses on reviewing relevant literature regarding the implementation of SLAM in automatic parking or automatic trajectory memory for driving. Secondly, it will discuss how SLAM technology effectively addresses practical problems in real-world applications. Lastly, it will analyze the future trends for implementing SLAM technology.

4.1 *Literature Review on the Implementation of SLAM in Automatic Parking or Automatic Trajectory Memory for Driving.*

Literature review on the implementation of SLAM technology in automatic parking or automatic trajectory memory for driving has gained significant attention from researchers in recent years. The ability of SLAM technology to create maps and navigate in unknown environments has made it a popular choice in various fields, including autonomous driving and robotics.

Numerous studies have investigated the application of SLAM technology in automatic parking systems. Wang et al. [15] introduced a novel method that utilizes SLAM technology to improve parking accuracy and efficiency. They used a 3D reconstruction algorithm to extract the parking environment's features and then used SLAM to estimate the vehicle's position and orientation.

Apart from automatic parking, the use of SLAM technology in automatic trajectory memory for driving has also been explored. Liu et al. [16] developed an automatic trajectory memory system that utilizes SLAM technology to map and remember the road environment. The system can automatically record and store driving trajectories and recall them when necessary, making it useful for autonomous driving applications.

Other researchers have concentrated on improving the accuracy and robustness of SLAM algorithms for automatic parking or trajectory memory systems. Li et al. [17] proposed a robust SLAM algorithm that can handle uncertain and dynamic environments, which is crucial for driving applications.

In conclusion, SLAM technology has demonstrated significant potential in automatic parking and automatic trajectory memory for driving. Ongoing research in this area is necessary to enhance the accuracy and efficiency of these systems and to promote the widespread adoption of autonomous driving technology [18]-[20].

4.2 *The Effective Application of SLAM Technology in Real-World Problem-Solving*

Based on the review of existing literature, it is evident that there are multiple potential applications of SLAM technology in indoor parking lots. Therefore, this article aims to provide an in-depth exploration of four key areas where SLAM technology can be effectively utilized. These areas are discussed in detail in this section [21]-[27].

1. **Parking lot mapping:** Using SLAM technology to construct a map of the indoor parking lot and obtain the location information of vehicles and other objects inside the parking lot. These maps and location information can be used for autonomous navigation and automatic parking of vehicles.
2. **Localization and navigation:** In indoor environments where GPS signals are unavailable, SLAM technology can be used to achieve vehicle localization and navigation through sensors installed on the

vehicle, such as visual cameras, lidars, ultrasonic sensors, etc., to help vehicles find available parking spaces.

3. **Object detection and recognition:** SLAM technology can be used to detect and recognize objects within an indoor parking lot environment, such as vehicles, pedestrians, and ground markings. This information can be used for intelligent navigation and obstacle avoidance of vehicles.
4. **Task planning:** In busy parking lots, vehicles may need to wait for available parking spaces or perform other actions within the parking lot, such as waiting for other vehicles to leave their spots. SLAM technology can be used for task planning to help vehicles efficiently utilize the resources within the parking lot.

In summary, there are many directions of SLAM technology applications in indoor parking lots, among which parking lot mapping and localization, and navigation are relatively basic and core applications.

4.3 *Future Trends in Implementing SLAM Technology*

Previous studies have applied quantitative methods to calculate the co-occurrence frequency of keywords that represent research content and have used keyword correlations to cluster research themes, thereby tracing the developmental trajectory of subject knowledge. However, such approaches often fall short in illustrating the relationships among studies and forecasting future research directions.

In this section, we employ VOSviewer to examine keyword distribution and analyze their semantic content. The keywords analyzed are extracted from the titles, abstracts, and keyword fields of academic publications. Keyword co-occurrence refers to the frequency with which specific terms appear together within the same documents. By identifying these patterns, we gain insights into prevailing research topics and potential future trends, which may assist researchers in recognizing underexplored areas. This study focuses on analyzing all available keywords to uncover such patterns.

Based on the VOSviewer display, there are a total of 512 keywords. Table 2 shows the top six keywords, with "Artificial Intelligence" appearing the most frequently, with a total of 6 appearances and a high total link strength. "Augmented Reality" is the second most frequent keyword, appearing approximately 5 times, while "Computer Vision" appears 8 times and "Deep Learning" approximately 9 times. "Machine Learning" appears 7 times, and other keywords, such as "Navigation," appear around 5 times.

Table 2

Co-occurrence of all keywords

Keyword	Occurrences	Total link strength	Rank
Artificial Intelligence	6	4.00	1
Augmented Reality	5	1.00	2
Computer Vision	8	2.00	3
Deep Learning	9	2.00	4
Machine Learning	7	2.00	5
Navigation	5	4.00	6

The VOSviewer software generated the map depicted in Figure 2, which exhibits several keywords. Currently, SLAM technology is primarily focused on six major domains, which are explained below:

SLAM and Artificial Intelligence: The development of SLAM is closely related to artificial intelligence, as artificial-intelligence (AI) technologies such as deep learning and machine learning can help address some of the challenges in SLAM, thereby improving the accuracy and efficiency of localization and mapping (as shown in Part 1 of Figure 2).

SLAM technology is widely utilized in augmented reality (AR) due to its ability to localize and track objects in the real world, which is also a crucial aspect of AR. By incorporating SLAM, virtual objects can be positioned and tracked more accurately, resulting in a more realistic and immersive AR experience, as illustrated in Part 2 of Figure 2.

In the field of computer vision, SLAM is a significant application that enables autonomous navigation and control of robots by simultaneously estimating their positions and environment maps. While computer vision is typically used to analyze and understand the content in images and videos, SLAM's ability to perform simultaneous localization and mapping makes it a valuable addition to the computer vision toolkit, as shown in Part 5 of Figure 2.

SLAM and Deep Learning: Deep learning techniques can be used to extract features from visual images, thereby helping the SLAM system better understand the environment. At the same time, deep learning can also be applied to motion estimation, depth estimation, and other aspects, further improving the accuracy and efficiency of the SLAM system (as shown in Part 4 of Figure 2).

SLAM and Machine Learning: Machine learning can be used to optimize the parameters and models of the SLAM system, thereby improving the stability and robustness of the system. Machine learning

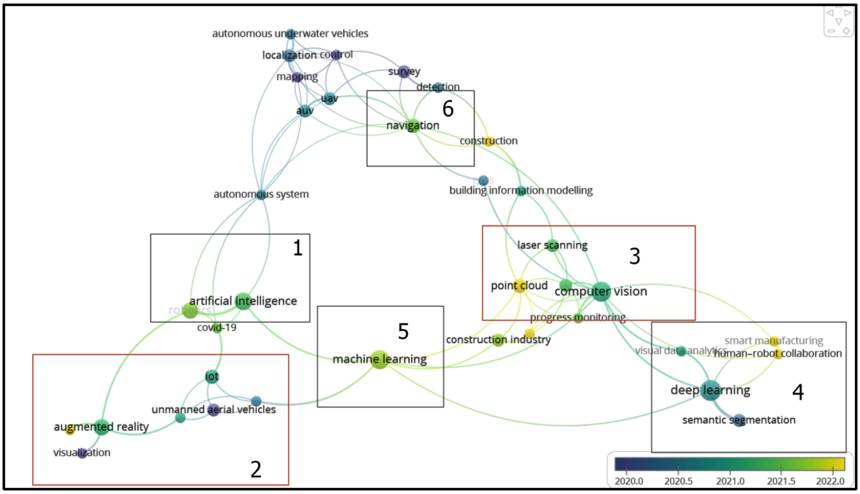

Figure 2

Research distribution of SLAM technology keywords

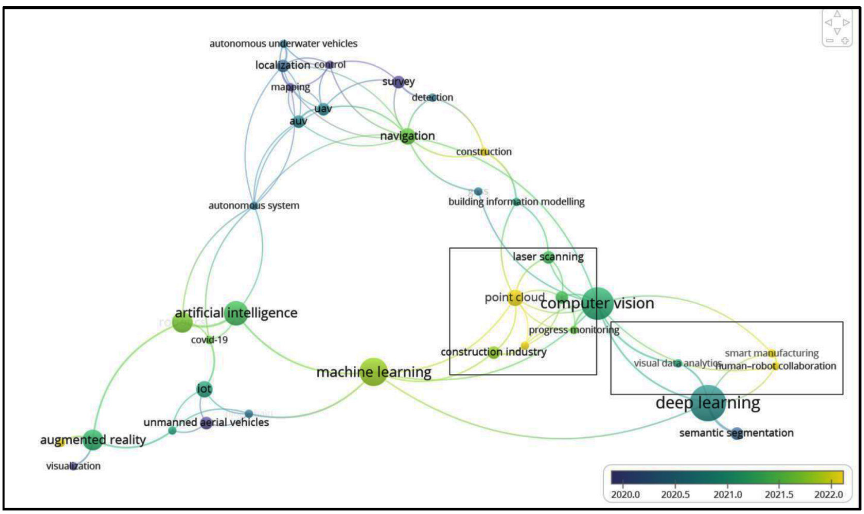

Figure 3

SLAM technology future research trends

can also be applied to SLAM in dynamic environments, multi-robot cooperative localization, and other areas, expanding the application of SLAM technology in different fields (as shown in Part 5 of Figure 2).

SLAM and Navigation: SLAM is widely used in robot navigation and control, thus achieving autonomous movement and control of the robot. In indoor and outdoor environments, robots can use SLAM technology to accurately and efficiently navigate and perform tasks (as shown in Part 6 of Figure 2).

According to the data shown in Figure 3 by VOSviewer, it can be inferred that the future research trends in SLAM technology will be closely related to deep learning and machine learning. This is supported by the fact that these two topics are prominently featured in the literature and research being conducted in this field [28]-[37].

The SLAM technology refers to the simultaneous estimation of a robot's position and its surrounding map without relying on any external reference system. Traditional SLAM methods typically rely on sensor outputs such as cameras, radar, and LIDAR to achieve localization and mapping through data fusion. However, traditional SLAM methods often face many challenges such as data noise, environmental changes, motion blur, etc., which can affect the accuracy of localization and mapping [38][39].

Deep learning and machine learning techniques can help address these challenges. For example, deep learning can be used for semantic segmentation of visual images, extracting useful feature information to aid in SLAM system mapping and object recognition. Specifically, deep learning can learn to extract meaningful features from visual images, such as edges, corners, and textures, to better understand the environment for the SLAM system. Additionally, deep learning can be applied to motion estimation, depth estimation, and other aspects to further improve the accuracy and efficiency of SLAM systems [40]-[48].

Machine learning techniques can also be used to optimize the parameters and models of the SLAM system, thereby improving its stability and robustness. Specifically, machine learning can use training data to learn the parameters and models of the SLAM system, thereby minimizing the errors in positioning and mapping. Additionally, machine learning can be applied to SLAM in dynamic environments, multi-robot collaborative localization, and other areas, thereby expanding the application of SLAM technology in different fields [49]-[51].

5. Conclusion

According to the research in this paper, the application of SLAM technology in automatic parking and automatic driving trajectory memory has shown great potential, and continued research in this field is necessary to improve the accuracy and efficiency of these systems to promote the widespread adoption of automatic driving technology. Effective application of SLAM techniques to real-world problem solving has been discussed in four key areas, including parking lot mapping, localization and navigation, object detection and recognition, and mission planning. In these fields, parking lot mapping and positioning and navigation are relatively basic and core applications.

Secondly, Using VOSviewer to analyze keyword distribution reveals that SLAM technology has close ties with artificial intelligence, specifically deep learning and machine learning. The use of SLAM technology extends to augmented reality with increasing attention on object detection and recognition applications. Additionally, deep learning-based end-to-end SLAM methods have been introduced, which extract features from raw sensor data to perform localization and mapping, bypassing the complex processes of traditional SLAM methods. While these methods can yield higher accuracy in some cases, they require significant amounts of data and computing power. In general, the integration of deep learning and machine learning technologies has been instrumental in advancing SLAM development, and their continued use is expected to facilitate further practical applications. Future trends in SLAM technology may involve exploring its potential in these areas and developing more sophisticated SLAM algorithms to overcome challenges.

Finally, the conclusions and recommendations presented here are based on the model constructed, sample data collected, and research methods used. Therefore, research hypotheses and variations must be considered, and any applications based on these findings must be further adjusted to arrive at more accurate conclusions.

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