A Survey of SLAM based on Submap Strategies

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Abstract. Simultaneous localization and mapping (SLAM) is a technology used to assess the state of robots and build maps. SLAM technology has made amazing progress in the past 30 years and has achieved large-scale real-world applications. It has been widely studied and applied in various industries, such as autonomous driving, the medical field, unmanned aerial vehicles, etc. With the wide application of SLAM technology, SLAM based on sub-map strategy has become a research direction that has attracted much attention. This paper first summarizes the submap-based SLAM technology and emphasizes the research purpose of submap application in SLAM technology. Then, this paper introduces the research status of SLAM based on the sub-map strategy. After that, the advantages and limitations of SLAM systems based on submap strategies are evaluated. Finally, the research results are summarized, the possible improvement direction in the future is suggested, and the practical application direction of the SLAM system based on the sub-map strategy is discussed.

Keywords: Robot; Simultaneous Localization and mapping; Sub-map Strategy; Cooperative exploration and Mapping; Perception.

1 Introduction

SLAM is a method where a robot evaluates its state while automatically building a map for optimal path planning. Submap-based SLAM performs SLAM with possibly small applications of sensing data. Submap-based SLAM can be seen as a graph optimization of traditional SLAM by using different methods such as information theory (IT), control theory and reinforcement learning (RL), filtering, etc., combined with different methods such as lidar, Sensors for stereo vision, or other SLAM optimization methods such as multi-robot, guide the robot to achieve its goal.In the process of path planning, the SLAM robot using the sub-map strategy extracts feature points to form a local map, which is integrated into a global map after reaching a certain threshold. Trajectory planning combines these points with time to generate a path for the robot to follow, and then the robot follows the resulting trajectory to reach the goal position.

SLAM using the submap strategy aims to reduce the burden of front and back end redundant computing.It improve the data processing efficiency while ensuring

Y. Wang (ed.), *Proceedings of the 2024 International Conference on Artificial Intelligence and Communication (ICAIC 2024)*, Advances in Intelligent Systems Research 185,
https://doi.org/10.2991/978-94-6463-512-6_15

relatively accurate path planning. Thus further reducing the time cost of autonomous navigation and environmental exploration. Most SLAM constructs a global map to make the most appropriate path planning. However, some of the data have little impact on path planning, and some of the data will have adverse effects on path planning. These redundant data increase the computational cost and computational time of SLAM, which is not conducive to efficient real-time path planning. Its computational complexity and uncertainty will grow rapidly with the increase of feature points and the expansion of map coverage. SLAM based on sub-map strategy shows a certain prospect in reducing the computational cost. It provides a more accurate solution than filtering methods, which can improve computational efficiency, reduce computational complexity, and improve computational speed. SLAM based on the sub-map strategy tries to extract the feature points in the environment, and when the feature points reach a certain threshold, they are integrated into the global map, so as to achieve more efficient and relatively accurate path planning. The sub-map strategy also shows its unique advantages in combination with other SLAM algorithms.

This paper mainly introduces the application of local submapping technology in SLAM. This paper reviews the papers published in the past and summarizes their research results. There is no systematic summary and analysis of SLAM research based on the local submap method in the past, and the possible research directions and future application prospects are pointed out, and there is no systematic comment and method summary. Compared with previous works, this paper provides a deeper exploration of the summary evaluation, methods, limitations, future prospects of SLAM based on local submap methods.The review proposes innovative and in-depth qualitative features.It’s particularly valuable for emerging researchers.

2 State of the Art of Submap-based SLAM

In order to have a better understanding of SLAM based on sub-map strategy, this paper is divided into three sub-modules according to its optimization direction from three perspectives: recognizing the target location, the best action execution, and the number of robots: 1.Sensor optimization 2.Algorithm optimization 3.Robot cooperative optimization The research status of SLAM based on submap strategy is comprehensively introduced.

2.1 Sensor Optimization of SLAM Based on Sub-map Strategy

In SLAM based on a sub-map strategy, in order to better recognize the surrounding environment, the common sensors include cameras (including monocular cameras, binocular cameras and depth cameras RGB-D) and lidar. Among them, lidar and depth camera RGB-D are common directions for sensor optimization. Gu P,Zhou F, and Yu D combined RGB-D with the sub-map strategy and inserted 3D point cloud into the sub-map, which overcame the problem that the traditional camera needed to consume additional computer resources to obtain the depth image. The lidar compensates the cumulative error in the sub-map strategy [1]. Yang D,Bi S, and Wang W tightly coupled the information of RGB-D and two encoders, eliminated dynamic pixels, and used keyframes to realize the construction of sub maps in dynamic and static [2]. Schleicher D,Bergasa L M, and Ocana M used wide-angle stereo cameras and standard low-cost GPS as sensors to divide the map into local submaps for vehicle pose recognition [3]. Pinies P,Paz LM, and Galvez-Lopez D used a trocular camera and a continuous spanning tree to update the submap in real time [4]. Nie F,Zhang W,Yao Z applied Rao-Blackwellized Particle Filter (RBPF) lidar SLAM, and the efficiency and accuracy of its loop detection depended on the segmentation of the submap. It can be drawn that the sensor optimization of SLAM based on sub-map strategy of RGB-D camera and lidar has certain research value. Compared with the traditional monocular and binocular cameras, RGB-D camera can better adapt to the dynamic environment, reduce the consumption of computing resources, and lidar can reduce the cumulative error, which is suitable for large-scale mapping. The application and combination of the two can make the submap-based SLAM more accurate and efficient [5].

2.2 Algorithm Optimization of SLAM Based on Sub-map Strategy

In SLAM based on sub-map strategy, in order to perform actions better, many related algorithms have been proposed. Sub-maps are applied in combination with filters: Pinies P,Paz L M, and Galvez Lopez D proposed CI-Graph SLAM, which performs a single propagation from the current map to the old submap along the spanning tree to update the old submap at any time to realize the dynamic update of the map [3]. Nie F,Zhang W, and Yao Z adopted a segmentation algorithm to reduce the error within the submap by splitting the submap with higher scan matching error [5]. Huang S and Wang Z proposed the Exact Sparse Extended Information Filter (SLSJF) for local subgraph connection, which applies the Extended Information Filter (EIF) to fuse the submaps so that the information matrix associated with the SLSJF is completely sparse. The sparse structure is combined with the novel state vector and covariance submatrix recovery techniques, which greatly improves the computational efficiency [6]. Fairfield N, Wettergreen D, and Kantor G proposed a new real-time hierarchical (topological/metric) SLAM system that divides the entire map into local submaps for vehicle pose recognition, uses a Bayesian approach for top-down 3D mapping, and uses a Bayesian approach for 3D mapping. Adding MLR algorithm with other advanced SLAM to reduce the error [7]. Schuster M J,Schmid, and Brand C adopted a novel graph topology and used the sub-map strategy to improve the computational efficiency [8]. Wang S X R applied the VSLAM algorithm based on RGB-D camera combined with submap mapping to map, and inserted 3D point cloud into the submap to complete real-time map construction [9]. Xiong H,Chen Y, and Li X improved the accuracy of submap-based graph-SLAM by making the cumulative error of submaps bounded by additional criteria [10]. Zheng B and Zhang Z combined EKF-SLAM with local submaps to reduce the computational data [11]. Yuan J,Zhang J,Ding S based on Kalman filter, used PROPET algorithm to further integrate the fusion results of sparsely distributed multi-sensor nodes and the SLAM results of the robot into the local submap, and used the constrained local submap filter (CLSF) to project the submaps and fuse them into the global map. The localization accuracy is significantly improved. It can be concluded that the research of the algorithm improves the sparsity of the sub-map, the accuracy in the dynamic environment, and reduces the cumulative error. It is well combined with the advantages of improving the computational efficiency and calculation amount of submap [12].

2.3 Multi-robot Cooperative Optimization of SLAM Based on Sub-map Strategy

In SLAM based on sub-map strategy, multi-robot cooperation is also an important research direction. Fernandez-Madrigal J A,Sanfeliu A,Andrade-Cetto J proposed a multi-robot filter framework based on local sub-map method for SLAM of robots. They adopted the idea of a distributed filter, where the local submap is used as input to the filter and the local map is updated based on the measured data. Then, through information transmission and fusion, the state synchronization and map consistency between multiple robots were realized. This method has achieved good results in the experiment, which proves the effectiveness of the local submap-based method in the synchronous localization and mapping of multi-robots [13]. Grzonka S,Rybski P, and Cremers D proposed a multi-robot SLAM method based on local submaps to deal with localization and mapping problems in dynamic environments. They obtain a model of the environment by using features extracted from moving objects and integrating it into a local submap. Then, by correlating and matching the local sub maps, the synchronous localization and mapping between robots are achieved. The proposed method shows good robustness and accuracy in complex dynamic scenes [14]. In addition, the multi-robot active synchronous localization and mapping method based on local sub-maps can also be applied to other fields. Karaman S,Fink J, and Kumar V applied the proposed method to a multi-UAV system to achieve cooperative detection and monitoring tasks among Uavs. They improved the detection efficiency and accuracy of the system by maintaining and updating local submaps to achieve simultaneous localization and map construction among Uavs [15].

3 Statistical analysis of research based on sub-map strategy

Table 1 summarizes the selected articles by sensor type, SLAM method, number of robots, algorithm application, and publication year. Figure 1 shows the annual distribution of SLAM articles based on local submaps from 2008 to 2024. After collating the data in this paper, it is found that in most SLAM based on the local submap strategy lidar (33%), RGB-D (25%) camera sensors are used as the main input data source for extracting corona and images. There has been an increase in sensor fusion research between laser sensors and vision sensors.

Novel filter applications (26%), innovations to EKF-SLAM (41.6%), V-SLAM applications (25%) The review concludes that the combination of the local submap strategy and EKF-SLAM is relatively robust compared to the more efficient and less memory consumption new SLAM methods. Ensuring the high applicability of the proposed solution in the simulated environment. In the case of robust research on EKF-SLAM, research on V-SLAM based on local submaps has also grown.

In the related research, the proportion of single robot is 63%, and the proportion of multi-robot collaborative research is 36%. The single-robot SLAM based on local sub-map with low cost is still the mainstream of research. Only 21% of the research results have been applied to real robots, and the remaining 79% of the research results have not been applied to real robots. The application of real robots has increased. In summary, such research results are encouraging, improving the accuracy and efficiency of SLAM, increasing computational efficiency, reducing computational complexity, increasing computational speed, and enhancing real-world relevant applications.

Table 1: Statistics of sensor, SLAM method, number of robots, Real robot applications,year of articles.

Articles	Year of publication	Sensor	SLAM method	Algorithm Application	Number of robots	Real robot applications
1	2008	/	/	SLSJF(filter)+EIF(filter)	/	There is no
2	2010	/	SegSLAM	Rao-Blackwellized(Particle filter), Evidence network	single	There is no
3	2018	High frequency vision sensor	6D SLAM(vision-based)	Novel graph topologies	more	There is no
4	2020	Lidar and RGB-D camera	V-SLAM	laserSLAM algorithm	single	There is no
5	2019	Vision sensors	EKF-SLAM	Introduce a new threshold	single	There is no
6	2019	RGB-D camera	V-SLAM	Tight coupling eliminates dynamic pixels and introduces key frames	/	There is no
7	2017	Multiple sensors	EKF-SLAM	PROPET algorithm, Kalman filter, local submap filter CLSF	single	There is no
8	2009	Wide-angle stereo	EKF-SLAM, advanced	MLR, Bayesian approach	single	There are

		camera, standard low-cost GPS	SLAM			
9	2010	Trinocular camera	Cl-Graph SLAM	Build a submap graph and a spanning tree for that graph	/	There is no
10	2020	Lidar and RGB-D camera	/	Local submapping, loop closure detection, global mapping	single	/
11	2020	LIDAR	RBPF lidar SLAM	LCPF loop detection, dynamic submap segmentation	single	There are
12	2018	Laser sensor	EKF-SLAM	Submapping-based graph-SLAM, the new standard	/	There is no
13	2015	/	/	Distributed filter	more	There is no
14	2018	Vision sensors	Multi-robot SLAM	Extracting environment models, matching and correlating	more	There is no
15	2018	Vision sensors	EKF-SLAM	Cooperative detection and monitoring	more	There are

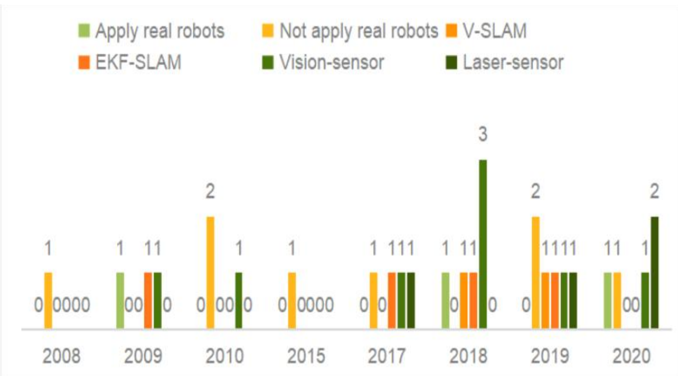

Figure 1: Statistics for real robots applying , sensor using.

4 Results and Discussion

Through the literature review and analysis of SLAM based on local submap strategy, this paper reveals the research progress, main challenges and potential research directions in this field. Although the submap strategy has shown its unique advantages in SLAM, such as improving computational efficiency, reducing the complexity of data association, and adapting to large-scale environments, there are still several limitations in current research.

First of all, there is limited consideration of real-time analysis of dynamic environments in related research. As mentioned above, SLAM based on local submap method may encounter dynamic obstacles in some unknown environments, such as some dynamic scenes in real life, but the existing research lacks consideration of dynamic environments. Therefore, future research needs to pay more attention to how to achieve more robust submap-based SLAM in dynamic environments. Gu P,Zhou F,Yu D. RGB-D cameras still have typical limitations in large-scale indoor scenes, mainly reflected in that dynamic objects bring additional errors and even lead to operation failure. Some inevitable changes in lighting, human movement, and object movement can lead to the loss of position and pose of the mobile robot, which in turn leads to inaccurate mapping. The weakness of lidar is that it may lead to the loss of a large amount of environmental information for data only obtained from a certain spatial level, which will reduce the accuracy of map construction. Both can be combined in research, or loop-back testing can be performed to verify the accuracy [1].

Secondly, although the submap-based SLAM method has advantages in computational efficiency and data association, it still faces challenges in ensuring map consistency and completeness. Loop closure is very important in SLAM, which can ensure the consistency and integrity of the map, and further improve the accuracy of the map. In related research, the use of loop closure is very limited, because of the minimization of positioning errors and a large number of calculations, and its suitability with the local submap-based SLAM method is open to question. Therefore, it is worthwhile to explore how to effectively integrate loop closure into submap-based SLAM. The system of Schleicher D,Bergasa LM and Ocana M has certain limitations, which will reduce the accuracy of the map in high undulating terrain. Loop closure detection has a strong dependence on the terrain, and there is still a certain gap in related research based on local submaps in high and low undulating terrain [3].

In addition, there are relatively few real robot applications, and the application of SLAM based on local submap method to real-life robots is very important, because it can improve navigation efficiency, enable robots to decide where and how to choose informative target locations, adapt to changing environments, and operate effectively and autonomally in complex and dynamic environments. However, there are relatively few real robot applications in related research. In the research of Karaman S,Fink J and Kumar V, Uavs only play the function of sensors [15]. Future research can try to design more intelligent and efficient cooperation strategies to improve the application efficiency of multi-robot systems. In order to promote the popularization of submap-based SLAM in practical applications, future research needs to pay more attention to how to apply these methods to actual robot platforms and solve the problems and challenges that may be encountered in practical applications.

At the same time, there is a lack of application of heterogeneous robots, and most of the existing research is traditional robotic cars and drones. Using heterogeneous robots can improve the mapping accuracy, improve the robustness of the system, increase the coverage, realize multi-view mapping, and support effective exploration by utilizing complementary sensors between robots.

Finally, research related to multi-sensor fusion can be further developed, where multi-sensor fusion has enhanced perception, adaptation, obstacle detection, reliability, loop closure, tracking, and localization in real-world submapping-based SLAM. Sensor fusion can optimally solve some of the problems of distortion and missing data in SLAM based on submap strategy, and further improve the accuracy of the obtained information. At the same time, it will also promote the application and development of SLAM technology in more fields and scenarios.

In summary, although SLAM based on the local submap method has made important progress, there are still some challenges and limitations. Future research can focus on solving the problems of real-time and accuracy of data association, improving the robustness and accuracy of state estimation, and further optimizing the cooperation strategy. These efforts will further improve the performance and application range of SLAM systems.

5 Conclusion

Through the literature review and analysis of SLAM based on local sub-map strategy, this paper summarizes the research progress, main challenges and potential research directions in this field.Although SLAM based on local sub-map strategy has shown advantages in improving computational efficiency, reducing the complexity of data association, and adapting to large-scale environments, there are still limitations in current research. Future research should pay more attention to the robustness in dynamic environments, effectively integrate loop closure to ensure map consistency and integrity, and apply the method to real robot platforms to solve problems in practical applications. At the same time, exploring the application of heterogeneous robots and multi-sensor fusion technology are also important directions for future research. Despite the lack of timeliness and research depth in this paper, SLAM based on local sub-map strategy still has a broad research prospect, which is expected to provide more reliable and efficient support for robot autonomous navigation and perception.

References

1. Gu, P., Zhou, F., Yu, D.: A 3D Reconstruction Method Using Multisensor Fusion in Large-Scale Indoor Scenes. Complexity (2020)

2. Yang, D., Bi, S., Wang, W.: DRE-SLAM: Dynamic RGB-D Encoder SLAM for a Differential-Drive Robot .Remote Sensing **11**(4) (2019)
3. Schleicher, D., Bergasa, L. M., Ocana, M.: Real-Time Hierarchical Outdoor SLAM Based on Stereovision and GPS Fusion. IEEE Transactions on Intelligent Transportation Systems **10**(3),440-452 (2009)
4. Pinies, P., Paz, L. M., Galvez-Lopez, D.: CI-Graph Simultaneous Localization and Mapping for Three-Dimensional Reconstruction of Large and Complex Environments Using a Multicamera System[J].Journal of Field Robotics **5**(27) 2010
5. Nie, F., Zhang, W., Yao, Z.: LCPF: A Particle Filter Lidar SLAM System with Loop Detection and Correction. IEEE Access, (2020)
6. Huang, S., Wan,g Z., Dissanayake, G.: Sparse Local Submap Joining Filter for Building Large-Scale Maps. IEEE Transactions on Robotics **24**(5), 1121-1130 (2008)
7. Fairfield, N., Wettergreen, D., Kantor, G.: Segmented SLAM in Three-Dimensional Environments[J].Journal of Field Robotics **27**(1), 85-103 (2010)
8. Schuster, M. J., Schmid, K., Brand, C.: Distributed stereo vision - based 6D localization and mapping for multi - robot teams. Journal of Field Robotics (2018)
9. Wang, S. X. R.: A submap joining algorithm for 3D reconstruction using an RGB-D camera based on point and plane features. Robotics and Autonomous Systems (2019)
10. Xiong, H., Chen, Y., Li, X.: A two-level optimized graph-based simultaneous localization and mapping algorithm. Industrial Robot (2018)
11. Zheng, B., Zhang, Z.: An Improved EKF-SLAM for Mars Surface Exploration.International Journal of Aerospace Engineering **1**, 1-9 (2019)
12. Yuan, J., Zhang, J., Ding, S.: Cooperative localization for disconnected sensor networks and a mobile robotin friendly environments. Information Fusion **37**, 22-36 (2017)
13. Fernandez-Madrigal, J. A., Sanfeliu, A.: Andrade-Cetto J. A distributed filtering framework based on local submaps for multi-robot SLAM. Robotics and Autonomous Systems **67**, 199-214 (2015)
14. Grzonka S, Rybski P, Cremers D. Probabilistic data association for semantic SLAM using spatial and semantic context, 2018 IEEE International Conference on Robotics and Automation (ICRA) (2018)
15. Karaman, S., Fink, J., Kumar, V.: Incremental Active SLAM: Integrating Active Collision Avoidance and Mapping. IEEE Transactions on Robotics, 2018, 34(4): Author, F.: Contribution title. In: 9th International Proceedings on Proceedings (2010)