Proceedings of the 2nd International Conference on Mathematical Physics and Computational Simulation
DOI: 10.54254/2753-8818/41/2024CH0172

Prospects for the development of cartography through the integration of SLAM technology with GIS technology

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Abstract. With the continued development of Simultaneous Localization and Mapping (SLAM) and Geographic Information Systems (GIS) technologies, their application scenarios have become increasingly complex. Combining these technologies can significantly enhance operational efficiency in challenging environments. This paper presents an analysis of existing cases where SLAM and GIS technologies have been integrated, demonstrating that such a merger facilitates the consolidation and complementarity of spatial data. This integration allows robots or systems to simultaneously utilize the global information provided by GIS and the dynamic local data captured by SLAM for a more comprehensive and detailed environmental analysis, which is highly beneficial for the field of cartography. Further research has developed a series of operational procedures for integrating SLAM and GIS, utilizing MATLAB as a tool. This study also reviews several existing technical challenges, including real-time performance and computational capacity, environmental complexity and dynamic changes, and multi-scale data processing, and proposes potential solutions. The paper concludes by predicting that the integration of SLAM and GIS will play a crucial role in areas such as smart city management and disaster emergency response, indicating that this research area will become a hot topic in future cartographic technology.

Keywords: Cartography, Simultaneous Localization and Mapping, Geographic Information Systems.

1. Introduction

In recent years, with the rapid development of mobile robotics and autonomous driving technologies, Simultaneous Localization and Mapping (SLAM) technology has gradually become a research hotspot. The core of SLAM technology lies in a robot's ability to construct maps in real-time and self-localize in an unknown environment, addressing critical issues in autonomous navigation. Andréa Macario Barros et al. have provided a detailed introduction to the current fundamental functions of SLAM technology [1]. Geographic Information Science (GIS), a technology for collecting, storing, analyzing, and displaying geospatial data, has played a significant role in urban planning, environmental monitoring, and resource management.

The integration of SLAM and GIS technologies not only compensates for the real-time and precision deficiencies in traditional GIS data acquisition but also provides SLAM technology with rich geospatial information support. This greatly expands the application scope and potential of both

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technologies. Dorra Larnaout and her team attempted in 2012 to use DEM data constraints commonly used in GIS for bundle adjustment, resulting in a threefold increase in positioning accuracy, thereby demonstrating the complementary nature of combining GIS data with SLAM technology [2]. Moreover, the integrated application of SLAM and GIS technologies is gaining increasing attention and has found applications in various areas, especially in the construction of smart cities. K. Ghosh and K. S. S. Musti proposed a framework for developing a GIS-based intelligent traffic system for energy-aware smart cities by combining GIS and SLAM technologies [3].

According to Chen Chen and Cheng Yinhang, who introduced and demonstrated various SLAM algorithms on the MATLAB platform, it can be inferred that MATLAB's mobile robot SLAM simulator is easier to operate compared to commercial simulators [4]. This is because the MATLAB language is widespread and easy to program, with numerous built-in functions supporting matrix operations. Additionally, MATLAB offers various toolboxes to address issues in signal processing, image processing, fuzzy logic, etc., allowing users to focus on SLAM algorithms and theory. On this basis, the integrated application of SLAM and GIS can fully leverage MATLAB's powerful data processing and algorithm implementation capabilities, providing new opportunities and solutions for the development of the cartography field.

This paper aims to explore the background and significance of the integration of SLAM and GIS technologies, analyze their prospects for development in the field of cartography, and discuss the feasibility and advantages of combining the two through MATLAB, as well as potential application directions and prospects. By delving into these topics, this research is believed to offer new insights and references for the advancement of cartography.

2. Overview of SLAM and GIS technologies

2.1. Overview of SLAM

SLAM and GIS are crucial technological concepts in modern science and technology, playing pivotal roles in their respective domains.

SLAM technology refers to the ability of mobile devices (such as robots, drones, smartphones, etc.) to autonomously locate themselves and construct maps in an unknown environment. The core idea of SLAM is to use sensors (such as cameras, LiDAR, etc.) to observe and determine the device's position and orientation during movement, then incrementally build a map based on this positional information. Several widely used algorithms are common in SLAM technology. Firstly, LiDAR-based SLAM algorithms, such as Hector SLAM, Gmapping, and Cartographer, primarily rely on LiDAR sensors to obtain environmental information through laser scanning, thereby achieving localization and mapping. Another category is visual-based SLAM algorithms, such as ORB-SLAM (Oriented FAST and Rotated Brief SLAM), LSD-SLAM (Large-Scale Direct Monocular SLAM), and PTAM (Parallel Tracking and Mapping), which mainly depend on cameras to extract environmental features through image processing techniques, enabling localization and mapping. Additionally, there are algorithms like EKF-SLAM (Extended Kalman Filter SLAM) and FastSLAM, which employ different mathematical models and optimization strategies to adapt to various environments and application requirements [5]. SLAM technology is crucial for realizing truly autonomous mobile robots, allowing them to explore and understand their surroundings and achieve autonomous navigation and task execution without prior knowledge.

2.2. Overview of GIS

GIS technology is a technology for capturing, storing, managing, analyzing, and displaying geographic data. GIS technology is based on geospatial data and employs geographic modelling analysis methods to provide various spatial and dynamic geographic information. It can transform tabular data into geographic graphical displays, facilitating user browsing, operation, and analysis. The primary data types handled by GIS technology include vector data, raster data, terrain data, topological data, and address data. Vector data, composed of geometric elements like points, lines, and polygons, represents specific locations and shapes on a map. Raster data, consisting of pixels where each pixel represents an area on the map, is often used for continuous data such as remote sensing images and digital elevation models. Terrain data primarily describes surface morphology and elevation information, serving as the main source for digital elevation models. Topological data emphasizes spatial relationships between geographic features, such as adjacency and connectivity. Address data links geographic coordinates with postal addresses, supporting location queries and positioning services. GIS technology has extensive applications in various fields such as urban planning, environmental monitoring, disaster management, and agricultural resource management. It helps individuals better understand and interpret geographic phenomena, supporting decision-making and problem-solving. By integrating SLAM and GIS technologies, the strengths of both fields can be leveraged to develop innovative solutions for various applications.

3. The necessity of integrating SLAM and GIS

As the application scope of SLAM technology continues to expand in various aspects of daily life, certain limitations of SLAM have been exposed in specific environments. For instance, the autonomous monitoring of water supply and sewage pipeline networks presents significant challenges. When robots operate within underground water supply and sewage pipelines, they often cannot receive GPS signals to estimate their positions accurately. The interiors of these pipelines are undeniably complex and difficult to navigate. Deep within these pipes, it is pitch dark and perpetually filled with water. Although the water level in supply pipes is relatively stable, the sewage level in sewer pipes fluctuates over time. More critically, sensors within the sewer may be obstructed by various types of waste. The dirty environment not only increases the risk of sensor contamination but also heightens the likelihood of sensor failure. Therefore, in such scenarios, integrating GIS data images, which feature distinct and clear attributes, could significantly enhance the stability and efficiency of robotic operations [6].

Although GIS data contain extensive global geographic information and can accurately describe critical aspects of the environment such as topography and landmarks, this information is typically static. Conversely, maps generated by SLAM technology are often localized and real-time. By combining the two, spatial data integration and complementarity can be achieved. This allows robots or systems to utilize both the global information provided by GIS and the dynamic local data acquired through SLAM, enabling more comprehensive and detailed environmental analysis. This integration is also crucial in the research and development of smart cities and autonomous driving technologies. Therefore, the integration of SLAM and GIS technologies is highly necessary [3].

4. Feasibility analysis of integrating SLAM and GIS technologies

In a study conducted by D. Larnaout, S. Bourgeois, V. Gay-Bellile, and M. Dhome in 2012, the integration of SLAM and GIS technologies was successfully realized by incorporating DEM (Digital Elevation Model) constraints into the BA (Bundle Adjustment) optimization process. The results of the BA optimization with added DEM constraints were significantly superior to those without such constraints. The data indicated that the median error for SLAM with DEM constraints was approximately 3.16 meters, whereas the median error for classical SLAM exceeded 9 meters. This implies that the addition of DEM constraints can enhance positioning accuracy by a factor of three [2].

In 2017, a team consisting of Manhui Sun, Shaowu Yang, Xiaodong Yi, and Hengzhu Liu proposed a method for autonomous large-scale environmental navigation based on GIS and SLAM. Utilizing real urban spatial road network information and leveraging the storage and computational capabilities of GIS spatial databases, they developed a comprehensive system that includes a spatial database, SLAM, and navigation algorithms. This system demonstrated good reusability and scalability, making it suitable for real-life scenarios and capable of guiding robots in navigation and mapping activities under extensive conditions [7].

In 2020, a team comprising F-J Serrano, V Moreno, B Curto, and R Álves proposed a new approach to global localization for mobile robots by storing GIS map data in a PostGIS database. This method involved using GIS map data as an information source and initializing the filter based on the probability distributions generated from sensor readings. The proposed solution, termed Environmental Stimulus Localization (ESL), helps mitigate the impact of measurement errors and allows for quicker recovery from localization failures [8].

5. Technical methodology for integrating SLAM and GIS (Using MATLAB as an Example)

The integration of SLAM data with GIS data involves a multi-step process aimed at leveraging the strengths of both systems to achieve more accurate environmental perception and localization.

5.1. Data fusion

5.1.1. Data preprocessing. The data generated by the SLAM system needs to be cleaned and organized, which includes noise removal, error correction, and other preprocessing steps. This ensures the accuracy and reliability of SLAM data, such as robot trajectories and environmental maps. People could acquire relevant geospatial data from GIS platforms, such as topographic maps, road networks, and building information. Convert the SLAM-generated map data into GIS-compatible formats. Depending on the requirements, GIS data may need to be converted or clipped to align with SLAM data in the same or similar coordinate systems.

5.1.2. Coordinate system unification. It is necessary to ensure that SLAM data and GIS data use the same coordinate system. This typically requires coordinate transformation or calibration to enable seamless fusion of the two data sets.

5.1.3. Data registration and alignment. It requires registering and aligning SLAM data with GIS data using known landmarks or feature points. This can be achieved through feature extraction and matching algorithms, ensuring spatial consistency between the two data sets.

5.1.4. Data fusion. After completing data preprocessing and coordinate system unification, SLAM data can be fused with GIS data. This can be achieved through overlaying, merging, or other fusion algorithms, depending on the application context and requirements. For example, local maps generated by SLAM can be overlaid on the global maps provided by GIS to obtain more comprehensive environmental information.

5.2. Data visualization

After the data fusion is done, the next step is to utilize MATLAB to process the point cloud data generated by SLAM, which includes filtering, registration, and feature extraction. Then both SLAM and GIS data in MATLAB can be visualized. This step involves the graphical representation of the fused data to facilitate analysis and interpretation.

6. Technical challenges and solutions

6.1. Real-time performance and computational efficiency

SLAM requires real-time processing of sensor data (e.g., LiDAR, cameras) to update positional information and maps, whereas GIS data is often large-scale and complex, demanding considerable processing time. In this case, high-performance computing and parallel processing techniques can be employed to enhance data processing efficiency. Additionally, the development of incremental update algorithms can allow GIS data to be updated in real-time based on SLAM outputs.

6.2. Accuracy and robustness

The accuracy and robustness of SLAM systems are affected by sensor noise and environmental changes, while GIS data requires high precision and stability. However, integrating multiple sensor data sources (such as IMU, GPS, LiDAR, and vision) can improve the accuracy and robustness of

SLAM [9]. Moreover, using existing high-precision GIS data for calibration and error correction can enhance the overall system accuracy.

6.3. Environmental complexity and dynamic changes

SLAM technology is prone to errors in complex and dynamically changing environments (e.g., urban settings with moving crowds and vehicles), whereas GIS systems typically assume static geographic information [10]. While it is found that Dynamic object detection and tracking technologies can be used to isolate the impact of moving objects on SLAM, ensuring the accuracy of the static parts of the map. Machine learning methods can also be employed to enhance the system's adaptability to environmental changes.

6.4. Multi-scale data processing

SLAM data is usually local and fine-grained, while GIS data can cover large areas with various resolutions. Converting and processing data across different scales is required. Developing multi-scale data fusion algorithms can enable seamless transitions and integrations from local details to global maps.

6.5. Loop closure and global optimization

SLAM requires loop closure and global optimization to improve the overall consistency of the map. These processes can become complex and computationally expensive when dealing with large-scale GIS data. Efficient graph optimization algorithms and feature-based loop closure detection methods can be utilized to reduce computational complexity and enhance global map consistency.

7. Future prospects

The integration of SLAM and GIS technologies sees a rising development trend and this research presents some of it for future practice and study guidance.

7.1. Intelligent city management

The integration of SLAM and GIS technologies can be applied to intelligent city management systems to achieve refined management of urban infrastructure.

Urban management departments can use drones equipped with SLAM technology for aerial inspections, generating real-time 3D map data of the city and integrating this data into GIS systems. By comparing new and old map data, issues such as road damage and building violations can be quickly identified, thereby improving city management efficiency.

7.2. Disaster emergency response and rescue

Combining SLAM's rapid mapping capabilities with GIS's global data management can enhance the response speed and accuracy of disaster emergency response and rescue operations.

After disasters like earthquakes or floods, rescue teams can use robots or drones equipped with SLAM technology to quickly generate real-time 3D maps of the affected areas. By integrating these maps with existing geographic information data in GIS systems, rescue teams can swiftly formulate rescue plans and identify optimal rescue routes.

7.3. Augmented reality and virtual reality applications

Integrating SLAM technology with GIS data can be applied in the fields of Augmented Reality (AR) and Virtual Reality (VR) to achieve more realistic scene reconstruction and interactive experiences.

At tourist sites, AR glasses or mobile devices can use SLAM technology for real-time positioning and environmental perception, overlaying virtual information onto the real world. For instance, visitors can see virtual reconstructions of historical buildings and real-time guide information, all managed and updated through GIS systems.

7.4. Precision agriculture

Utilizing SLAM's precise positioning and real-time environmental sensing in combination with GIS technology can enhance agricultural production efficiency and precision management.

Agricultural robots can use SLAM technology for autonomous navigation in fields, generating real-time 3D maps and uploading this data to GIS systems for analysis and management. Farmers can then use the real-time map data for precise irrigation, fertilization, and pest control, thereby improving crop yield and quality.

7.5. Indoor navigation and management

Applying SLAM technology to indoor environments in conjunction with GIS systems can achieve high-precision indoor navigation and management.

In complex indoor environments such as large shopping malls, hospitals, and airports, users can use mobile devices equipped with SLAM technology for indoor navigation [11]. These indoor map data, integrated with other information such as shop locations and emergency exits via GIS systems, can provide more accurate and comprehensive navigation services.

8. Conclusion

This study primarily focuses on SLAM and GIS technologies, delving deeply into the current state of both fields. It proposes the idea of integrating SLAM technology with GIS for cartographic applications. Through further exploration, this study infers the necessity and feasibility of combining these two technologies in the present era. On this basis, the research also discusses and analyzes the technical challenges that may arise during the integration of SLAM and GIS technologies in the cartographic domain, proposing potential solutions to these issues. The findings suggest that the integration of SLAM and GIS technologies in mapping is both meaningful and achievable. Although there are certain technical difficulties at present, viable solutions can enhance the combined mapping effects of these technologies. Finally, this study presents some prospects for the integration of SLAM and GIS technologies in the field of mapping, including intelligent city management, disaster emergency response and rescue, augmented reality and virtual reality applications, and precision agriculture.

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