Hindawi
Journal of Robotics
Volume 2024, Article ID 9792362, 1 page
https://doi.org/10.1155/2024/9792362

Retraction

Retracted: Collaboration and Management of Heterogeneous Robotic Systems for Road Network Construction, Management, and Maintenance under the Vision of "BIM + GIS" Technology

Journal of Robotics

Received 23 January 2024; Accepted 23 January 2024; Published 24 January 2024

This article has been retracted by Hindawi following an investigation undertaken by the publisher [1]. This investigation has uncovered evidence of one or more of the following indicators of systematic manipulation of the publication process:

(1) Discrepancies in scope
(2) Discrepancies in the description of the research reported
(3) Discrepancies between the availability of data and the research described
(4) Inappropriate citations
(5) Incoherent, meaningless and/or irrelevant content included in the article
(6) Manipulated or compromised peer review

The presence of these indicators undermines our confidence in the integrity of the article's content and we cannot, therefore, vouch for its reliability. Please note that this notice is intended solely to alert readers that the content of this article is unreliable. We have not investigated whether authors were aware of or involved in the systematic manipulation of the publication process.

Wiley and Hindawi regrets that the usual quality checks did not identify these issues before publication and have since put additional measures in place to safeguard research integrity.

We wish to credit our own Research Integrity and Research Publishing teams and anonymous and named external researchers and research integrity experts for contributing to this investigation.

The corresponding author, as the representative of all authors, has been given the opportunity to register their agreement or disagreement to this retraction. We have kept a record of any response received.

References

[1] Z. Liu, W. Yan, J. Kou, and Z. Li, "Collaboration and Management of Heterogeneous Robotic Systems for Road Network Construction, Management, and Maintenance under the Vision of "BIM + GIS" Technology," *Journal of Robotics*, vol. 2023, Article ID 8259912, 8 pages, 2023.

Hindawi
Journal of Robotics
Volume 2023, Article ID 8259912, 8 pages
https://doi.org/10.1155/2023/8259912

Research Article

Collaboration and Management of Heterogeneous Robotic Systems for Road Network Construction, Management, and Maintenance under the Vision of "BIM + GIS" Technology

Zhizhong Liu, Weishen Yan, Jianguo Kou, and Zhida Li

Hebei Expressway Yanchong Management Center, Zhangjiakou 075400, Hebei, China

Correspondence should be addressed to Zhizhong Liu; 15211020408@stu.cpu.edu.cn

Received 4 October 2022; Revised 21 December 2022; Accepted 27 March 2023; Published 12 April 2023

Academic Editor: Shahid Hussain

In modern society, intelligent spatial analysis services have been playing an important role in building smart cities. Especially, people's spatial information needs have changed with the technological progress of times, from traditional two-dimensional appearance to three-dimensional interior. In this case, the construction of street networks is a key part of spatial information analysis research. Establishing an integrated indoor-outdoor street network data model with accurate information and complete attributes can provide strong technical support for indoor-outdoor navigation, emergency evacuation, and other application services. However, most of the current studies on internal and external road networks are independent of each other. This means that indoor road networks are mainly based on floor plans, which contain little information and do not represent the spatial relationships between floors. Indoor and outdoor links often suffer from poor connectivity and data loss. Heterogeneous robotics is a high degree of integration of intelligent control and platform control technologies. In a sense, it is a technology platform for connecting heterogeneous robotic populations. By developing effective collaboration and control strategies, tasks can be performed with the highest success rate and the lowest risk while respecting spatial and temporal constraints. As a result, the study of the coordination and management of heterogeneous robotic systems for road network construction, management, and maintenance is a topic of a great theoretical value and significance. Therefore, this paper proposes an intelligent road network construction method that incorporates BIM and GIS technologies. This study uses the building information model to enrich the information of indoor building components and combines the strong spatial analysis capability of outdoor areas with GIS road network technology to build an indoor road network and design a connection scheme for indoor and outdoor areas. After that, the construction of an integrated indoor-outdoor street network is completed, and the interaction between indoor as well as outdoor spatial data is very smooth.

1. Introduction

With the development of urbanization, information, and automation technologies and the rapid spread of the Internet, people's movements are becoming more complex and diverse [1]. Under such circumstances, spatial information technology becomes increasingly necessary. However, as urban population continues to grow, building density is also increasing [2]. At the same time, the configuration of urban space and road networks is becoming more and more complex. Outdoor navigation technologies are also becoming more and more complex. Nevertheless, research on spatial data analysis has been slow due to the complex spatial structure of buildings, high accuracy requirements, and the major technical bottlenecks of traditional indoor positioning technologies [3]. As urbanization progresses, people are also increasingly moving indoors. Consequently, GPS positioning technology, which is widely used outdoors, is no longer applicable to geographic environments with complex spatial structures and high requirements for positioning accuracy [4]. As a result, for applications that affect human life and safety, such as pedestrian navigation and emergency evacuation, there is an urgent need for spatial data that can support precise geometric locations and clear hierarchical relationships in complex indoor and outdoor environments. In short, the development of road networks will play an important role in the overall urban life cycle and the use of geospatial data [5].

In the rapidly developing information age of the Internet, outdoor navigation is widely used in people's lives. For example, location-based services of Gaode Map and Baidu Map are ubiquitous. However, indoor navigation technologies are relatively lagging behind compared to outdoor navigation applications [6]. As a result, research on indoor navigation technologies is becoming increasingly essential. As a matter of fact, indoor navigation systems are different from outdoor navigation systems to some extent. In particular, the technology of outdoor navigation systems cannot be directly applied to indoor navigation systems because geographic signals are sensitive to buildings [7]. After all, people now spend most of their day indoors. Actually, this means that there is a growing demand for location-based services inside buildings. Indoor navigation enables people to know exactly where they are indoors and get to their indoor destinations quickly. At the same time, this makes people's lives easier. In short, using indoor navigation to establish spatial relationships between people and objects can make people's lives more comfortable [8]. Indoor navigation systems need more research in many aspects than outdoor navigation systems. As illustrated in Figure 1, the main research directions in this field focus on positioning methods, positioning accuracy, and building road network models, as well as road network representation.

In fact, the needs about road network construction are included in the idea of a smart city. To be specific, a smart city is a beautiful vision. It is a solution that integrates multiple ICT and IoT in a secure way [9]. As a result, in order to understand what is happening in a city and how to improve the quality of life of its inhabitants, smart city applications require a large amount of data, both static and dynamic, contemporary and historical, geometric and semantic, and microscopic and macroscopic [10]. Collecting, managing, and applying these data often require the use of technologies such as building information modeling (BIM) and geographic information systems (GISs). In particular, BIM technologies can be used to create, manage, and share data across the vertical facility lifecycle [11]. GIS technologies can be applied to store, manage, and analyze descriptions of the urban environment. As a result, the combined application of BIM and GIS is quite essential for smart city applications that require facility and urban environment data. In other words, while GIS has a long history of application and BIM has been developed for more than a decade, their combined application begins a new direction that is still in the early stages of exploration [12].

With the continuous development of GIS technology, GIS can integrate spatial information and spatial analysis into different applications. For pedestrian navigation and emergency response, indoor and outdoor route planning is quite crucial [13]. As a result, such route planning requires detailed indoor information. This information is often obtained from industry floor plans for architectural design, engineering, and construction services [14]. Currently, most of the outdoor navigation systems that people come across for route planning and navigation are two-dimensional. In other words, planning and navigation information needed for these electronic maps can be obtained from existing spatial datasets. However, for indoor navigation, since indoor is a three-dimensional space, the indoor road network model in indoor navigation should also be a three-dimensional model [15]. Therefore, route planning should be carried out on a three-dimensional basis. However, there is no mature unified standard for the construction of indoor road network models. At the same time, BIM technology, as an emerging technology in the field of architecture, engineering, and construction, is widely used in the whole life cycle of buildings [16]. In addition, BIM is regarded as an ideal source of spatial information because it contains rich geometric and semantic information on building components [17]. In summary, the study of 3D road network model technology for indoor navigation with a data-rich building information model and GIS integration is of great significance for the indoor navigation industry based on location services.

Along with the technological development of computers, artificial intelligence, and robotics, robotics, one of the greatest creations of mankind, has developed rapidly in just a few decades. Today, the scope of robotic applications has expanded to include all aspects of human life. Figure 2 illustrates the applications of robotics in various fields such as healthcare, services, and entertainment.

In real-life situations, many single robots are unable to complete tasks due to the variability of living conditions and the complexity of tasks [18]. Especially in dynamic environments with complex tasks and special situations, it is quite necessary to consider multiple robots or a mix of different types of robots working together [19]. As tasks become more difficult, the quest for efficiency increases. In other words, a single robot is no longer sufficient to meet many requirements. As a result, there is a growing interest in the development of multiple robots. To be specific, there is a desire to coordinate different types of robots or robots with other tools to accomplish many tasks that cannot be performed by a single robot [20]. In the past, research on multirobot systems has focused more on homogeneous robotic systems. Heterogeneous robotic systems, on the other hand, often have widely varying dynamics and kinematics due to different functions and shapes, loads, and motion capabilities of individual robots [21]. As a result, when these individuals work together, there are redundancy and coupling effects, which are challenging.

There are two main types of robots, namely, aerial drones and ground mobile robots [22]. Table 1 lists the relevant characteristics of unmanned aircraft and mobile robots. Table 1 shows that, on the one hand, both unmanned aircraft and mobile robots have their own limitations. In fact, this can reduce the efficiency of their tasks to some extent. On the other hand, unmanned aircraft and mobile robots are very complementary [23]. In fact, the complementarity between unmanned aircraft and mobile robots can be seen in several ways. To start with, sensors located on drones are often

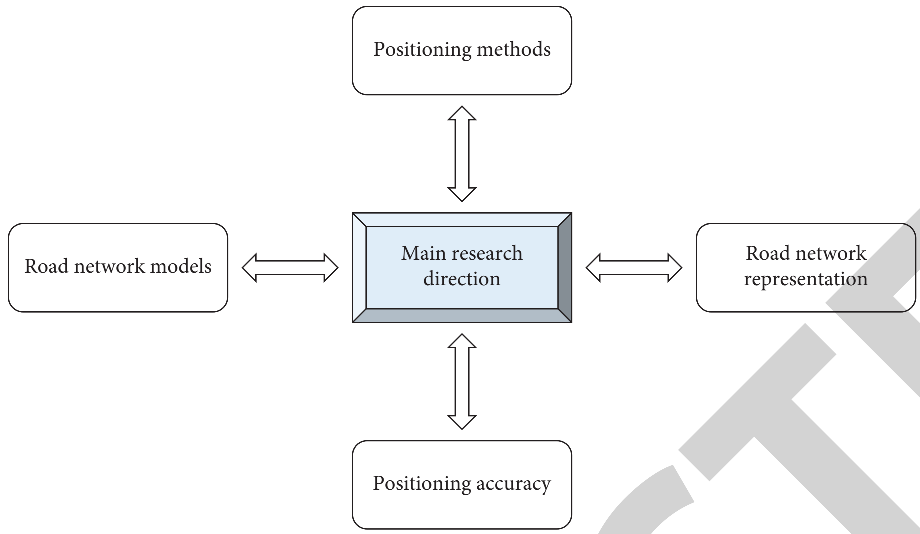

FIGURE 1: Main research directions in indoor navigation systems.

FIGURE 2: Applications of robotics in various fields.

limited by flight speed and altitude when capturing ground features [24]. As a result, mobile robots can be deployed to precisely locate ground targets. Furthermore, the communication links between unmanned aerial vehicles are less likely to be blocked by obstacles due to the altitude advantage. Consequently, mobile robots at different locations can be indirectly connected with the support of unmanned aerial vehicles used as communication relays. Finally, unmanned aerial vehicles are often limited by short-range navigation due to load energy constraints, while mobile robots have a larger payload capacity [25].

Existing studies on path planning for heterogeneous robotic systems often do not consider the motion range of ground mobile robots [26]. In real environments, roads are intricate and complex. As a result, the ground vehicle should move in the road. In addition, there are some studies that consider the limitation of the motion range of ground mobile robots and restrict the motion of ground robots to the road network. However, the ground robot following the given path may not necessarily get the best path to complete the task, nor is it guaranteed to get the shortest time to complete the task, which results in energy waste.

In fact, traditional indoor data collection is time consuming. After all, there are many technical difficulties in automatically extracting interior information from complex buildings. At the same time, this information is influenced by the type of input data. As a result, interior building properties are often incomplete. BIM technology has the potential to become the indoor road network data with its advantages of including data information of the whole building life cycle and 3D visualization [27]. As a database of the whole building information, the introduction of BIM technology and building spatial topological relationship analysis in the indoor path planning study is both an effective way to improve the accuracy of indoor road networks and a useful extension of the application area of BIM models. BIM and GIS each have their own common data standards. In other words, their geometric modeling, semantic networks, and logical relationships are significantly different [28]. As a result, more and more research is focused on the integration of building-scale and city-scale spatial information for different applications, especially those requiring indoor and outdoor information. At the same time, the integration of BIM and GIS will become a key task in smart city applications. To this end, this paper proposes a BIM-based indoor network model and the integration with outdoor GIS models.

TABLE 1: Relevant characteristics of unmanned aircraft and mobile robots.

Categories	Advantage	Disadvantage
Unmanned aircraft	Fast speed	Low load
Mobile robot	High load	Slow speed

2. Overview of Related Technologies

2.1. BIM Technology. Building information modeling (BIM) is the digital transmission of information about the entire life cycle of a building in the form of a three-dimensional digital building information model, which includes information about the building at all stages of its life cycle, from design, construction, and completion to operation and maintenance. BIM is a three-dimensional digital building information model that contains information about the building at all stages of its life cycle, from design, construction, and completion to operation and maintenance. As a result, it can be used as a lifecycle solution to integrate building information through digital technology and be used for the design, construction, operation, and maintenance of buildings. In other words, BIM technology can integrate all building information into one 3D model database.

As a carrier of information exchange among various units in the construction process and an important part of the construction big data, the building information model expresses the information about urban buildings comprehensively. As a result, BIM technology plays an important role in the application of big data in smart cities. At the same time, BIM can be converted into 2D or 3D forms by using engineering application software. Consequently, its rich data forms increase the cross-use of data. In addition, with the popularity of the mobile Internet and smart phones, people can view building data information in real time on their cell phones. In other words, this has significantly improved the ease of information interaction. For example, Figure 3 shows the building information model of a building and the construction attributes.

In practical application, in order to make BIM support the storage and interaction of information about the whole construction project, researchers build BIM servers as the carrier of information. Then, they can complete the storage of BIM data by interacting with the server through the client. As shown in Figure 4, the information interaction mode can be divided into the C/S architecture and B/S architecture according to the different forms of interaction between the client and the server. At present, commonly used BIM servers are the C/S architecture. In other words, when people use BIM applications, they need to download the corresponding BIM application client to their computers, and then, they can perform BIM modeling and information maintenance after installation. In addition, there are also some differences in the operation methods of different clients. As a matter of fact, users usually need to go through training before they can operate the application, and the B/S architecture has a clearer separation between data processing and result appearance than the C/S architecture. In short, with the development of mobile communication technology and mobile application technology, especially the maturity and popularity of mobile browsers, the advantages of the B/S architecture's flexibility are becoming more and more obvious.

In recent years, with the development of 3D web rendering technologies, there are 3D web-side rendering technologies such as HTML5 and WebGL. These technologies can be effectively applied to 3D graphics rendering on the website. Although most of the research studies focus on the application of WebGL technology, these research studies also provide reference for the combination of BIM technology and WebGL technology. In addition, although the existing rendering technologies can improve the efficiency of model loading to some extent, the speed of model loading and rendering is very low. However, model loading and rendering speed is largely affected by the volume of the building information model itself. Therefore, according to the specific purpose of the model, the BIM data should be processed redundantly, and some unnecessary model information should be removed through light weighting. In fact, the process of BIM light weighting mainly includes the analysis of the BIM model information organization structure and BIM model data format conversion. After that, through the reorganization of the BIM data structure and format conversion, we achieve the purpose of simplifying the building information model. In this study, the road network model BIM data preprocessing process is illustrated in Figure 5.

2.2. GIS and Road Network Model. A road network model is a network model that maps the spatial and attribute information about roads and relationships between them and can manage and reprocess the data in the model. In fact, the early studies of road network models were oriented towards the geometry of lanes and the representation of traffic information. In other words, road network data were commonly used for route analysis. With the rapid development of computer technology, the information accuracy of road network models has been continuously improved. As a result, the road network model has been able to meet the transformation of complex terrain in outdoor environments in terms of spatial capability and focus on the construction of topological logic relationships between road networks. For the study of outdoor road network models, the centerline of streets is usually extracted as edges and formed into a network and road intersections are extracted as nodes, and then, information is given in the nodes and edges.

In contrast to navigation in an outdoor network, navigation in an indoor environment is not efficient for route planning because there is no clear road network to navigate. In fact, pedestrians and vehicles can navigate in outdoor networks. However, in indoor environments, it is also necessary to predefine the road network for indoor navigation so that the algorithms for outdoor route planning can be applied to indoor route planning. This requires a navigation network with indoor access conditions and then proposes a corresponding data organization method for the map model of the indoor navigation network. After all, the indoor map model is the basis for the implementation of indoor location services. In fact, one of the goals of building an indoor map model is to abstract the indoor navigation network for indoor positioning and navigation as well as for route planning. Therefore, the indoor road network model is the basis for indoor location services such as navigation and route planning, which directly affect the effectiveness of indoor navigation and route planning. As the current research and application of indoor positioning technology

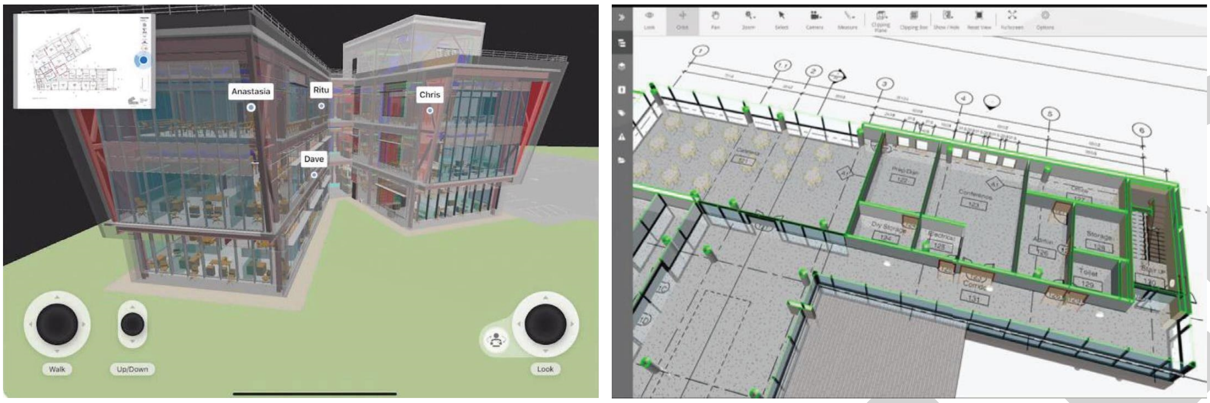

Figure 3: Building information model of a building and the construction attributes.

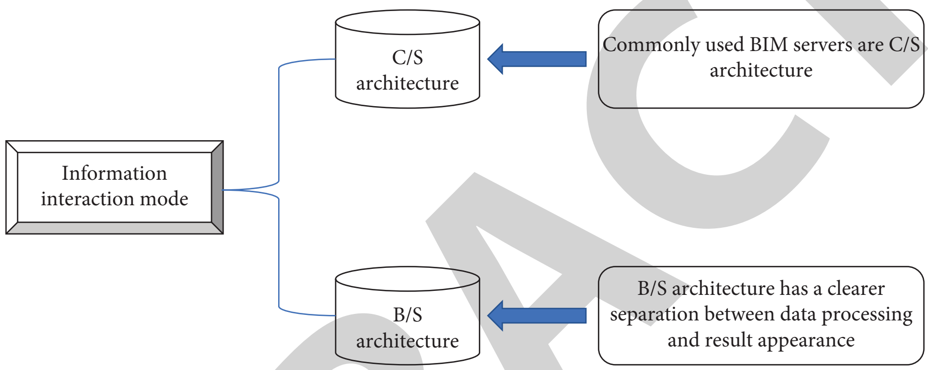

Figure 4: Architectures of information interaction mode.

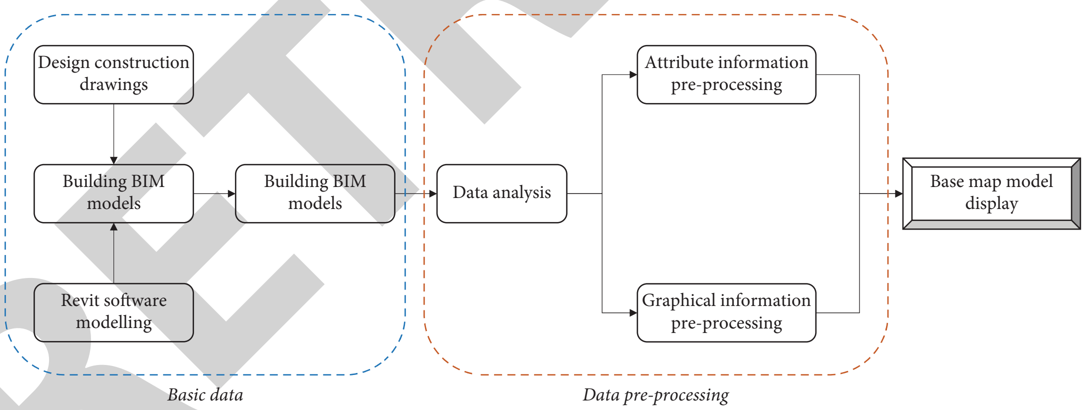

Figure 5: Road network model BIM data preprocessing process.

continue to mature, the research on the construction method of indoor road network models becomes particularly important. This is of great importance to promote the development of indoor navigation technology. In summary, the interior space of the building is divided, as shown in Figure 6.

3. Heterogeneous Robotic System for Road Networks

3.1. Road Network Model. When designing, designers often use a series of grids to fill in interior spaces. In fact, this is a method of interior space segmentation, which can be further defined as a grid model. Each grid represents a subspace of the interior space in the road network model. Thus, the topological relationships in the interior space can be expressed by the connections between adjacent grids. As a matter of fact, there are two types of cellular grids: regular and irregular. The regular grid is usually a square, hexagonal, or spatial cube. The information accuracy of the regular grid model is closely related to the grid size. In other words, the finer the grid is divided, the higher the accuracy of the model. The processing of a large amount of grid data is very demanding on the computer equipment. When applied to

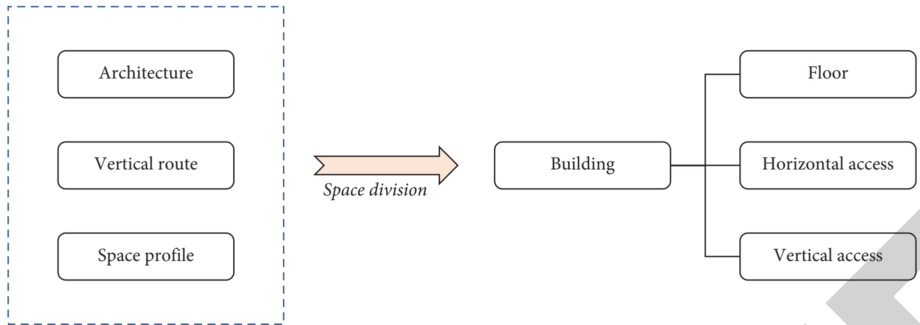

Figure 6: Interior space of the building.

a real system, it will generate a large memory load and affect the operation efficiency of the overall spatial service system. Figure 7 illustrates a partitioning diagram of an irregular triangular mesh. To be specific, it could form a road network model by extracting the center points of triangles and the midpoints of neighboring edges between triangles.

In fact, graph-based models have a greater advantage in describing the relational information and structure of interior spaces. More specifically, the diagram model is able to represent complex spatial structures with simple logical relationships. At the same time, the graph model also supports hierarchical classification of building entity information in interior spaces. As a result, the graph-based node and edge model has much room for development in terms of geometric information complementation, model semantic network construction, and model extraction efficiency. In summary, the structure of nodes and edges should be used as the basis for the construction of road network models for path planning and further research on road network construction.

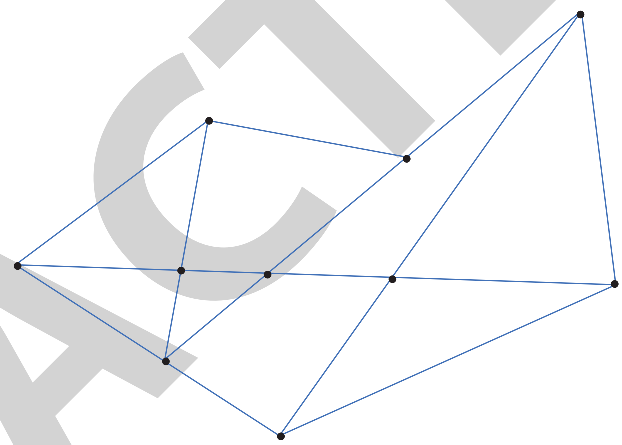

Figure 7: Partitioning diagram of an irregular triangular mesh.

3.2. Heterogeneous Robotic System. As one of the most popular branches of robotics, mobile robotics is a hot and difficult area of research. As a result, the scope of research includes navigation and localization, multisensor information fusion, path planning, multirobot coordination, and robot vision. Path planning, as one of the most important aspects of robotics, is a classical yet challenging area of research. In fact, for some specific tasks, mobile robots often need to make further decisions about their motion behavior based on the corresponding environmental characteristics. For example, pipeline inspection, robotic mine clearance, and high-voltage line work all require the robot to generate its own flow or path according to the actual working environment in order to prepare for the next task. These are essentially path planning problems for mobile robots.

Heterogeneous robotic systems are often connected together in some ways when performing a task and can move separately and independently when certain conditions are met. In fact, the diverse distribution of task points and the obstacles in the environment are the main factors that affect the motion decisions of a robotic system. Therefore, the establishment of a safe and effective model is the key and difficult part of path planning for heterogeneous robotic systems. An understanding of architectural requirements is essential for the research and design of new generic control systems for heterogeneous mobile robots. Currently, there are two requirements for the study of generic control system architectures. The first requirement is standardization, i.e., the need for a unified, standard control strategy technology that can be applied to different controllers. In addition, the second requirement is openness, i.e., the need for a middleware module that is scalable and can run in a variety of heterogeneous computing environments. The commonality between these two requirements is the urgent need for an approach to improve the general serviceability of mobile robotic software modules. This approach can greatly improve the openness, scalability, and reusability of intelligent robotic architectures.

4. Conclusion

In recent years, the concept of a smart city has gradually gained popularity. In this context, intelligent information services have been greatly popularized by the rapid development of communication technology. Especially in spatial location information analysis, although the traditional outdoor traffic network can bring great convenience to people's travel, it is slightly insufficient in dealing with complex indoor space. Especially in intelligent spatial services such as indoor and outdoor navigation or emergency evacuation, complete and accurate integrated indoor and outdoor information data are needed to support. The construction of integrated indoor-outdoor road networks is the key to solving these problems. In this paper, we propose to integrate the BIM model and GIS data to build an indoor-outdoor integrated road network to achieve a seamless connection between indoor and outdoor road networks and finally to realize the application in the web-based route planning system, in response to the problems of simple indoor data structure, poor information completeness, and poor indoor-outdoor communication in the current indoor-outdoor road network research.

In terms of theoretical research, this paper investigates the current research on indoor and outdoor road networks at home and abroad and summarizes the basic needs and outstanding problems of indoor and outdoor road networks. For the difficult indoor space in road network construction, we focus on the analysis of indoor space characteristics and choose the diagram-based model as the indoor road network model according to indoor characteristics. Then, this study introduces the BIM model as an indoor data source and analyzes the advantages of BIM in indoor information representation. In the indoor-outdoor integration part, this paper proposes to build an integrated road network model that integrates BIM model data and GIS outdoor road network data. Based on the current research on the integrated application of BIM and GIS, this study further investigates the feasibility of the indoor-outdoor road network integrating BIM and GIS and illustrates the advantages and significance of the integrated indoor-outdoor road network integrating BIM and GIS. In the future, related research can be performed in the following aspects. In terms of the loading speed and rendering efficiency of the indoor road network map model, the loading time of the indoor road network map model obtained through experiments is long, which affects the user's use effect, and the loading method of the model needs to be further improved.

Data Availability

The labeled dataset used to support the findings of this study is available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

This work was supported by the Hebei Expressway Yanchong Management Center.

References

[1] H. B. Ticha, N. Absi, D. Feillet, and A. Quilliot, "Empirical analysis for the VRPTW with a multigraph representation for the road network," *Computers & Operations Research*, vol. 88, pp. 103–116, 2017.

[2] H. Ben Ticha, N. Absi, D. Feillet, and A. Quilliot, "Vehicle routing problems with road-network information: state of the art," *Networks*, vol. 72, no. 3, pp. 393–406, 2018.

[3] T. Chen, S. Wu, J. Yang, G. Cong, and G. Li, "Modeling of emergency supply scheduling problem based on reliability and its solution algorithm under variable road network after sudden-onset disasters," *Complexity*, vol. 2020, Article ID 7501891, 2020.

[4] A. Miatto, H. Schandl, D. Wiedenhofer, F. Krausmann, and H. Tanikawa, "Modeling material flows and stocks of the road network in the United States 1905–2015," *Resources, Conservation and Recycling*, vol. 127, pp. 168–178, 2017.

[5] G. Shi, J. Shan, L. Ding, P. Ye, Y. Li, and N. Jiang, "Urban road network expansion and its driving variables: a case study of Nanjing City," *International Journal of Environmental Research and Public Health*, vol. 16, no. 13, p. 2318, 2019.

[6] W. C. Simões, G. S. Machado, A. Sales, M. M. de Lucena, N. Jazdi, and V. F. de Lucena, "A review of technologies and techniques for indoor navigation systems for the visually impaired," *Sensors*, vol. 20, no. 14, p. 3935, 2020.

[7] D. Plikynas, A. Žvironas, A. Budrionis, and M. Gudauskis, "Indoor navigation systems for visually impaired persons: mapping the features of existing technologies to user needs," *Sensors*, vol. 20, no. 3, p. 636, 2020.

[8] R. N. Kandalan and K. Namuduri, "Techniques for constructing indoor navigation systems for the visually impaired: a review," *IEEE Transactions on Human-Machine Systems*, vol. 50, no. 6, pp. 492–506, 2020.

[9] L. W. Chen and J. X. Liu, "Time-efficient indoor navigation and evacuation with fastest path planning based on Internet of Things technologies," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 51, no. 5, pp. 3125–3135, 2021.

[10] A. Meliones and D. Sampson, "Blind MuseumTourer: a system for self-guided tours in museums and blind indoor navigation," *Technologies*, vol. 6, no. 1, p. 4, 2018.

[11] B. Cheng, K. Lu, J. Li, H. Chen, X. Luo, and M. Shafique, "Comprehensive assessment of embodied environmental impacts of buildings using normalized environmental impact factors," *Journal of Cleaner Production*, vol. 334, Article ID 130083, 2022.

[12] W. Jeamwatthanachai, M. Wald, and G. Wills, "Indoor navigation by blind people: behaviors and challenges in unfamiliar spaces and buildings," *British Journal of Visual Impairment*, vol. 37, no. 2, pp. 140–153, 2019.

[13] N. A. Giudice, B. A. Guenther, T. M. Kaplan, S. M. Anderson, R. J. Knuesel, and J. F. Cioffi, "Use of an indoor navigation system by sighted and blind travelers: performance similarities across visual status and age," *ACM Transactions on Accessible Computing*, vol. 13, no. 3, pp. 1–27, 2020.

[14] W. Sakpere, M. Adeyeye-Oshin, and N. B. Mlitwa, "A state-of-the-art survey of indoor positioning and navigation systems and technologies," *South African Computer Journal*, vol. 29, no. 3, pp. 145–197, 2017.

[15] M. Sattarian, J. Rezazadeh, R. Farahbakhsh, and A. Bagheri, "Indoor navigation systems based on data mining techniques in internet of things: a survey," *Wireless Networks*, vol. 25, no. 3, pp. 1385–1402, 2019.

[16] D. Liu, S. Guo, Y. Yang, Y. Shi, and M. Chen, "Geomagnetism-based indoor navigation by offloading strategy in NB-IoT," *IEEE Internet of Things Journal*, vol. 6, no. 3, pp. 4074–4084, 2019.

[17] C. Schuldt, H. Shoushtari, N. Hellweg, and H. Sternberg, "L5in: overview of an indoor navigation pilot project," *Remote Sensing*, vol. 13, no. 4, p. 624, 2021.

[18] Y. Rizk, M. Awad, and E. W. Tunstel, "Cooperative heterogeneous multi-robot systems: a survey," *ACM Computing Surveys*, vol. 52, no. 2, pp. 1–31, 2019.

[19] A. Prorok, M. A. Hsieh, and V. Kumar, "The impact of diversity on optimal control policies for heterogeneous robot swarms," *IEEE Transactions on Robotics*, vol. 33, no. 2, pp. 346–358, 2017.
[20] T. Kim, S. Lee, T. Hong, G. Shin, T. Kim, and Y. L. Park, "Heterogeneous sensing in a multifunctional soft sensor for human-robot interfaces," *Science Robotics*, vol. 5, no. 49, Article ID eabc6878, 2020.
[21] W. Shule, C. M. Almansa, J. P. Queralta, Z. Zou, and T. Westerlund, "Uwb-based localization for multi-uav systems and collaborative heterogeneous multi-robot systems," *Procedia Computer Science*, vol. 175, pp. 357–364, 2020.
[22] H. Wang, W. Chen, and J. Wang, "Coupled task scheduling for heterogeneous multi-robot system of two robot types performing complex-schedule order fulfillment tasks," *Robotics and Autonomous Systems*, vol. 131, Article ID 103560, 2020.
[23] J. Lee, "Heterogeneous-ants-based path planner for global path planning of mobile robot applications," *International Journal of Control, Automation and Systems*, vol. 15, no. 4, pp. 1754–1769, 2017.
[24] S. Mayya, R. K. Ramachandran, L. Zhou et al., "Adaptive and risk-aware target tracking for robot teams with heterogeneous sensors," *IEEE Robotics and Automation Letters*, vol. 7, no. 2, pp. 5615–5622, 2022.
[25] W. Yao, H. Lu, Z. Zeng, J. Xiao, and Z. Zheng, "Distributed static and dynamic circumnavigation control with arbitrary spacings for a heterogeneous multi-robot system," *Journal of Intelligent and Robotic Systems*, vol. 94, no. 3-4, pp. 883–905, 2019.
[26] A. Ali, H. Azevedo-Sa, D. M. Tilbury, and L. P. Robert, "Heterogeneous human–robot task allocation based on artificial trust," *Scientific Reports*, vol. 12, no. 1, pp. 15304–15315, 2022.
[27] B. Cheng, J. Huang, K. Lu et al., "BIM-enabled life cycle assessment of concrete formwork waste reduction through prefabrication," *Sustainable Energy Technologies and Assessments*, vol. 53, Article ID 102449, 2022.
[28] C. Ju and H. I. Son, "Modeling and control of heterogeneous agricultural field robots based on Ramadge–Wonham theory," *IEEE Robotics and Automation Letters*, vol. 5, no. 1, pp. 48–55, 2020.