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REVIEW OF THE APPLICATIONS OF BUILDING INFORMATION MODELLING IN ROBOTICS

Byers, G.[1], RazaviAlavi, S.[2],*, and Kiavarz, H.[3]
[1] Department of Computer and Information Science, Northumbria University, UK
[2] Department of Mechanical and Construction Engineering, Northumbria University, UK
[3] Department of Earth and Space Science and Engineering, York University, Canada
* reza.alavi@northumbria.ac.uk

Abstract: Adopting robots in the construction industry can address the main issues existing for a long time in this industry, i.e., low productivity, high safety incident and injury rates, and skilled labour shortage. Due to the advancements in artificial intelligence, sensing and computing technologies over the past few years, robot applications for automating manual and repetitive construction activities have been rising. Dynamics, uniqueness, and complexity of construction sites are the primary hindrances for adopting robots in the construction environment. Building Information Modeling (BIM) can assist robots to overcome these hindrances by providing geometric, topological, and semantic data about the construction and built environment in a digital format. Recent studies have attempted to exploit BIM data for enhancing robot navigation, planning robot tasks, and construction progress tracking. This study aims to report the state of the art in the emerging applications of BIM in robotics through systematically reviewing the literature and providing the trend of the studies for utilising BIM in promoting robot applications in the construction industry.

Keywords: Building Information Modeling; Construction Automation; Robot; Construction Robotics; Systematic Literature Review

1 INTRODUCTION

Industrial progress through the adoption of Computer Science (CS) has allowed many important and populated sectors to advance at an unprecedented rate. However, the construction industry has failed to make the innovative leaps observed in other industries; this is largely attributed to the lack of technological innovation and underwhelming adoption of new technologies in the construction project lifecycle (Xue, Zhang et al. 2014). Uniqueness and unstructured nature of the construction and built environment (e.g., typology, shape, materials, components' function, appearance, etc.) have been the main challenges of using robots in the construction projects (Carra 2018). Consequently, most of the construction robots operate at a low level of autonomy (Liang 2021), which further limits their applications. One of the major technological gaps for autonomous construction robots such as Unmanned Ground Vehicles (UGV) is lack of integration with other systems and not enough knowledge dissemination (Czarnowski et al. 2018). BIM is one of the systems that can be integrated with construction robotics to bridge this gap.

In this research, the integration of BIM with robotic systems to aid, maintain and manage construction projects is explored primarily for autonomous robots navigating in the built environment. BIM models contain information to be used throughout the project lifecycle and contain geometric, semantic, and topological information of assets. Once this information is aggregated, it can be used to plan and support throughout the design, construction, and operation phase of an asset. Using BIM's information in cooperation with robotic systems such as Robot Operating System (ROS) can be instrumental to pushing towards Industry

4.0 and improving the areas in the construction projects that are dangerous or difficult to do on a regular basis. Other industries such as production and manufacturing have seen productivity increases when integrating robotic systems into the regular workflow both independently and in collaboration with humans (Brosque et al. 2020). The consensus is that human-robot collaboration and the integration of autonomous robots will enhance efficiency in the completion of construction tasks such as site inspections and material handling, which are considered repetitive, and often unsafe and expensive.

This research explores the current state of the literature regarding the applications of BIM in robotics through Systematic Literature Review (SLR). To this end, a keyword search is used on some of the most popular literary databases and subjecting the results to screening to collect the most relevant studies and identify trends throughout the citation library. The results are then discussed to identify the trend of the research in this area.

2 METHODOLOGY

In this research the Systematic Literature Review (SLR) method was used to collect and identify scientific papers that are relevant to the research by adopting a variation on the approach detailed in Kitchenham et al (2009). The process outlined in Figure 1 shows the methods and resources used during the SLR process in this research. The steps of this method are: (1) collect papers using keywords and statements from various platforms and databases (2) remove duplicate studies using citation tools such as EndNote (3) screen through study titles to filter irrelevant studies (4) determine if the studies meet the inclusion criteria by reviewing abstracts (5) evaluate the quality of the studies, and (6) extract useful information from the final selection of studies.

In the SLR process, the used keywords were BIM, Building Information Modelling, Robotics and Robot. To reduce the number of studies that are returned with little relation to the research, we specifically searched for the keywords of building information modelling with robotics, due to the saturation of studies on these individual topics. The primary databases for the literature aggregation in this research were Web of Science, Science Direct, and Scopus. The exact search terms used were:

- “BIM” or “building information modelling” + “Robotics” or “robot”
- “BIM” + “Robotics”
- “BIM” + “Robot”
- “Building information modelling” + “Robot”
- “Building information modelling” + “Robotics”

Due to the nature of this research, many of the studies that the keyword search provides are not directly relevant. Given the state of the construction industry, literature on the subject tends to focus on the lack of progression and CS adoption rather than outlining methods and tangible research that moves the industry forward. Furthermore, many of these studies are unrelated or duplicates available on multiple databases and therefore unusable in this research. Consequently, all results were cited using EndNote X9 to remove duplicates from the screening process. Once the citation library was completed and all duplicate studies were removed, 203 studies were left. This allowed the review to continue to the next stage in the screening process.

The next stage involves inspecting the title and abstract of each study to evaluate those relevant to this research, which is a more in-depth evaluation than what has been done during the initial screening. The search function of EndNote X9 allows to search titles for keywords; therefore, making the title screening process easier as the list of studies can be further reduced using the search terms specified at the start of the SLR process. At the end of this process, 137 studies remained for a detailed review and evaluation.

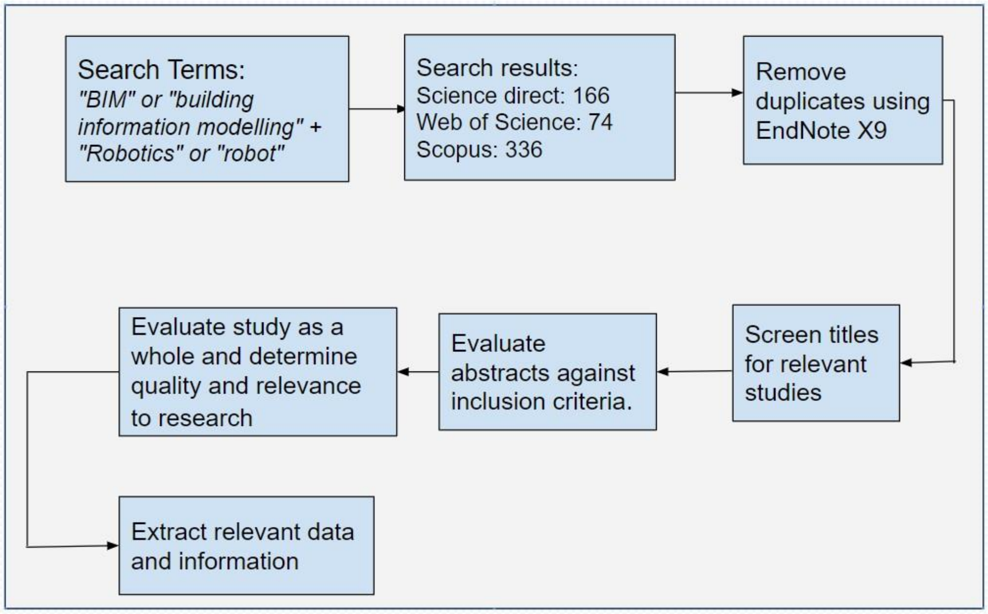

Figure 1: The steps for the SLR process

The studies deemed relevant are screened through their abstract and if the topic of the study is aligned with the research and all inclusion criteria are met; then, the rest of the study are evaluated and rated based on the quality and relevance to the research. For rating of the relevance, three categories are considered: high, moderate, and low. The papers are rated based on their relevance to this research and sorted into one of the three categories. This enables the reviewer to remove unrelated studies with ease from the citation database and group them accordingly. Upon completion, the most relevant category contained 32 studies, the studies with moderate relevance were 41, and finally the ones with low relevance were 64 studies.

This process ensures that the information collected from the sources is traceable and within the scope of the research, which improves the quality of the research. Once the studies have been evaluated, the relevant data and information is extracted and used to fortify the findings in this research.

3 RESULTS

Upon completion of the SLR process the number of relevant studies that are directly related to the adoption of BIM and the relation between BIM and robotics was 32. These studies have been mapped, categorized, and grouped to identify trends within the academic literature created around the applications of BIM in robotics. Table 1, 2 and 3 contain the studies from the SLR process that were the most related to this research. The tables provide a reference to each study, reference type, and a brief description of the studies.

Table 1-A: Summary of studies collected in the SLR process

Study	Problem Category	Reference Type	Description
Cai (2022)	Intelligent systems	Journal Article	Used AI to improve the interaction between BIM and robot systems for calibration and construction operations.
Chen et al. (2018)	Project management	Conference Proceedings	Explored solutions for addressing difficulties of transferring large and complex BIM models to robot systems to increase productivity in the construction industry.
Follini et al. (2021)	Inspection	Journal Article	Jsed BIM to provide a more inclusive environment for robotics on a construction site using BIM information to monitor progress on site.
Frías, et al. (2019).	Inspection	Journal Article	Used an algorithmic grid-based approach with BIM's information to calculate the optimum scan locations for monitoring progress in a construction environment.
Hamieh, et al. (2017)	Navigation	Serial	Used an algorithmic approach to improve indoor path planning using BIM information in a construction environment.
Hamledari et al. (2018)	Project management	Conference Proceedings	Improved the accuracy and effectiveness of BIM models over time by automating inspection using UAV visual data to update BIM models, bridging the gap between as built and as designed discrepancies.
Huston et al. (2014)	Inspection	Conference Proceedings	Used BIM and robotics for inspection of eroded structures through image processing and integration of robot sensing and BIM information.
Kang et al. (2012)	Inspection	Conference Proceedings	Tested various robotics vendors for quality analysis of as-built discrepancies to improve the quality and accuracy of the as-built structure in accordance with the BIM model.
Kayhani et al. (2020)	Navigation	Conference Proceedings	Used BIM's information and a tag-based approach to localization of UAVs to collect information on indoor environments in areas where GPS cannot be relied upon. This is done using information from a BIM model and tags in specific locations to provide localization within the indoor environment.
Kim et al. (2021)	Project Management	Journal Article	Used a combination of BIM's information and robot systems to allow task planning and scheduling for autonomous painting robots, and incorporated BIM for robot task planning and scheduling in a construction environment.
Liang et al. (2020)	Project Management	Conference Proceedings	Integrated BIM and Gazebo simulation to plan tasks in a digital twin, then transfer planning information to the robot in the physical space for safer and more effective co-operation between robots and humans in a construction environment.
Lundeen et al. (2019)	Project management	Journal Article	Used an algorithmic approach to integrating BIM and robot sensors to adapt work plans in a construction environment with low in-accuracy.

Table 1-B: Summary of studies collected in the SLR process (Cont'd)

Study	Problem Category	Reference Type	Description
Mattern et al. (2016)	General application	Conference Proceedings	Used robotic simulation to evaluate the economic and technical requirements for the integration of robot and BIM technologies.
Memon et al. (2022)	Inspection	Journal Article	Used a fleet of rovers to generate multiple 3D point clouds to combine for detailed 3D modelling for BIM modelling of existing structures.
Moura et al. (2021)	Navigation	Conference Proceedings	Used a 3D map generated from BIM information for faster localization and navigation in an unexplored construction environment.
Muhammad et al. (2021)	Inspection	Journal Article	Used a BIM-driven AI training for on-site inspection and BIM-based navigation to automate and improve the current method of site inspections using BIM information.
Patel et al. (2021)	Inspection	Conference Proceedings	Used a BIM-enabled Unmanned Aerial Vehicle (UAV) for project inspection in a construction environment and utilized findings to evaluate the usage of BIM-enabled robotics.
Prieto et al. (2020)	Inspection	Conference Proceedings	Proposed a methodology for developing inspection systems through BIM enabled intelligent robots equipped with 3D scanners and a gripper.
Qiu et al. (2021)	Navigation	Journal Article	Used a grid-based approach to map generation from BIM information both 2D topological and 3D grid-based maps were used for autonomous navigation for increased efficiency with path planning.
Sacks et al. (2020)	General Application	Journal Article	scussed the potential future applications of AI and BIM in the construction industry.
Schlette and Roßmann (2016)	Navigation	Conference Proceedings	Used BIM's information and motion planning to generate paths for navigation and conducted analysis on the paths to understand potential planning trends in the designed environment.
Shan et al. (2021)	Navigation	Conference Proceedings	Used an algorithmic approach to localization using sensor readings and BIM's information for the real-time localization in a BIM environment.
Siemiątkowska et al. (2013)	Navigation	Conference Proceedings	Developed semantic navigation with varying levels of abstraction to test the efficiency of semantic based navigation within a BIM designed environment.
Song et al. (2020)	Project management	Conference Proceedings	Developed an algorithmic approach to scan-based planning using LiDAR-equipped UAVs in a BIM designed environment and calculated the best collision free route to waypoints.
Tandur (2015)	Inspection	Conference Proceedings	Evaluated possible use cases for autonomous ɘd robots for the site inspection and construction tasks.

Table 1-C: Summary of studies collected in the SLR process (Cont'd)

Study	Problem Category	Reference Type	Description
Trabucco (2019)	Intelligent systems	Conference Proceedings	Assessed the future of the construction industry with the incorporation of intelligent systems, and the adoption of emerging technologies and the effects it will have on humans in the industry.
Wang et al. (2020)	Project management	Conference Proceedings	Used a BIM-defined digital twin to outline tasks for human robot interaction to create a safer and more efficient workflow.
Wu et al. (2021)	Project Management	Journal Article	ɘd a BIM-based algorithmic approach to increase efficiency and accuracy of orienting materials in a construction environment; therefore, reducing waste.
Zhang et al. (2022)	General Application	Journal Article	Presented a road map for integration of BIM and robotics in the construction industry and reviews BIM-related studies over an 18-year period.
Zhou et al. (2020)	Navigation	Journal Article	Combined grid based and topological maps and reviewed their effectiveness for navigation within a BIM environment.
Zhu et al. (2021)	Project Management	Journal Article	Explored solutions for allowing true cooperation between robots for construction tasks within a BIM environment.
Zhu and Liu (2021)	Navigation	Journal Article	Used BIM's information and an algorithmic approach to improve indoor navigation for construction and reduce the time taken to calculate paths.

4 PUBLICATION DATES

Figure 2 shows the publication dates for each of the studies present in the final stage of the SLR process. From the information contained in this figure, it is clear to see that the applications of BIM with robotic systems is a topic that is becoming increasingly investigated.

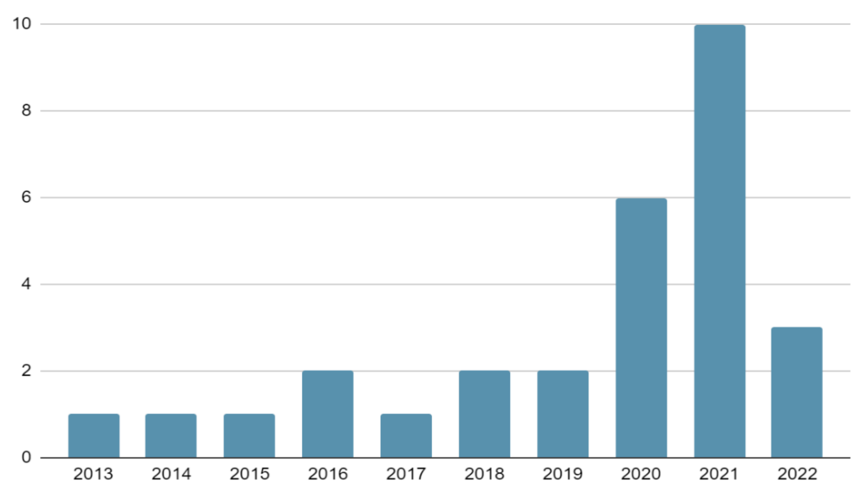

Figure 2: The publication dates of the studies collected in the SLR process

5 COUNTRIES OF PUBLICATIONS

Figure 3 shows the countries associated with the studies collected during the literature review. This information shows the countries around the globe that are most interested in the advancement of BIM and robot systems and the applications of these systems. It can be seen from the graph that China and the United States of America are the main contributors to the studies collected in this research. This shows the increasing interest around the world on integrating these systems into the existing construction workflow.

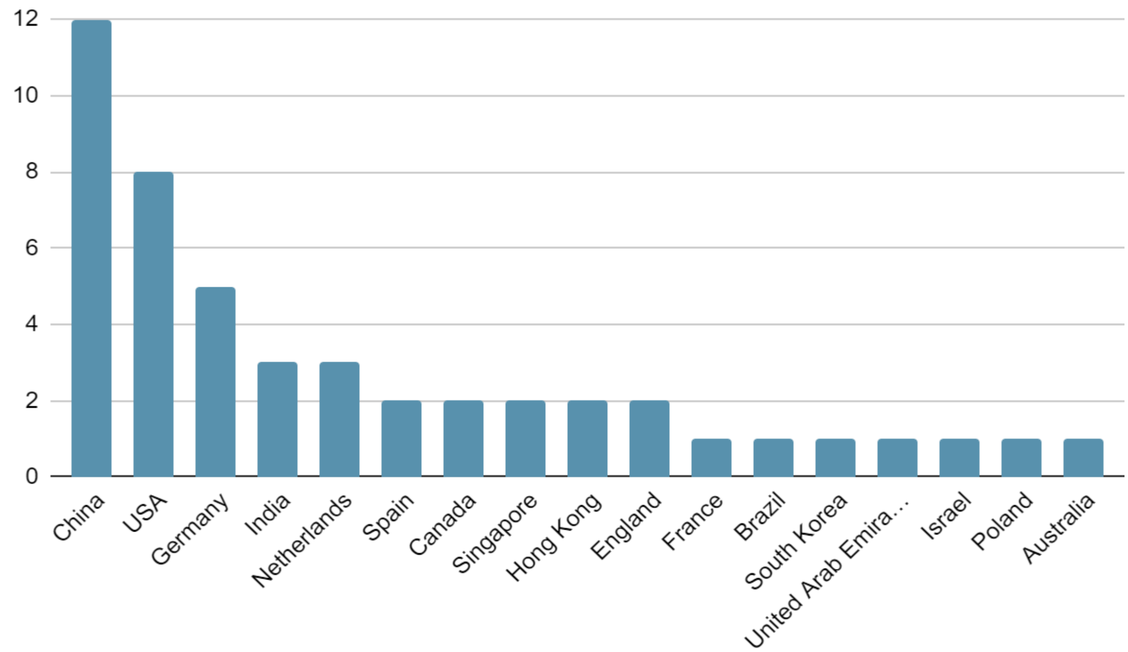

Figure 3: The countries containing the universities and institutions associated with the studies collected in the SLR process.

6 RESEARCH TOPICS

Figure 4 shows the problem category of each of the studies collected in the SLR. Through this figure, it is shown that the most explored applications of BIM are for project planning and management, navigation, and inspection of a construction environment. This shows the limitations of the existing construction workflow and the areas that stand to benefit from the active integration of BIM enabled robotics. From the studies on BIM-assisted navigation, it is shown that the consensus is that BIM can be used to save time mapping environments for Autonomous Mobile Robot (AMR) traversal as the geometric information from the BIM model can be used to navigate the space (Qiu et al., 2021). Another key area of the focus is automated inspection using BIM. Many of the studies combine environmental scans of the construction environment and the geometric information contained in the BIM model to monitor construction progress of the environment or perform inspection. This approach provides a promising solution to automated inspections using point clouds for an accurate representation of the “as-built” environment as shown in Memon et al. (2022). Another area containing a large portion of the reviewed studies is the “Project Planning and Management” group. This group contains studies such as Wang et al. (2020) that uses BIM to streamline the workflow between robots and workers in a construction environment and focuses more on implementing BIM to alter the construction workflow. This approach allows for better task allocation and structuring of an otherwise unstructured environment for robots. Finally, the “Other” group outlines various general applications of BIM into the automated construction workflow.

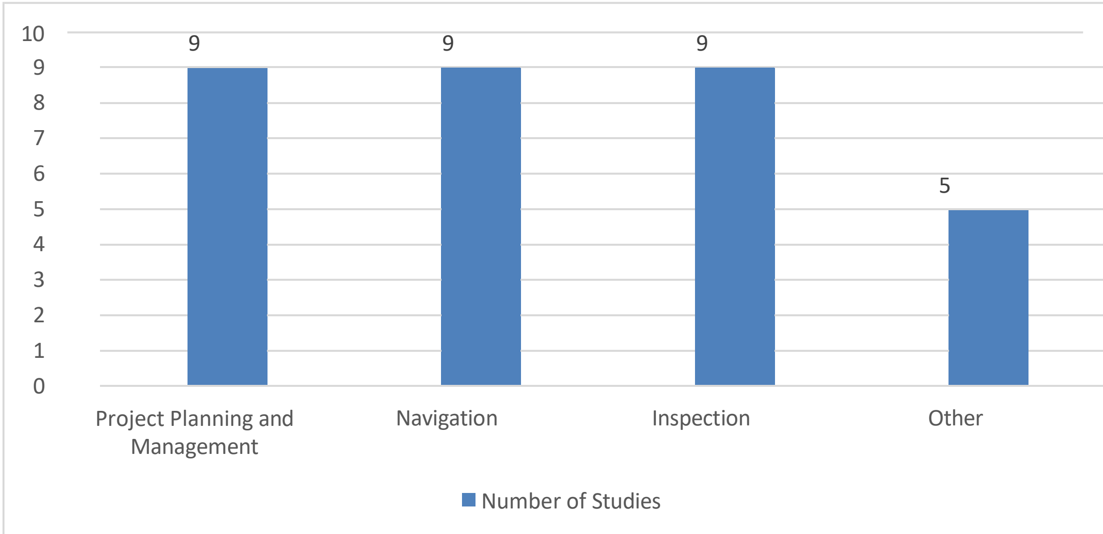

Figure 4: The number of studies utilising BIM to address a given problem

7 DISCUSSION

The results of this review revealed that a consensus among the construction industry is that integration of existing technologies can improve construction productivity and efficiency. For instance, Chen et al. (2018) suggested the idea of integrating the vast amounts of information contained within BIM with robotic systems will allow the construction industry to create a more intelligent and informed robot and overcome some of the existing challenges. The exponential increase in the number of studies published on the topic shows that with the increased adoption of BIM within the construction industry, the extended applications of the BIM framework is being considered. The trend shown in Figure 2 supports the statements made in Trabucco (2019) that the construction industry needs to invest their time adopting and integrating new technologies such as BIM and robotics to push towards Industry 4.0. Due to the asset metadata contained in BIM in each stage of the project, BIM integration with robotic systems introduces new opportunities to interact with robots in a more efficient manner and increase productivity and accuracy in the construction industry.

The trends found in Figure 4 show the key areas for the application of BIM in an automated construction environment and shows the areas that researchers feel BIM can be applied with the highest impact. Navigation, inspection, and project planning and management are all key areas that need to be mastered for the safe, accurate and efficient integration of robotics into the construction industry as it moves towards industry 4.0. Particularly, automated inspection and construction monitoring have a considerable potential for integration of BIM with robotics. Utilising the information contained in the BIM models to conduct inspections by robots and updating the BIM models as the project progresses can significantly improve construction productivity and safety as the existing methods require well-trained workers to enter potentially dangerous environments for conducting these inspections. Moreover, robots may be able to provide more accurate readings by using several sensors and scanners.

8 CONCLUSIONS

This research showed that the integration of BIM with robotic systems can improve the efficiency of the robots and provide them with more information than they would natively have. This information can be used to improve the construction industry in ways that will push towards a more efficient and technologically innovative operation than the one seen in recent years. The integration of BIM with robot systems can introduce methods and opportunities for improvement within autonomous navigation, maintenance inspection and various other foundational aspects for autonomous robot actions within the built environment. Continued integration between emerging technologies can stand to provide new applications to improve the construction industry, and incorporate more intelligent systems into the overall construction workflow. The reviewed studies show that the applications of integrated BIM and robotics can span from general navigation in a built environment to many other applications throughout the project lifecycle such as automated on-site inspection, and progress monitoring.

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