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Layout Modelling of the Built Environment for Autonomous Mobile Robots Using Building Information Modelling (BIM) and Simulation

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ABSTRACT
Robotics is a fast-growing technology in the construction industry, particularly in off-site construction and Modern Methods of Construction (MMC). Recent advancements in the technological sector have made robots more intelligent and capable of autonomously undertaking tasks. Navigation of the robots in the built environment requires analysis of robots' sensor data, which is computationally sophisticated and time-consuming. Modelling the layout of the built environment using BIM and simulation can reduce the computational burden of the sensor data analysis. This research aims to develop a method to transfer the geometry data from BIM models to virtual robots in the simulation environment and provide the robots with a priori knowledge about the built environment. This method is simple-to-use and can enhance robot navigation in terms of accuracy and efficiency. The method proposed has also been implemented in a case study to demonstrate its usefulness and practicality.

KEYWORDS
Robotics; Building Information Modelling (BIM); Simulation; Layout modelling; Construction Automation; Autonomous Mobile Robot (AMR)

INTRODUCTION
The technological advancement in robotics has made a boost in its applications within the construction industry, particularly in off-site construction and Modern Methods of Construction (MMC). Robots (e.g., industrial robot arms and Automated Guided Vehicles (AGVs)) are being utilized to automate labour-intensive and repetitive construction activities such as heavy lifting, assembly, and material handling. Using robots can address the underlying issues in the construction industry, including low productivity (Barbosa et al., 2017), high incident rate (Choi et al., 2011) and skilled labour shortage (Kim et al., 2020).

The recent evolution in artificial intelligence (AI), sensors, Internet of Things (IoT), and ubiquitous computing has made robots more intelligent, and capable of autonomously doing many tasks in the construction industry such as bricklaying, painting and site inspections. Conventional AGVs can navigate to predefined locations on the guide path by following fixed paths while AMRs can navigate to any accessible and collision-free location within a given environment (Fragapane et al., 2021). AMRs need to be able to 1) do task allocation, 2) do route/path planning to reach the assigned task's location 3) localize their location, and 4) navigate to the locations of interest. (Mantha, 2018). To this end, they may employ different sensors such as cameras, Light Detection and Ranging (LiDAR) or laser scanners for recognizing the environment, performing Simultaneous Localization and Mapping (SLAM), and navigating the environment by avoiding obstacles. Analyzing the acquired data from sensors in real-time requires the development of complex algorithms and high computational power for implementing the algorithms. In addition, data collection and data processing in an unstructured construction environment may entail errors in object detection and navigation, which cause safety concerns. Consequently, the construction industry has faced many challenges in widely using AMRs due to the uniqueness and unstructured characteristics of the construction and built environment (e.g., typology, shape, materials, components' function, appearance, etc.) (Carra 2018). Therefore, most construction robots operate at a low level of autonomy (Liang 2021).

BIM can address these issues by providing information on the layout of the built environment, which assists robots in navigation and selection of the quickest path before discovering their surroundings using the sensors. In addition, simulating the robot operation, and modelling the layout can identify some potential issues such as collisions and safety issues in a risk-free virtual environment. This research aims to use BIM and simulation for modelling the layout of the built environment and providing the robots with prior knowledge about the built environment. The proposed approach can enhance AMRs' navigation in the complex and unstructured construction environment in terms of accuracy, and reduce the computational efforts for discovering the environment by the robots.

The remainder of this paper consists of the literature review on using simulation and BIM for layout modelling. The next section succeeding the literature review explains the method developed in this research to use BIM and simulation in layout modelling of the built environment for AMRs. Following the methodology section, the implementation of the developed method in a case study is described. Finally, the last section summarizes the research with a conclusion.

LITERATURE REVIEW

Robots are commonly used in manufacturing and off-site construction plants. Researchers have developed many approaches for modelling, planning, and optimizing facility layouts in the plants to maximize the throughput. Simulation has been a suitable tool to model manufacturing or construction operations in a virtual environment and evaluate how the layout affects the efficiency of the operation. Zhang et al. (2019) developed a simulation-based approach for layout planning of a workshop, in which industrial robots and AGVs were utilized. Chen et al. (2019) attempted to optimize the size arrangement of the workstations in an AGV-based modular prefabricated manufacturing system using simulation and a genetic algorithm. RazaviAlavi and AbouRizk (2017a) developed an integrated genetic algorithm-simulation optimization method for facility layout planning of construction projects. For layout planning, some constraints such as safety and closeness constraints may exist. RazaviAlavi and AbouRizk (2017b) developed a simulation-based framework for decision making in site layout planning considering these constraints as well as project costs. Safety in robot path planning was considered by Praserttaweelap et al. (2018) using Particle Swarm Optimization (PSO) for AGVs in manufacturing plants. To facilitate using simulation for layout planning, some tools have been developed in academia and industry.

RazaviAlavi and AbouRizk (2021) created a simulation-based decision support tool for layout planning of construction projects. Siemens (Siemens Digital Industries Software, 2022) has developed a commercial simulation-based tool (Tecnomatix® Plant Simulation) for production and layout planning in manufacturing plants. Németh et al. (2019) used the Siemens Plant Simulation software for layout configuration, maintenance planning and simulation of AGV-based robotic assembly systems.

BIM has been adopted in several studies for layout modelling (e.g., Kumar & Cheng (2015)) and code compliance checking (e.g., Schwabe et al. (2019)). For AMRs, BIM information can help the robots in navigating and planning tasks within the built environment. In recent years, some studies focused on extracting, converting, and transferring BIM information to robots. Qiu et al. (2021) developed a method for extracting 3D indoor maps using BIM data and a grid-based approach for indoor robots and autonomous navigation. Kim et al. (2021) used BIM information enabling task planning and scheduling for autonomous painting robots. They developed a converter to generate a ROS-compliant world file from industry foundation classes (IFC) files allowing robots to conduct localization, navigation, and motion planning. Liang et al. (2020) integrated BIM and Gazebo simulation to plan tasks and create bi-directional communications between digital twin simulations and physical construction robots. They transferred work tasks from BIM to virtual robots in Gazebo, then planned their trajectories by sending commands to the physical robots.

METHODOLOGY

After reviewing the past literature, it was found that the usage of BIM has been recently extended in pathfinding and site inspection using AMRs. Figure 1 shows the relation and data flow between IFC, and the Gazebo simulated environment containing an AMR. Throughout the data exchange between the BIM model and an AMR in the Gazebo, the geometric information is converted into the SD format (SDF) to be recognized by the Gazebo simulation and added to the environment. The relevant floor plan is exported as an image to be used during the Portable Grey Map (PGM) image generation process; this map is then passed to the ROS nodes to allow for path planning. Other research (e.g., Follini et al. (2021)) has utilized BIM information for map creation in a BIM-designed environment using open-source libraries such as IfcOpenshell and Python Open Cascade (PyOCC) to iterate through the contents of an IFC file and construct a layout plan of the BIM model. The camera view of this layout plan is then converted into a PGM image file and used to map and plan within the environment. However, in this research, the exporting tools featured in the Autodesk Revit software were used to capture the floor plan before using a Python script to convert the image into a PGM image file; therefore, eliminating the use of IfcOpenshell and PyOCC for map generation. As the need for IfcOpenshell and PyOCC is eliminated in this approach, the issues around Python versions and the creation of environments that allow for these libraries to interact are avoided. Moreover, the approach detailed in this research is more viable as it does not rely on the availability and maintenance of IfcOpenshell and PyOCC libraries. Upon generating the PGM map of the designed environment, the map and accompanying YAML file are used by the move_base ROS node for cost map generation and localisation. The cost map generated by the move_base node is then used for path planning and execution through the move_base topic. Localisation within the environment is done using the Adaptive Monte Carlo Localisation (AMCL) ROS node through which the LiDAR sensors on the robot use readings in comparison to the PGM map information for localisation.

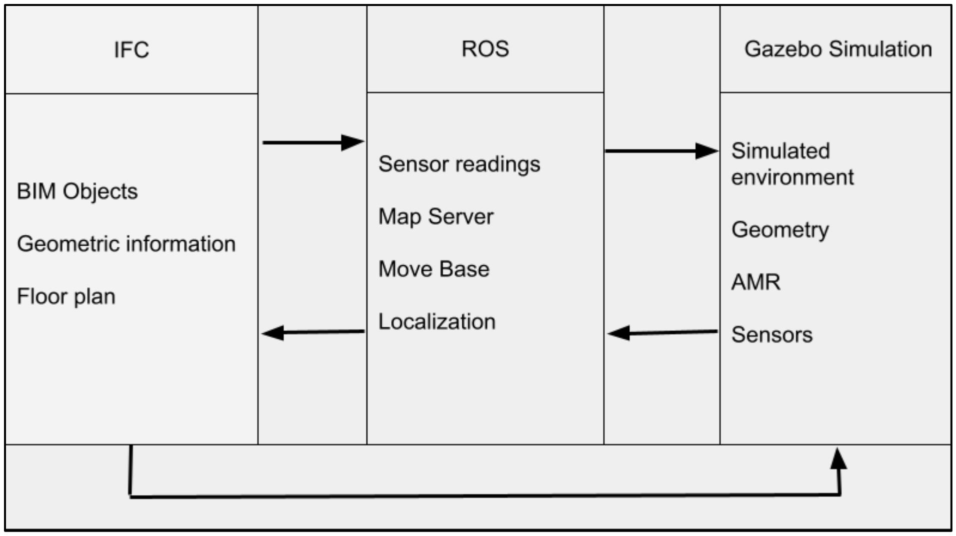

Figure 1. The data flow between Autodesk Revit, A Robotics Operating System, and Gazebo Simulation.

Navigation and Map Generation

The method used in this research for map generation for navigation within a BIM model utilizes the features present within Autodesk Revit to derive the relevant geometric information. Autodesk Revit was used due to its dominant position within the industry, and the vast amount of features it boasts. The information gathered from Revit is then subject to image processing through the use of the OpenCV python library to generate both the PGM and YAML files needed to translate the topological view of the BIM space into a format acceptable by the move_base ROS node. Upon publishing the PGM map to the “/map” topic the move_base node can be configured to generate local and global cost maps needed for navigation within the space. The cost maps generated allow for path planning and cost analysis and replanning based on the information acquired by Laser Scan or Point Cloud topics. This method allows for the BIM model to act as a foundation for navigation within the simulation environment and the map continues to update based on the information collected by the robot. Upon configuring this node along with the Adaptive Monte Carlo Localization (AMCL) ROS node for localization based on the sensor information collected by the robot, a cartesian goal can be provided to the move_base node. This is done through RViz or through publishing a Pose Stamped message to the move_base/goal topic, allowing for interaction with the node through Python and C++ scripts.

Geometry Transfer from BIM to Gazebo Simulation

Upon using the “Open IFC” option within Autodesk Revit, the IFC file containing the BIM model is loaded and both topological and three-dimensional views are available. When using the 3D view of the BIM model, the geometry information can be parsed from the BIM file through the use of the “CAD formats” branch of the export options featured in Autodesk Revit. Through these options, the geometry featured in the BIM model is exported to the Standard Tessellation Language (STL) format. Upon exporting the geometry information from the BIM model, it is then used as a mesh when building a custom Simulation Description Format (SDF) model to be used within the Gazebo simulator. This makes the model a 1:1 representation of the geometry information contained in the BIM file; once the model is defined, it is added to the robot simulator as a static model to be traversed.

CASE STUDY

The developed method was implemented for transferring the geometry of a two-story building from Revit (Figure 2(a) and Figure2(c)) to Gazebo (Figure 2(b) and Figure2(d)). Through these figures, it can be seen that the environment has successfully been converted to the SDF format and added to the Gazebo simulation. In this case study, two scenarios were experimented with: Scenario 1, where the BIM environment is navigated using a PGM map generated using BIM information and Scenario 2, where the AMR uses a sensor-generated map to navigate through the environment.

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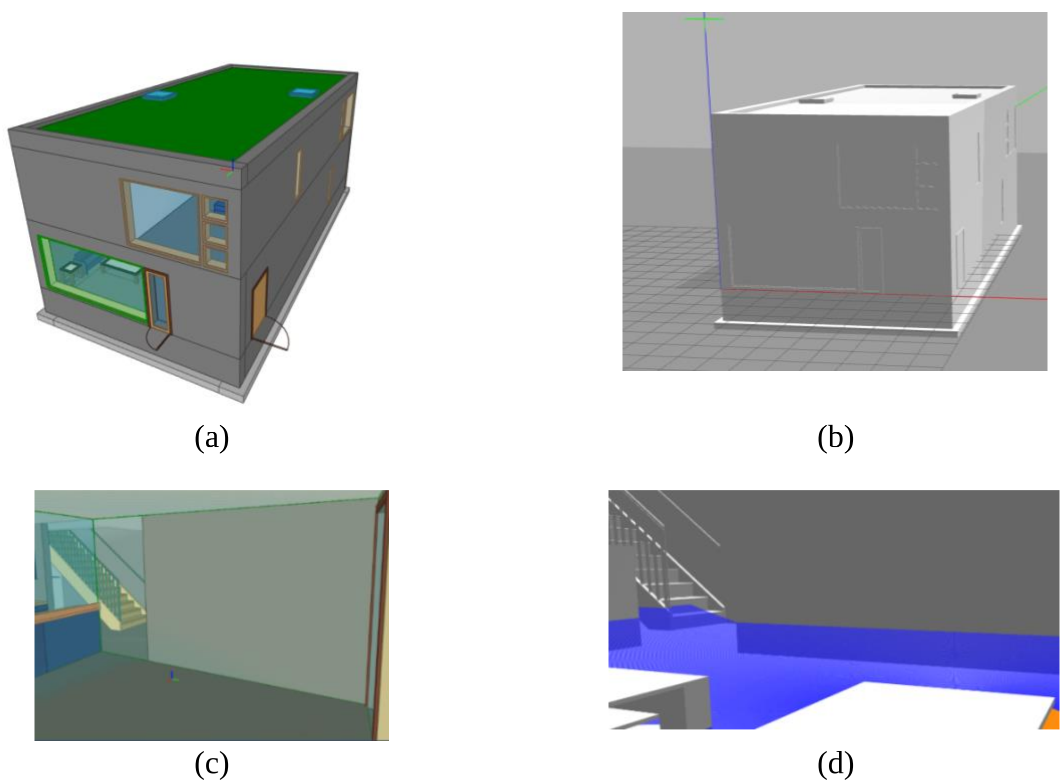

Figure 2. BIM and Gazebo views of the built environment and layout: (a) view of the building in Revit, (b) view of the building in Gazebo, (c) a layout view inside the building in Revit, (d) a layout view inside Gazebo

Navigation and Mapping

Figure 3(a) shows the PGM map created using information derived from the IFC file loaded into Revit. This map describes the layout and allows for navigation within the built environment, which was modelled from the original unedited BIM model. Using this map, Figure 3(b) shows the paths created by the AMR when given a goal position beyond a dividing wall. In Figure 3(b) the AMR uses the PGM map information to avoid the wall as it does not use the sensors to detect discrepancies within the environment; therefore, directing the route through the doorway opening. However, as shown in Figure 3(c), the map generated by the AMRs sensors is of lower quality and only contains the room that the AMR has occupied. The path generated using the sensors shows some clipping with the dividing wall due to the lower quality of the map; this path will be updated as the AMR approaches the dividing wall. From the computational time, it took on average 2.45 minutes to generate the map using the BIM information, and the python script (i.e., Figure 3 (b)) for both the PGM map and YAML files, which contains the entire first floor. In contrast, the sensor-generated map, shown in Figure 3(c), took on average 8.33 minutes to generate a map for the room occupied by the AMR. This map does not include the rest of the first floor though due to the mirrored nature of the BIM geometry, it would take approximately 17.06 minutes to map the first floor in its entirety.

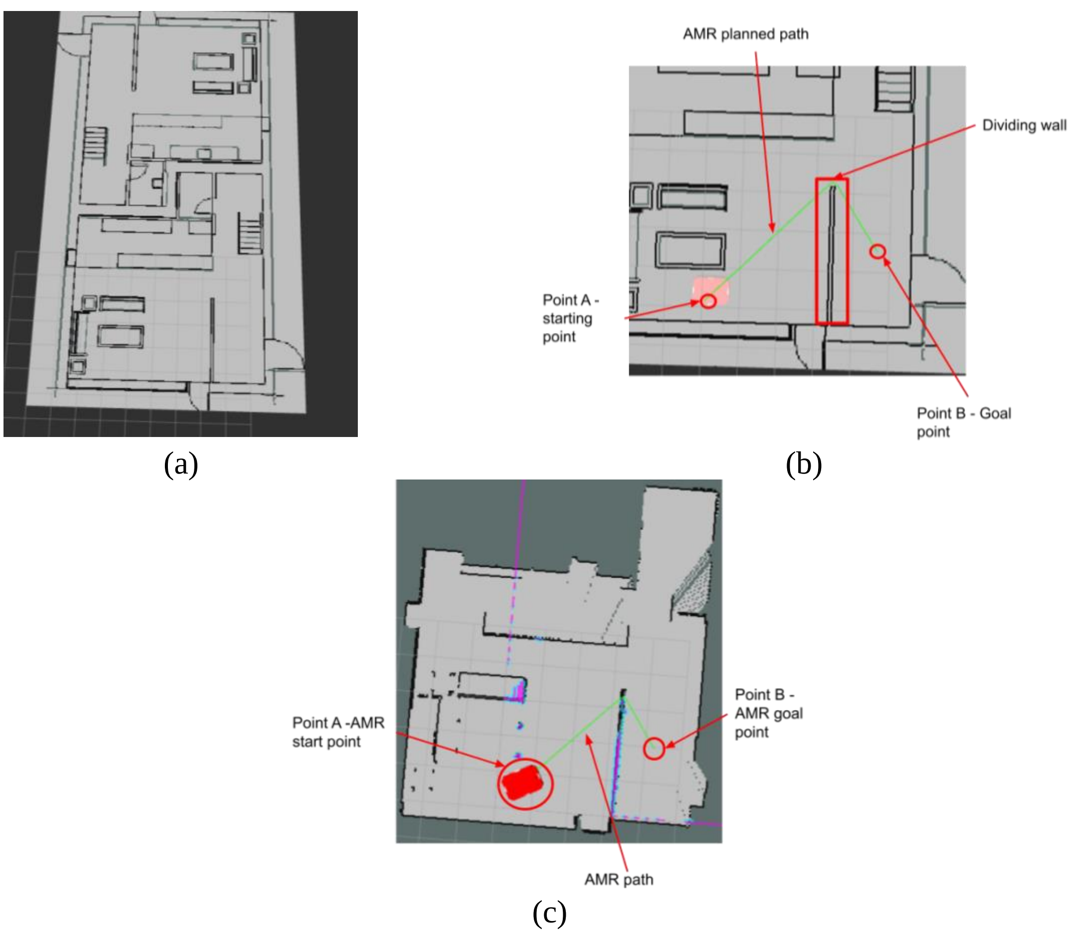

Figure 3. RViz views of PGM maps and AMR paths: (a) PGM map created using BIM information, (b) AMR pathing information based only on PGM map created using BIM information, (c) AMR pathing information, and the generated map based only on sensor readings

Through the case study, it was shown that without manually exploring the environment using the AMR and mapping using SLAM GMapping, the AMR is able to generate paths using the BIM information and navigate through the environment. Figures 3(b) and 3(c) show that the paths generated using the BIM information are more accurate, and the generated maps contain more information than the map generated using SLAM GMapping. This method of navigation allows AMRs moving within the built environment to utilize the BIM model for immediate navigation within the space; therefore, increasing the efficiency of the AMR operation.

CONCLUSION

This research outlines a method to extract the BIM geometry data, and transfer it to robot simulation (i.e., Gazebo) for modelling the layout of the built environment. This method assists AMRs to navigate more efficiently by providing prior knowledge about the environment to the robots for path planning. In a case study, it was shown how the information acquired from the BIM model was used for the creation of the PGM maps, and enhancement of the robot navigation within the simulated environment. In addition, it was observed that this BIM-enabled approach can significantly reduce the time for robots to discover their surroundings. This research was experimented within the simulation model as a proof of concept. In future research, an experiment can be conducted with a robot in a real environment to further substantiate the applicability of the developed method.

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