A Methodology to Monitor Construction Progress Using Autonomous Robots

S. A. Prieto [a], B. García de Soto [a] and A. Adán [b]

[a] S.M.A.R.T. Construction Research Group, Division of Engineering, New York University Abu Dhabi (NYUAD), Experimental Research Building, Saadiyat Island, P.O. Box 129188, Abu Dhabi, United Arab Emirates

[b] 3DVC&R Laboratory, University of Castilla-La Mancha, 13005 Ciudad Real, Spain

E-mail: Samuel.Prieto@nyu.edu, garcia.de.soto@nyu.edu, Antonio.Adan@uclm.es

Abstract –

In recent years, new technologies have improved the monitoring of construction progress by using the as-planned BIM of a building and comparing it with the current state of construction (i.e., the as-is model) to identifying differences and generating a progress report. However, in most cases, the different components required for the progress reports are still done by human operators. Those inspections typically consist of time-consuming and repetitive processes, making them a great candidate for automation, which can improve the quality of the methods used to monitor and assess the progress of buildings during the different construction phases.

This study proposes the development of an autonomous robot equipped with different sensors to collect data that can be used to conduct an automatic assessment of the state of construction, improving the current tedious and error-prone data collection and documentation processes. The proposed methodology is divided into three components: 1) Development of a robotic system able to navigate through construction sites in an autonomous way, 2) Data collection, and 3) Comparison of as-is with as-is conditions to identify discrepancies and generate a progress report. This paper focuses on the first two elements of the process.

The proposed robot is equipped with a 3D Terrestrial Laser Scanner (TLS). In addition, a robotic arm with a gripper is included so the robot can interact with different elements to achieve an autonomous robust robotic system. To test the autonomous navigation of the robot (including obtaining the optimal path through the building), the actions of the robotic manipulator, and the generation of the progress report, a simulation test was developed under the framework ROS (Robotic Operating System).

Keywords –

Progress Monitoring; Autonomous Robot; IFC; Inspection; Scan to BIM

1 Introduction

During the last years, new technologies have made the assessment and inspection of buildings much more efficiently and with better quality. However, in many cases, these inspections and assessments are still done by human operators who can induce errors in the process. Thus, a typical manual inspection entails time-consuming and repetitive processes that are usually carried out by two operators. This all leads to that, after some time, the operator is more susceptible to making mistakes and, therefore, might report a wrong assessment. The importance of the construction in the last years has brought to the table a need to automate and improve the quality of the methods used to assess buildings along with the different phases of construction projects.

By using an autonomous robot equipped with different sensors, an automatic assessment and inspection system can be used to perform this task, improving its quality and making it a much faster process.

The proposed methodology is divided into three components: a) development of a robotic system that can navigate through construction sites in an autonomous way (navigation and localization algorithms), b) data collection and c) analysis to quantify installed items, comparing as-is with as-planned conditions (BIM and project schedule). The work presented in this paper focuses on the two first components and provides details of the autonomous robotic system.

1.1 Previous work

The rising popularity of BIM models has allowed construction professionals to plan in a much more organized way all the construction processes before actual construction begins. However, up to this date, there is still a gap in how to keep track of the actual progress of construction tasks in an efficient way.

Photography and visual inspection are nowadays the most common way to compare the as-built model with the BIM reference (i.e., as-planned model). That means that someone has to collect all the images through the construction site and later inspect them in order to generate a report. In general, this process is very tedious, time-consuming, and human dependent, meaning it can lead to inaccuracies and subjective assessment regarding the actual state of construction.

With the development of terrestrial laser scanning (TLS) technologies, some of these reports are now being generated by using 3D point clouds [1]–[3] instead of visual inspection or 2D photographs [4], [5]. This process has significantly improved the way the as-built model is compared with the as-planned BIM model, with the point cloud containing a much higher density of data and, therefore, allowing the operator to inspect the building in more detail. However, a higher amount of data implies longer time requirements for the inspection and report generation. In addition, this 3D data collection is still supervised and handled by a human operator, which again is a very time-consuming process.

Research has already been done regarding the data processing stages [6], [7], improving the autonomous data analysis characteristic of the process. Automatic segmentation algorithms are able to analyze the raw data coming from the 3D point clouds and identify the different structural elements of the building [7]–[13]. Some of them focus on general aspects of the building, such as the recognition of large indoor spaces [7]. Others concentrate on particular structural elements such as the detection and identification of cylindrical components [13], which can later be used in order to assess the proper location and type of the installed components. The use of additional information such as thermographic data [14] can also be used in order to identify the structural elements. This way, an automatic report can be generated by comparing the generated as-built model with the as-planned BIM [3], [15]–[17].

However, few approaches deal with the automation of the data collection process. By automating the data acquisition, the whole process can become completely autonomous, and the system would be able to automatically collect the data, generate the model, and create a report to assess the progress of the building. Adan et al. [18] propose an autonomous system in order to gather data from the building and to generate an as-is model; however, it does not take into account the as-planned BIM model. Ibrahim et al. [19] present an autonomous robotic platform able to collect 3D geometric and RGB data from the building. The data acquisition process has to consider that the quality of the data must be good enough in order to process the information and generate the model [20]. Therefore, a good strategy has to be designed, considering the fact that the BIM model of the building is available, which can be used to obtain the floor plans in order to plan a valid path.

The method proposed in this paper fulfills the aforementioned requisite, hence becoming a fully autonomous system that automatically collects data using the existing (as-planned) BIM model, navigates through multi-story buildings, collects and processes data to generate a progress (as-is) model of the building, and later compares the as-is model with the as-planned model in order to generate a progress report of the building by identifying discrepancies found in terms of quantities, dimensions, locations, etc.

The scope of the work presented in this paper focuses on the autonomous collection of the data. It does not consider the generation of the as-is model and the progress report. The rest of this paper is organized as follows. Section 2 presents the proposed robotic system and an overview of the main points from the data collection process. Section 3 gives a preview of the work conducted by the authors related to the model generation and automatic comparison between the as-planned and as-is models with the ultimate goal to generate progress reports in an automatic way. Section 4 shows the experimental tests for the navigation and data collection in a simulated environment. Finally, Section 5 summarizes all the work.

2 Robotic system and data collection

This section addresses key elements of the robotic system and the overall process of the collection of data that would be used for the generation of the as-is models.

2.1 Robotic system

This section presents the different aspects related to the required characteristics of the mobile platform. Due to the complexity of the approach, a well-designed and equipped robotic platform is necessary. The platform is mainly composed of three elements, the mobile robot, the sensors, and the actuators. An example is shown in Figure 1.

2.1.1 Mobile robot

First, the locomotion aspect. Robots used in construction are usually limited to either tracks, legs, or outdoor all-terrain wheels [21], [22]. These locomotive systems are efficient when it comes to moving through rough terrain; on the other hand, they are not very precise, and they can be difficult to control in small indoor scenarios. However, means and methods of construction, as well as construction materials, have evolved during the last few years, making construction sites more approachable to robotic systems. For example, drywall is widely used for indoor construction, which, when compared to using bricks or any other conventional construction method, does not generate that much debris or dust.

(a) (b)

Figure 1. (a) Robotic platform based on Robotnik Kairos with UR10-e, (b) 3D scanner (Leica BLK 360)

Therefore, all-terrain locomotion systems are no longer necessary to achieve optimum navigation through a construction environment. Omni-wheels or any other kind of holonomic system would allow the robot to achieve much higher levels of control and precision, without sacrificing freedom of movement through the construction site.

2.1.2 Sensors

One of the key aspects is the localization system of the platform. GPS or any other satellite-based localization systems are widely used for outdoor scenarios, achieving a reliable and precise real-time position of the robot. Since our project is aimed to work indoors, this is not a valid option. Visual-based localization systems would need to have markers installed through the construction site. Since the approach is designed for the robot to be working in different stages of the construction process, this environment might be in constant change, which would not make the installation of visual markers a reliable method. Since the BIM model of the building will be available, information from the floor plans will be used in conjunction with LiDARs in order to obtain a precise and real-time position of the robot.

The type of data that the robot needs to collect includes, but is not limited to, structural geometry data of the building, thermal information, colored visual information, and surface reflectance information. Therefore, several sensors, such as 3D scanners, thermal cameras, and RGB-D cameras, are needed. The 3D scanner could be similar to the Leica BLK 360 (Figure 1b), which provides 3D geometric data, RGB color data, and thermal infrared data. This scanner also has a wide FOV of 360° (horizontal) / 300° (vertical) and a range of up to 60 m, which for most interior applications is more than enough. The ranging accuracy is 4 mm @ 10 m / 7 mm @ 20 m. Owing to its reduced size and weight (165 mm in height and 100 mm in diameter, and 1 Kg), this is a good scanner candidate for a mobile robotic platform.

2.1.3 Actuators

Finally, in order to facilitate a fully autonomous behavior on the scene, the robot will need to interact with the environment (e.g., obstacle removing, door opening, elevator access). To do this, a robotic arm with a suitable gripper is placed at the base of the robot. Given the platform will move through an inhabited construction site, populated with other construction workers, it is a must that this system complies with the collaborative robot background. This means the robot must be safe enough to be able to work side by side with human beings. The chosen robot arm, UR10-e, belongs to the spectrum of collaborative robots.

2.2 Navigation and data collection

The overview of the entire process is shown in Figure 2. This subsection presents the different elements related to 'Part 1: Flor plan extraction' and 'Part 2: Autonomous navigations & Data acquisition'.

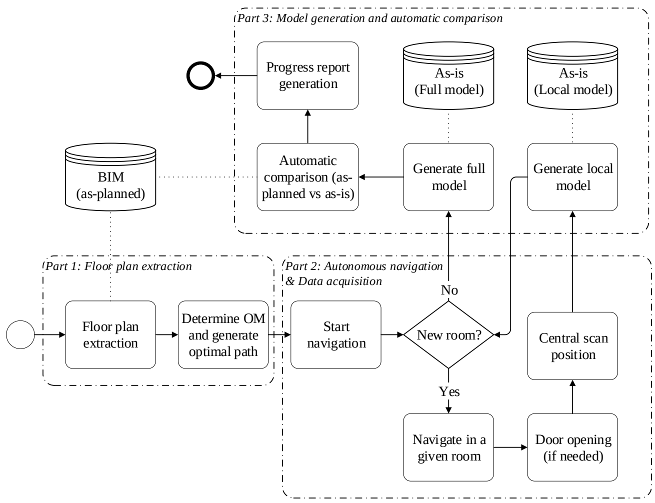


Figure 2. Overview of the navigation and data collection process

2.2.1 Floor plan extraction

All valuable information extracted during the 3D data processing stages is used for the positioning and secure navigation of the mobile robot. This consists of the following stages.

2.2.2 Optimal path generation

The only input the system is getting from the very beginning is the Industry Foundation Classes (IFC) file of the building. This file contains all the information related to the BIM model. A proper methodology to understand the structure of the file needs to be developed to automatically extract the information needed for each one of the stages (Figure 3).

Since a single file can describe multiple buildings, the first distinction that can be found inside an IFC file is the building tag. Under the building tag, there are multiple levels or stories of the building. Within the same level or story, all the defined spaces can be extracted, that is, all the different rooms and corridors inside the same floor. Lastly, the rooms and connections between the different spaces can be identified (Figure 3).

One of the main things to be considered in order to extract the information from the IFC file is the type of information present in it. The definition of the spaces, for example, can be provided in different ways in the tag IFCSHAPEREPRESENTATION [23]. There are multiple types of representation, but they can be separated into three main blocks: 2D curve representations, solid model representations, and surface model representations. The ideal scenario is the one where all the available representations can be found within the same file, in order to access each, one of them depending on the kind of information that needs to be extracted.

At this point, all the information required to proceed with the first step in the process has been extracted. Now, in order to provide the robot with a safe and approximate representation of the scene, an obstacle map (OM) of the current floor needs to be generated. This will guarantee safe navigation. The OM is obtained from the accumulated point cloud and the current floor plan (i.e., map).

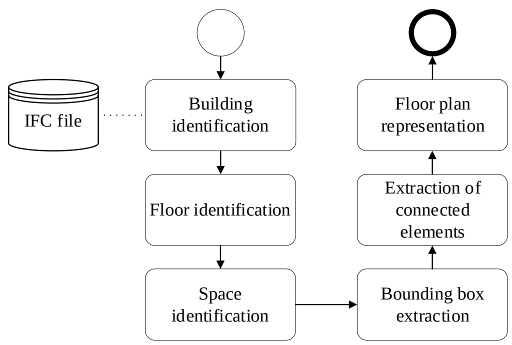
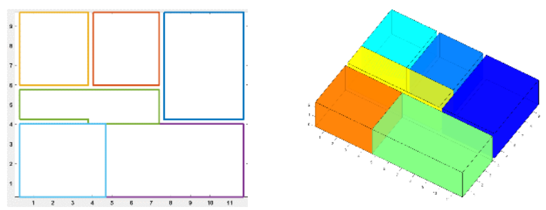


Figure 3. Structure within the IFC file in order to extract the floor plan representation.

In order to alleviate the post-processing stages, the 2D curve representation would be of a suitable type to extract the 2D floor plan (i.e., map) from the IFC file. If the IFC file does not contain a curve type representation, the 3D solid model or face representation (BREP) could then be used to generate the 2D map. Figure 4 shows a 2D curve representation and a BREP representation extracted from two different IFC files.

With the 2D representation of the floor plan extracted, a morphological set of operations are applied in order to generate a binary occupancy map, that is, the OM of the robot.

The robot will always begin the autonomous data acquisition process in the center of a room, indicated by the user as an input. In order to visit the other rooms on the same floor, a global navigation algorithm generates a room visiting schedule. According to this schedule, the robot moves towards the closest non/visited following room, updating on each iteration the list of visited rooms (Figure 5). More details on the generation of this schedule can be found in [18].



(a) (b)

Figure 4. (a) 2D and (b) BREP representations extracted from the IFC.

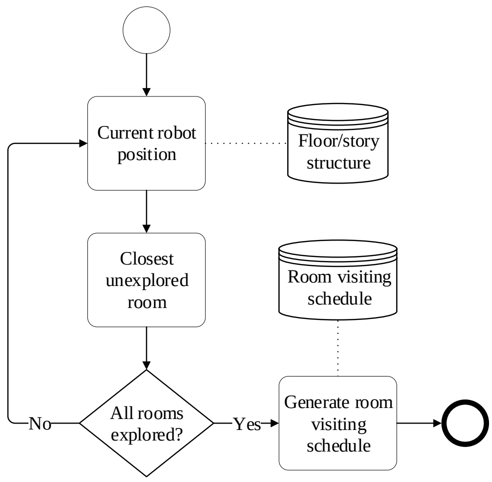


Figure 5. Generation of room visiting schedule.

The generated path needs to make sure that the robot visits all the individual rooms of the building, maximizing the coverage of all the structural elements present in the construction site.

This OM gets updated with each single scan performed by the robot before moving to the next goal, in order to add all the obstacles not present in the floor plan extracted from the IFC file.

2.2.3 Autonomous navigation

In addition to obtaining the map, the robot needs to know its position inside the map. This is accomplished by matching the data points provided by the LiDARs with a horizontal slice obtained from the point cloud at the height of these LiDARs, combining it with the boundaries of the 2D floor plan extracted from the IFC file. This is done using an Adaptive Monte Carlo Localization (AMCL) algorithm [24].

The path planning algorithm then yields an off-line theoretical path that the robot must follow by moving towards the different locations based on the existing BIM model. This path will have different stages. First, the robot needs to exit the current room, and therefore a path towards the exit door will be generated. Once the robot is in front of the door, it has to determine whether the door is either open or closed. This can be achieved by reading the front LiDAR data in order to detect a void. If the door is closed, a door opening approach will be executed. If the door is open, a second path will then be generated towards the entry room of the next room in the visiting schedule. Again, a procedure that detects the state of the door will be executed, with the door opening approach performed if needed. The third and last path in the sequence aims to lead the robot towards the center of the room in order to perform the next scan.

The NAVFN path planning algorithm will be used for the robot to navigate between goals. It is the most common global planner used in ROS (Robotic Operating System). This path planner is based on the Dijkstra's algorithm [25] approach.

If the robot encounters a closed door on its way to the final goal, it will begin a door opening approach. Since the coordinates of the door are already known from the IFC file, the robot will position itself in front of the door, in order to perform a detailed scan of the center section to detect the doorknob. Once the doorknob has been detected and the main parameters that define the door have been identified, the robot can safely open the door and continue its path towards the center of the room. A more detailed explanation of the door opening process can be found in [26].

The localization and the autonomous navigation would be implemented first in a simulated environment and then transferred to the real robot. This paper only focuses on the simulation part.

2.3 Data acquisition

As previously stated, every time the robot enters a new room, it performs a new scan from the center of the room. Of course, this will vary depending on the shape of the room. For example, corridors are treated as rooms by the algorithm, but due to the geometry of corridors, if the length of the room is larger than the maximum range of the 3D scanner, more than one scan will be needed to obtain the full geometry. That is why some factors need to be taken into account in order to compute the number of scans needed to digitize the room in its entirety. These factors depend mainly on the size of the room, the range of the scanner, and the shape of the room itself (concave or convex rooms).

The 3D scanner provides not only geometric data but also RGB, reflectance, and thermal information. This means that the generated point clouds have different layers of information, which will be used in subsequent 3D data processing stages.

In addition, all the data is progressively registered using the localization data coming from the robot. This position is obtained by fusing the data coming from the wheels odometry (read by the wheels' encoders), the Inertial Measurement Unit (IMU), and the output from the AMCL using the LiDARs. Also, all the data is time-stamped for further inspection. This data is registered for each room (in case multiple scans were needed for a single room), resulting in multiple raw local models representing different rooms of the current floor.

The resulting raw data is an accumulated point cloud of the whole building or a global model composed of all the singular 3D point clouds obtained in the different rooms. This accumulated point cloud includes all the sub-layers containing information about the surface reflectance, the 3D geometry, the RGB data, and thermal information captured by the cameras embedded in the Leica BLK 360.

3 Model generation and automatic comparison

After completing all the tasks indicated in Section 2, the raw data acquired is not structured in any way. Semantic meaning to all the collected data through the different stages of the process needs to be added. This is where the as-is model generation comes in place. Due to space constraints, only key components of these elements form the overall process are presented below.

3.1 As-is model generation

The segmentation process is aided by the fact that a semantic model of what the building is supposed to look like (i.e., as-planned BIM model) is available. Therefore, the raw data only needs to be fitted to the already existing model.

In order to do that, the first thing is to identify the envelope of each space. That is, a BREP representation of the current state of the building. For that, the BREP representation obtained from the BIM model in earlier stages will be used. With the obtained geometric faces, the raw 3D data obtained from the building is fitted to the planes defined by the BIM model, locating which ones have or do not have data. This will determine whether the plane has been constructed or not.

Based on the existent data, it can be determined which of these faces is present in the current model and those that are not.

3.2 Autonomous progress report

With the as-is model generated from the raw data obtained, the evaluation of the progress of construction can be done. With the semantic information for the main elements of the building, such as walls, ceilings, columns, floors, as well as secondary elements like doors, windows, and wall-mounted objects, a progress report can be generated. This progress report would contain, amongst other things, the percentage of completion of all these elements with respect to the planned schedule.

4 Experimental test

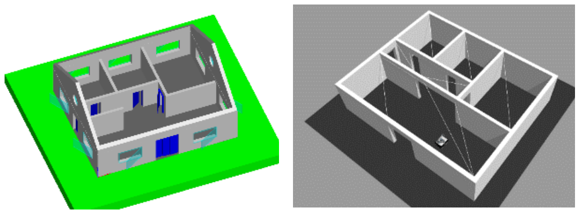
This section summarizes the experimental tests for the navigation and data collection under the framework ROS using the robot simulation software Gazebo and Blensor in a simulated construction environment.

4.1 Simulation test

In the current state of the research, the first part of the approach has been tested in simulation, successfully extracting the information from the IFC file and achieving autonomous navigation throughout the simulated environment.

Given the widespread use of BIM, there are plenty of available resources with different IFC files presenting different characteristics. For the current test, a simple two-story building was used. Given we are only testing the automatic IFC feature extraction and the autonomous navigation, the test focused on just the first story of the building, since the movement between floors is not the goal of this paper.

Multiple software is used in order to perform these simulations. First and foremost, Revit is used in order to inspect the IFC file and modify the state of the simulated building if needed (Figure 6a). For the robot simulation stages, the Gazebo simulation tool, natively working in ROS, was used (Figure 6b). This platform can test the different approaches regarding the robot, such as the localization and autonomous navigation or the door opening techniques. In order to obtain simulated 3D data, the Blensor add-on for the Blender software [27] is used. Finally, MATLAB is used to extract the features, control the robot, and process the obtained data.



(a) (b)

Figure 6. (a) Visualization in Revit of the IFC file of the tested building. (b) The same model inserted in Gazebo.

Once the building has been simulated with the information from the IFC file, the outline geometry of each one of the spaces within the floor is extracted from the IFC file. The location and size of each one of the openings (i.e., doors) are included in this map containing the previous information, and after applying an infill morphological operation to the void spaces between the different outline of the spaces, an OM map for the robot is generated (Figure 7).

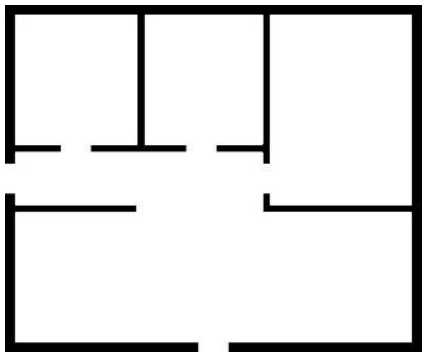
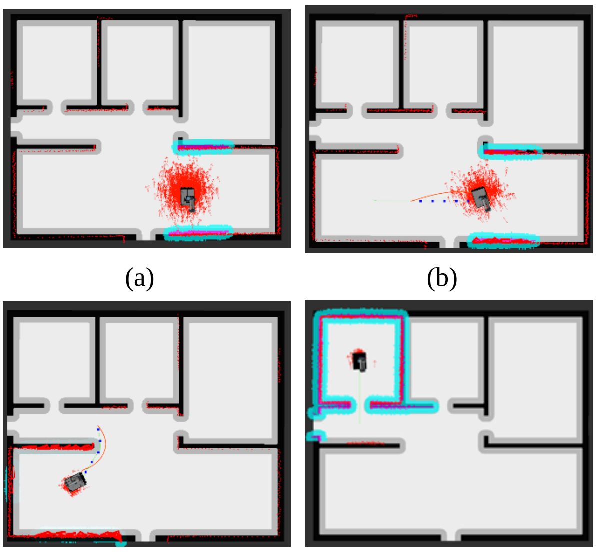


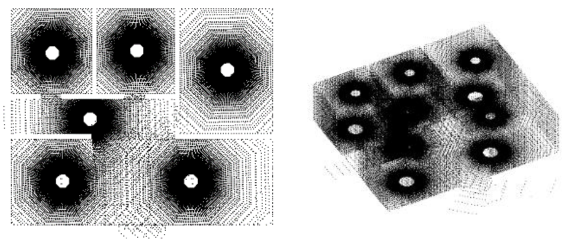
Figure 7. Obstacle map obtained from the information retrieved in the IFC file.

By using the obstacle maps and the inter-room navigation algorithm, the robot can autonomously visit the entire floor. Figure 8 shows the robot autonomously planning a path to navigate through the different rooms. In this figure, the cloud of small red arrows surrounding the robot represents the uncertainty in the position of the robot. That is why in its initial position (Figure 8a), the uncertainty is bigger than in the following positions, where the robot has already navigated through the scene and fully identified its localization. The local costmap calculated by the local planner is represented by the blue cells surrounding the obstacles. Figure 9 shows the accumulated raw data collected by the robot after performing a 3D scan in each of the visited rooms.



(a) (b) (c) (d)

Figure 8. Scenes representing different stages of the simulation process. (a) First initial position of the robot. (b) and (c) Robot moving towards the next goal, where the path generated by the global planner (red line) can be seen. (d) Robot completely localized within the map.



(a) (b)

Figure 9. Top (a) and 3D (b) view of the raw data collected by the robot at the end of the process.

5 Conclusions and outlook

This paper presents the early stages of what aims to be an autonomous approach to perform inspections during the construction process in order to generate a progress report automatically.

Given a generic IFC file, a methodology to automatically extract all the different elements of a building has been presented.

A test, under simulation conditions, has been conducted on an IFC file of a two-floor building. Our system computes 2D obstacle maps, takes simulate 3D data of the rooms, and provides safe autonomous navigation of the robotic platform.

Ongoing work focuses, on the one hand, on developing new 3D data processing algorithms, in order to provide a semantic as-is 3D model of a multi-floor building. On the other hand, we aim to establish a procedure that easily compares as-planned to as-is 3D models and automatically generate a building progress report. This work also includes testing the findings from the simulation using the proposed robotic system in a real-world environment.

References

[1] C. Feng, Y. Xiao, A. Willette, W. McGee, and V. R. Kamat, “Vision guided autonomous robotic assembly and as-built scanning on unstructured construction sites,” *Autom. Constr.*, 2015.

[2] C. H. P. Nguyen and Y. Choi, “Comparison of point cloud data and 3D CAD data for on-site dimensional inspection of industrial plant piping systems,” *Autom. Constr.*, 2018.

[3] C. Kim, C. Kim, and H. Son, “Automated construction progress measurement using a 4D building information model and 3D data,” *Autom. Constr.*, 2013.

[4] L. Klein, N. Li, and B. Becerik-Gerber, “Imaged-based verification of as-built documentation of operational buildings,” *Autom. Constr.*, 2012.

[5] A. Bhatla, S. Y. Choe, O. Fierro, and F. Leite, “Evaluation of accuracy of as-built 3D modeling from photos taken by handheld digital cameras,” *Autom. Constr.*, 2012.

[6] V. Pətrəucean, I. Armeni, M. Nahangi, J. Yeung, I. Brilakis, and C. Haas, “State of research in automatic as-built modelling,” *Adv. Eng. Informatics*, vol. 29, no. 2, pp. 162–171, Apr. 2015.

[7] I. Armeni *et al.*, “3D Semantic Parsing of Large-Scale Indoor Spaces (a) Raw Point Cloud (b) Space Parsing and Alignment in Canonical 3D Space (c) Building Element Detection Enclosed Spaces.”

[8] P. Tang, D. Huber, B. Akinci, R. Lipman, and A. Lytle, “Automatic reconstruction of as-built building information models from laser-scanned point clouds: A review of related techniques,” *Automation in Construction*. 2010.

[9] F. Wang, X. Xi, C. Wang, Y. Xiao, and Y. Wan, “Boundary regularization and building reconstruction based on terrestrial laser scanning data,” *2013 IEEE Int. Geosci. Remote Sens. Symp. - IGARSS*, no. 41271428, pp. 1509–1512, 2013.

[10] H. Son and C. Kim, “Automatic segmentation and 3D modeling of pipelines into constituent parts from laser-scan data of the built

environment," *Autom. Constr.*, 2016.

[11] H. Son, C. Kim, and C. Kim, "3D reconstruction of as-built industrial instrumentation models from laser-scan data and a 3D CAD database based on prior knowledge," *Autom. Constr.*, 2015.

[12] Y. Zhuang, X. Lin, H. Hu, and G. Guo, "Using scale coordination and semantic information for robust 3-D object recognition by a service robot," *IEEE Sens. J.*, vol. 15, no. 1, pp. 37–47, 2015.

[13] F. Bosché, M. Ahmed, Y. Turkan, C. T. Haas, and R. Haas, "The value of integrating Scan-to-BIM and Scan-vs-BIM techniques for construction monitoring using laser scanning and BIM: The case of cylindrical MEP components," *Autom. Constr.*, 2015.

[14] S. Lagüela, L. Díaz-Vilariño, J. Martínez, and J. Armesto, "Automatic thermographic and RGB texture of as-built BIM for energy rehabilitation purposes," *Autom. Constr.*, 2013.

[15] A. K. Patil, P. Holi, S. K. Lee, and Y. H. Chai, "An adaptive approach for the reconstruction and modeling of as-built 3D pipelines from point clouds," *Autom. Constr.*, 2017.

[16] K. J. Shrestha and H. D. Jeong, "Computational algorithm to automate as-built schedule development using digital daily work reports," *Autom. Constr.*, 2017.

[17] M. Bueno, F. Bosché, H. González-Jorge, J. Martínez-Sánchez, and P. Arias, "4-Plane congruent sets for automatic registration of as-is 3D point clouds with 3D BIM models," *Autom. Constr.*, 2018.

[18] A. Adán, B. Quintana, S. A. Prieto, and F. Bosché, "An autonomous robotic platform for automatic extraction of detailed semantic models of buildings," *Autom. Constr.*, vol. 109, no. April 2019, p. 102963, 2020.

[19] A. Ibrahim, A. Sabet, and M. Golparvar-Fard, "BIM-driven mission planning and navigation for automatic indoor construction progress detection using robotic ground platform," *Proc. 2019 Eur. Conf. Comput. Constr.*, vol. 1, pp. 182–189, 2019.

[20] D. Rebolj, Z. Pučko, N. Č. Babič, M. Bizjak, and D. Mongus, "Point cloud quality requirements for Scan-vs-BIM based automated construction progress monitoring," *Autom. Constr.*, 2017.

[21] B. R. K. Mantha and B. Garcia de Soto, "Designing a Reliable Fiducial Marker Network for Autonomous Indoor Robot Navigation," in *36th International Symposium on Automation and Robotics in Construction, ISARC 2019.*, 2019, pp. 74–81.

[22] B. R. K. Mantha, B. Garcia de Soto, C. C. Menassa, and V. R. Kamat, "Robots in indoor and outdoor environments," in *Construction 4.0: An Innovation Platform for the Built Environment*, 1st Editio., A. Sawhney, M. Riley, and J. Irizarry, Eds. Routledge, London, 2020, pp. 307–325.

[23] "Building Smart foundation." [Online]. Available: https://www.buildingsmart.org/. Last access 15/06/2020.

[24] S. Thrun, *Probabilistic Robotics. Communications of the ACM.* 2002.

[25] E. W. Dijkstra, "A note on two problems in connexion with graphs," *Numer. Math.*, vol. 1, no. 1, pp. 269–271, 1959.

[26] S. A. Prieto, A. Adán, A. S. Vázquez, and B. Quintana, "Passing through Open/Closed Doors: A Solution for 3D Scanning Robots," *Sensors*, vol. 19, no. 21, p. 4740, Oct. 2019.

[27] M. Gschwandtner, R. Kwitt, A. Uhl, and W. Pree, "BlenSor: Blender sensor simulation toolbox," *Lect. Notes Comput. Sci. (including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics)*, vol. 6939 LNCS, no. PART 2, pp. 199–208, 2011.