Towards an Ontology for BIM-Based Robotic Navigation and Inspection Tasks

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Abstract –

The availability of inspection robots in the construction and operation phases of buildings has led to expanding the scope of applications and increasing technological challenges. Furthermore, the Building Information Modeling (BIM) based approach for robotic inspection is expected to improve the inspection process as the BIM models contain accurate geometry and relevant information at different phases of the lifecycle of a building. Several studies have used BIM for navigation purposes. However, the research in this area is still limited and fragmented, and there is a need to develop an integrated ontology to be used as a first step towards logic-based inspection. This paper aims to develop an Ontology for BIM-based Robotic Navigation and Inspection Tasks (OBRNIT). The semantic representation of OBRNIT was evaluated through a case study. The evaluation confirms that OBRNIT covers the domain's concepts and relationships, and can be applied to develop robotic inspection systems.

Keywords –

Ontology; BIM; Robotics; Navigation; Inspection

1 Introduction

Inspection is indispensable in the construction industry. Robots are used to automate the process of inspection during the construction and operation phases. The use of advanced technologies (e.g. scanners, sensors) has made the inspection process more accurate and reliable [1]. The complexity of the interactions with the surrounding building environment is the main challenge for inspection robots [2]. To overcome this challenge, an ontology can be used as a basis for the robot's task planning and execution. The robotic system utilizes and processes the ontology as the robot's central data store [3]. To accomplish the tasks correctly, the autonomous robot needs to deal with high-level semantic data along with low-level sensory-motor data. Therefore, a variety of knowledge, including the robot low-level data related to perception and high-level data about the environment, objects, and tasks, needs to be integrated [4].

Building Information Modeling (BIM) is an approach to model all the information related to buildings by representing the geometrical and spatial characteristics, and is supported by the international standard *Industrial Foundation Classes* (IFC) [5, 6]. BIM models comprise useful information about the building environment, which can help the inspection robot to overcome task complexity. On the other hand, the Robot Operating System (ROS) [7] uses several navigation methods, such as Lidar Odometry and Mapping (LOAM) and Simultaneous Localization and Mapping (SLAM), which help the robot to build its map based on the collected data about the environment [8]. Regarding the different lifecycle phases, BIM models of a building include as-designed at the design phase, as-built at the construction phase [9, 10], and as-is at the operation and maintenance (O&M) phase. These models should be considered in the navigation and inspection processes. It should be noted that each of these models has several versions and should be continuously updated to reflect design, construction, renovation, and repair changes in the different phases of the lifecycle. Mismatches between the as-designed BIM model (or as-built BIM model) and the as-is state of the surrounding environment can create problems during the navigation and inspection tasks.

The navigation concepts in this paper are based on using the semantic knowledge and the BIM concepts for navigation tasks. The BIM-based approach is also expected to improve the inspection process. The robotic task must be performed in such a way that the process considers reliability, repeatability, and safety. Therefore, it is necessary to enhance operational consistency in the inspection environment [11]. Robotic systems' capabilities have progressed over time, and these systems have become dependent on multiple components with diverse functions. In most developed systems, the modules are created independently by different individuals with different technical expertise. Thus, a clear definition of the relationships between the system's various components is needed. The system's structure and related components must have a straightforward design and documentation to solve this problem [3]. A clear and accurate description of the environment and the task can help the robot to achieve the tasks more autonomously [12]. The robot declarative knowledge represents the task's objects, properties, and objects' relationships in a semantic model [13]. The robot can use this declarative knowledge to perform the task more accurately. However, the research in this area is still limited and fragmented, and there is a need to develop an integrated ontology to be used as a knowledge model for logic-based inspection of building defects. The objective of this paper is to develop BIM-based ontology to cover the different types of information and concepts related to robot navigation and inspection tasks. The ontology is called OBRNIT (ontology for BIM-based robotic navigation and inspection tasks). OBRNIT covers the high-level knowledge of the robot comprising robotic and building concepts, and navigation and inspection information. The use case context is an inspection robot that is navigating in a building with partial knowledge of the environment because of changes in the available information due to construction and renovation scheduling issues, unexpected obstacles in the building, etc.

2 Methodology Workflow

The methodology for developing OBRNIT is METHONTOLOGY, which is clear, well-documented, mature, and based on the experience of other domains ontology development [14]. OBRNIT development based on METHONTOLOGY includes the initial, development, and final stages. The best practices and knowledge in the robotic inspection domain are used to develop OBRNIT. The initial stage involves steps to specify the scope, main concepts, and the taxonomies of OBRNIT. The scope of OBRNIT is defined based on the requirements. Research papers, textbooks, and online resources are used as sources for the requirements (e.g. properties). The ontology needs to cover all the concepts about the robot characteristics, building characteristics, and inspection and navigation tasks. The competency questions are defined as a part of the requirements of the robotic inspection domain [15]. Furthermore, this step helps to consider the size of the development and the level of detail that needs to be covered in OBRNIT. The next step is defining the concepts and taxonomies for OBRNIT. The data related to OBRNIT are gathered in this step. Communication with experts and end-users along with getting feedback from them is essential at the whole cycle of this stage. The development stage is devoted to constructing and verifying the initial structure of OBRNIT. In the first step of the development stage, the conceptualization model is clearly represented and implemented in a formal language (e.g. OWL) to be later accessible by computers and used by different systems [16]. The development of OBRNIT involves reusing and adapting BIM concepts. Building Element Ontology (BEO) [17], which is based on the IfcBuildingElement subtree in the IFC specification and ifcOWL ontology [18], is a good starting point for including the relevant BIM concepts to OBRNIT. The ontology integration in the METHONTOLOGY method can be done at the conceptualization level [19]. The ontology integration method is selected in this research as it saves the effort to reuse and adapt the components that are needed to complete OBRNIT [20]. The next step of the development stage is verifying the developed ontology. Based on the consistency rules and competency questions, this process examines the ontologies from the technical perspective. The final stage is to add new, or modify existing, relationships, and validate OBRNIT with experts and end-users through evaluation questions. In this stage, the ontology is improved with the suggestions of the domain experts and end-users to fulfill the real-world requirements. OBRNIT evaluation is done through a case study. The final step is documenting the developed OBRNIT.

3 Developing OBRNIT

Some concepts from BIM and KnowRob ontology [21] are used as parts of this study. Protégé [22] is used to develop OBRNIT and to integrate it with BEO [23]. HermiT OWL Reasoner is used for identifying subsumption relationships and consistency evaluation. The current version of OBRNIT is available at https://www.obrnit.info.

OBRNIT covers four main groups of concepts including: (1) robot concepts, (2) building concepts, (3) navigation task concepts, and (4) inspection task concepts, which are explained in the following sections. Figure 1 shows the main concepts and relationships of OBRNIT. Color coding is used to group the concepts pertaining to each of the four groups. The relationships between concepts show how the ontology components are semantically interrelated. The types of relations used in the developed ontology are: *is*, *has*, *uses*, *affects*, *performs*, *causes*, *captures*, *has state*, *has time*, *has target*, and *measures* (e.g. thermal camera *measures* temperature).

3.1 Robot Concepts

The robot concepts of OBRNIT cover the main functions of a robot along with the related knowledge of the inspection and navigation tasks. Declarative abstract knowledge about the tasks and environment should be encoded in the robot controller and used to determine proper actions for a specific task.

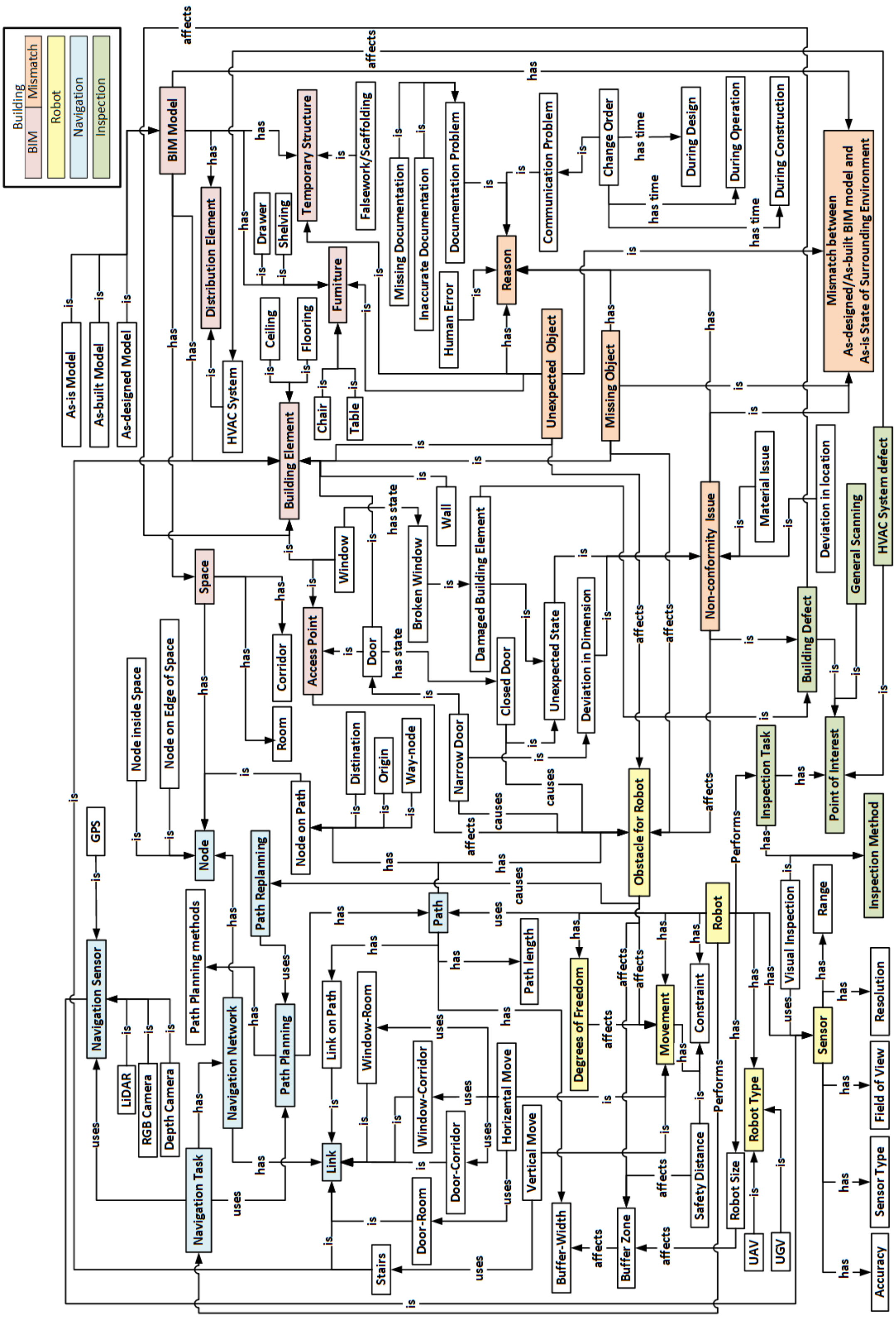

Figure 1. Main concepts and relationships of OBRNIT

KnowRob ontology represents semantic models using object detection applied to the acquired point clouds enriched by encyclopedic, common-sense, and action-related knowledge [24]. From the BIM point of view, this ontology is primitive and does not provide full support of building elements. For example, the concept of a wall is only mentioned as a part of the edges of a region's surface and does not have dimensions, material, connectivity, type, etc. Walls may play a major role in inspection and navigation tasks because they define the boundaries of robots' movements or can be obstacles, or the main target of inspection. Other building elements, such as ceilings, columns, and windows, are not covered in KnowRob.

As shown in Figure 1, mobility and sensing are the two main functions of robots. The mismatches between the path found based on the non-updated BIM model and the as-is state of the surrounding environment will cause an obstacle for the robot movement, and consequently its performance. Robot concepts cover basic attributes (e.g. type, size), robots' performance (e.g. movements, degrees of freedom (DOF)), robots' constraints (e.g. safety distance), and sensors for navigation and inspection tasks. The DOF define the modes for the motion capability of the robot. The types of robots considered in OBRNIT are UAV and UGV. UGV refers to any type of crawling, climbing, and other ground-based robots. The movement of UAVs is in the 3D spaces of the building. However, UGVs move following the floors and may be able to climb the stairs. In this case, there are some constraints on the movement, such as the maximum height of a stair step that they can climb. Also, the flying movement of a UAV has constraints, which mainly depend on the size of the UAV.

Sensors can be used for inspection (e.g. RGB camera, thermal camera) and navigation purposes (e.g. depth camera, GPS). LiDAR and cameras are two different types of sensors. Cameras collect images, which can be RGB/depth/thermal images. LiDAR scanners is a remote sensing method, which collects point cloud from the environment. The accuracy and field of the view of the robots' sensor, as well as its type, affect the robot's inspection performance.

3.2 Building Concepts

The BIM model can provide information about the environment of the robotic inspection. Every building element that affects the robot navigation and inspection processes should be included in OBRNIT. As explained in Section 2, the integration process starts with integrating BEO. The required concepts, which are not included in BEO, are added from ifcOWL ontology or defined based on the required concepts for robotic navigation and inspection. The process of integrating BIM concepts with OBRNIT aims to link the available BIM concepts with the developed OBRNIT concepts, including related building concepts (e.g. BIM mismatch concepts), robot concepts, and inspection and navigation tasks concepts. Some research focused on robots that can open a closed-door with specific access control or use a handle, knob, or button. For example, Cobalt Access [25] can open locked doors by using the door's access control reader. However, passing through locked doors without human intervention is still the main issue for most robots. The state of the door can be open or closed, locked or unlocked, mechanically locked, or electronically locked.

Building concepts of OBRNIT includes the following: (1) Concepts reused from BEO ontology; (2) Concepts reused from ifcOWL: Some necessary concepts, which are not included in BEO (e.g. the *space* concept), are added from ifcOWL. HVAC elements are also added from ifcOWL in order to consider HVAC system defects; (3) Concepts adopted from Building Management Systems (BMS): Some concepts related to the state of the door are required for navigation purposes. These concepts are adopted from BMS; and (4) New building concepts defined based on OBRNIT needs: These concepts include BIM mismatch concepts. In addition, the following relationships are defined to link building-related concepts to navigation and inspection concepts: (1) Relationships to define the links between spaces for navigation paths (e.g. door-corridor), (2) Relationships to define a BIM object as the point of interest of inspection, and (3) Relationships to define obstacles or constraints for the robot movement (e.g. a narrow door). Furthermore, the mismatches between the as-designed or as-built BIM model and the as-is state of the surrounding environment should be semantically represented in OBRNIT. Identifying the potential types of mismatches is the first step to define a logic-based robotic inspection system that can reduce delays and reworks. Also, the information about the path has a major role when the goal is finding the optimal route and avoiding collisions with existing barriers. Spaces in the building (e.g. rooms) can be used to generate nodes for generating the path of the robot. The dimensions of a space can be used to define these nodes inside or on the edges of the space. The main building spaces for robot path planning are rooms, corridors, and stairs.

The mismatches between the information in the available BIM model and the reality cause navigation problems for robots. In some cases, the lack of adequate communication in the design phase, insufficient documentation, or errors of the contractor can turn into unexpected results including information mismatches between the as-designed BIM model and the as-is state of the building. The same problem can occur in the operation phase, where renovation issues can cause mismatches between the non-updated as-built BIM and the as-is state of the building. The assumption in

OBRNIT is that the path planning is based on a reference BIM model, but this model is not as-is and reliable. The semantic mismatch between the as-designed BIM model (or as-built BIM model) and the as-is state of the surrounding environment could be caused by one of the following problems: (1) there is an object in the BIM model, which does not exist in reality. This problem can be the result of design changes during the construction phase (e.g. removing a door) where the changes are not applied in the BIM model; (2) there is an object in the building which is not included in the last updated BIM model; or (3) there is a discrepancy between the BIM model and the actual building with respect to objects' attributes, such as location or dimensions. As shown in Figure 1, these problems that the robot can face in a building are classified as missing objects, unexpected objects, and non-conformity issues. Each of these issues could be linked with fixed or mobile objects. For instance, building elements (e.g. access points) can be missing objects, and furniture and temporary structures (e.g. falsework) can be unexpected objects. Also, classes related to non-conformity should cover material issues, unexpected states (e.g. damaged building element, a closed-door which is expected to be open), and deviation in location or deviation in dimensions (e.g. narrow door), etc. Each of the main mismatch entities has one or more causes and effects. A narrow door (i.e. deviation in dimensions) or a closed-door (i.e. different states from what is expected) are examples of non-conformity that can cause problems for a robot during its operation.

3.3 Navigation Concepts

The navigation task in OBRNIT refers to the act of performing navigation by the robot. As shown in Figure 1, navigation concepts cover the main information related to the path of the robot including nodes and links, which can be used for path planning. The navigation task has a network, and it uses the information of this network for path planning. Different types of navigation sensors can be used including GPS, LiDAR scanner, and depth camera. A path has attributes including the length, direction, and buffer-width. A node can be the origin or destination of a path, or a way-node on the path. Spaces (e.g. room, corridor) and access point elements of a building (e.g. doors, windows) can be nodes of a path. For example, if a robot must move from a corridor to a room, the center point of the corridor is the origin node, the center point of the room is the destination node and a door of the room is a way-node. Positions of the way-nodes vary based on the obstacles on the way of the robot. These obstacles may be unexpected objects detected by the robot. New links on the path connect these way-nodes to the origin and the destination nodes and each other [26]. Links connect nodes and define the direction of the path. Examples of links are the links connecting a window to a room (in case of UAV), a door to a corridor, or a door to a room, based on the defined building elements and spaces. Links can be horizontal or vertical (e.g. stairs' links are vertical). The state and dimensions of access points (e.g. doors and windows) are important to enable the robot movement over the path.

3.4 Inspection Concepts

Inspection is the main task of the robot in OBRNIT and is mostly performed using vision sensors (e.g. LiDAR scanners, cameras). The attributes of inspection-related tasks of OBRNIT are defined based on common defects in buildings [27]. The inspection task has an inspection method, which can be visual inspection or a method for the measurement of physical conditions (e.g. broken glass) or environmental conditions (e.g. temperature). The method of inspection is based on the sensor's measurement and acquired datasets. Measurement devices for inspection include radio-frequency ID (RFID) readers, image sensors (i.e. RGB and thermal cameras), and LiDAR scanners. Images and point clouds can be used to detect surface defects, deformations, non-conforming elements, etc. Computer vision methods can be used for anomaly detection on the collected data. Also, the information of computer vision methods can be used for obstacle detection and navigation tasks.

The point of interest of the inspection task is defined based on the inspection purpose, which can be general scanning, inspecting mechanical systems (e.g. HVAC), or detecting building defects. General robotic scanning aims to update the BIM model or to collect data of a hazardous building, which is unsafe to inspect by human inspectors. The malfunctions of the HVAC system affect the environment temperature and air quality. Defected HVAC elements or related building elements (e.g. improper insulation) can be evaluated by thermal cameras. In the case of inspecting building defects, specific building elements are the points of interest, and each of them can be a target for the inspection task. Some issues related to non-conformity can be considered as building defects. Furthermore, the detected defects can be used to update the available BIM model to create an up-to-date as-is BIM model.

4 Case Study

Figure 2 shows a hypothetical case study of using an inspection robot to find the leakage in one of the rooms on the 9th floor in a building at Concordia University. The aim of the case study is to demonstrate the applicability of OBRNIT based on specific information about the building extracted from a BIM model and information about the inspection robot. The assumption is that the robot partially knows the environment based on a non-updated BIM model. After defining the inspection point of interest in Room 9-215, which is leakage in the ceiling, the robot should navigate to reach this point of interest to perform the inspection task. Path planning is based on a reference as-built BIM model. The inspection robot will use an image sensor to capture images of the ceiling. The FLIR PackBot robot [28] is assumed as the robot used in the case study. The robot type is UGV, and it has horizontal and vertical (e.g. climbing the stairs) mobility.

Examples of BIM-based information include the objects in Room 9-215 and the inspection point of the interest, as well as the spaces/objects from the elevator on the 9th floor to the door of Room 9-215. The origin node is in front of the elevators on the 1st floor, and the destination node is inside Room 9.215. The path has three parts. The first part is the vertical movement in the elevator from the origin node to the 9th floor. The second part of the path is the horizontal movement from the 9th floor elevator hall to the door of Room 9-215. The shortest path (Path A) uses Corridors 9-A1 and 9-A2 (Nodes 2, 3`, 4`, and 7). However, this path is blocked with scaffoldings, which are used for a renovation project, and create an obstacle for the robot. Therefore, the robot must follow a longer path (Path B) to reach the room. The robot could obtain information about the scaffoldings from an up-to-date BIM model, if available, or from its sensing ability. Having an up-to-date BIM model (i.e. as-is model) results in a higher confidence level with respect to obstacles. After detecting the obstacle, the robot should replan a new path (Path B).

The involved corridors to reach Room 9-215 in Path B are Corridor 9-A1, Corridor 9-A3, Corridor 9-A4, and Corridor 9-A2, which contain Nodes 2,3,4,5, 6, and 7. The last part of the path is the horizontal movement inside the room from the door to the destination node (i.e. the inspection point of interest). The robot will learn from performing the navigation task. After finding the mismatches with the as-built BIM model (i.e. the scaffoldings), the robot should store them as a reference point for performing the next tasks.

The case study demonstrates that OBRNIT can answer all the competency questions and it covers all the concepts necessary for the planning of the robotic building navigation and inspection. The case study also shows how several concepts are extracted from the BIM model of the building. Examples of these concepts include concepts related to the navigation task (moving to the specific floor and the specific room, and then moving to the point of interest in the room), as well as the inspection task (orienting the camera to the leakage area based on the field of view and collecting images). Integrating mobility characteristics of the robot and the knowledge about the surrounding environment can help the robot define the appropriate path based on the robot type and constraints. The robot can benefit from the BIM model to define the path based on defining the nodes and links of the path. In addition, the robot can benefit from the BIM model information to locate the inspected objects. Furthermore, the ontology can help the robot use a suitable sensor for the specific inspection task.

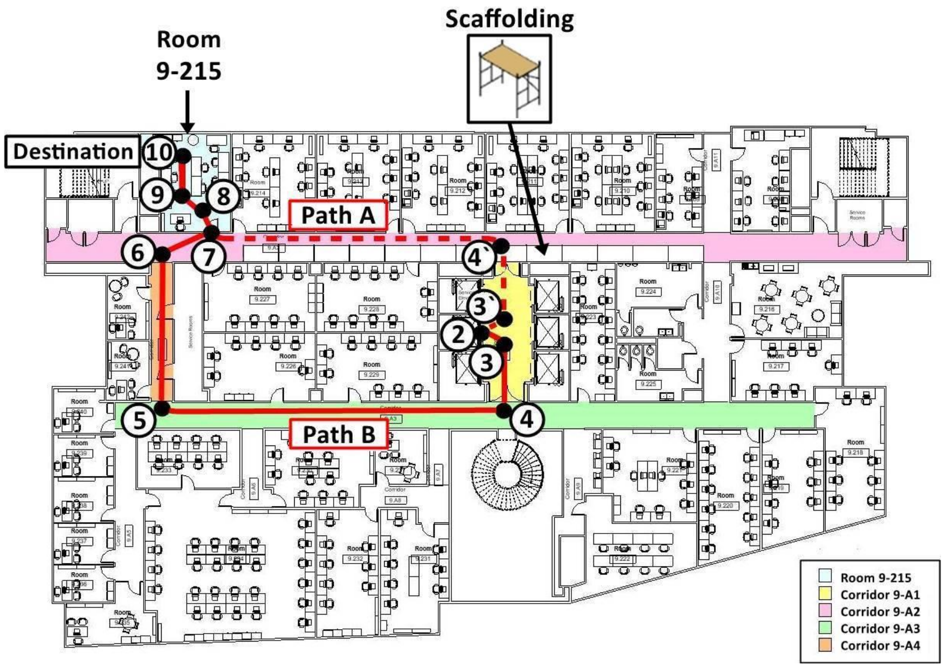

Figure 2. Case study of using an inspection robot

5 Conclusions and Future Work

This paper developed an integrated ontology, called OBRNIT, to extend BIM applications for robotic navigation and inspection tasks. OBRNIT comprises high-level knowledge of the concepts and relationships related to buildings, robots, and navigation and inspection tasks. BIM is considered as a reference that is integrated with the knowledge model. The application of OBRNIT was investigated in a case study. Based on the evaluation, OBRNIT was able to give a clear understanding of the concepts and relationships in the domain, and it can be applied for developing robotic inspection systems. OBRNIT is expected to provide the following benefits: (1) capturing the essential information from BIM can help to develop a seamless knowledge model to cover the missing parts of BIM; and (2) OBRNIT can be used as a first step towards logic-based inspection, which can help robots to perform inspection tasks autonomously without the help of human judgment.

Future work will focus on further development and implementation of OBRNIT to integrate it with low-level robotic capabilities to make the robot more autonomous. The abstract knowledge can be combined with robot action-related procedural knowledge to make the tasks executable [13].

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