Robot Navigation on Construction Sites using Building Information Modeling and Geographic Information System

by

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MANUSCRIPT-BASED THESIS PRESENTED TO ÉCOLE DE TECHNOLOGIE SUPÉRIEURE IN PARTIAL FULFILLMENT FOR A MASTER'S DEGREE WITH THESIS IN CONSTRUCTION ENGINEERING
M.A.Sc.

MONTREAL, MAY 12, 2021

ÉCOLE DE TECHNOLOGIE SUPÉRIEURE
UNIVERSITÉ DU QUÉBEC

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ACKNOWLEDGEMENTS

My Master's study could have not been more exciting and interesting. I would have not been able to come to this stage without the help, support, kindness of many individuals. First, I would like to say that I am very grateful to my supervisor, Dr. Ivanka Iordanova for believing in me and encouraging me to the explore the field of robotic in construction. Then, my co-supervisor, Dr. David St-Onge who always guided me through this by giving me kind advises. Both my supervisors provided me with inexplicable support – financial, moral, technical. Very grateful for your dedication, guidance, and inspiration. It was my pleasure to work with you and be inspired by you.

I would like to express my gratitude to my wife for her support and dedication during my Master's studies. She was very patient while I was nervous about my research and provided me with warm support. I also thank my parents who were always encouraging me to be strong in this journey.

I would like to show my respect and gratefulness to all who supported me especially my colleague, Rafael Gomes Braga, who kindly helped me.

Navigation par robot sur les chantiers de construction à l'aide de la modélisation des informations du bâtiment et du système d'information géographique

Sina KARIMI

RÉSUMÉ

La productivité est un des problèmes majeurs auquel l'industrie de la construction doit s'attaquer. L'intérêt de gagner en efficacité dans les projets de construction croit surtout grâce à l'avancement d'autres disciplines technologiques telles que la robotique, les capteurs, etc. Parmi les différentes propositions pour faire face aux problèmes de productivité, l'automatisation dans la construction a montré un grand potentiel. Le suivi de l'avancement des projets de construction est l'un des défis qui nécessite un certain niveau d'automatisation. Les méthodes conventionnelles de suivi des progrès reposent sur des données textuelles et une interprétation subjective des employés impliqués. Avec l'évolution des robots mobiles ces dernières années, l'intérêt pour leur déploiement sur chantier augmente grâce à leur capacité à naviguer et à acquérir des données de manière autonome. Les robots peuvent collecter de nouveaux types de données sur site qui peuvent être utilisées pour le suivi des progrès. L'une des étapes du déploiement des robots mobiles sur les chantiers est la navigation autonome. La navigation robotique intérieure et extérieure peut être améliorée avec les données relatives au bâtiment, tel que la modélisation des informations du bâtiment (BIM) et le système d'information géographique (GIS). Le BIM peut fournir les caractéristiques des éléments de construction et le GIS les informations sur le site environnant d'un projet de construction. Le BIM-GIS permettra d'utiliser des informations sémantiques qui pourraient être utilisées pour un meilleur évitement d'obstacles, une meilleure planification des trajectoires et une navigation sémantique. La navigation sémantique des robots mobiles est possible pour les non-experts car elle permet le partage de connaissances spécifiques au domaine. Dans cette thèse, nous développons les éléments suivants:

- une revue systématique de la littérature (SLR) utilisant de nouvelles méthodes d'analyse bibliométrique combinées à une analyse qualitative pour identifier l'état de l'art et les lacunes dans l'utilisation du BIM et du SIG pour la navigation robotisée.
- une approche basée sur l'ontologie pour relier les connaissances de la construction et de la navigation robotique à l'aide d'ontologies établies. L'ontologie est ensuite utilisée pour récupérer les informations pertinentes à traduire dans le système robotique.
- un "Path Planning" basé sur le BIM utilisant la sémantique de l'IFC, qui est intégrée au système de navigation du robot en utilisant la géométrie et la sémantique des éléments de construction.

Les connaissances liées au bâtiment utilisées dans cette recherche sont rassemblées à partir de différentes sources, incluant une revue documentaire détaillée et approfondie, une étude de cas et des normes établies du domaine robotique. Avec l'aide d'un partenaire industriel, nous avons réalisé des tests expérimentaux sur le terrain pour valider notre approche. Ces recherches contribuent du déploiement de robots sur les chantiers de construction pour la collecte de données utilisables pour de nombreuses applications telles que la surveillance de l'avancement, le contrôle qualité ou la sécurité. Les solutions développées peuvent être utilisées pour un déploiement de robot mobile plus sûr, plus facile et plus intuitif sur les chantiers de construction.

Mots-clés: BIM, GIS, IFC, robot mobile, ontology, path planning, collecte de données, navigation

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ABSTRACT

Productivity is one of the issues that construction industry needs to address. The interest in gaining higher rate of efficiency in construction projects is growing especially with advancement in other technological disciplines such as robotics, sensors, etc. Among different propositions to cope with productivity issue, construction automation has shown great potential in this regard. Progress monitoring of construction projects is one of the challenges that requires some level of automation. Conventional methods of progress monitoring rely on textual data and subjective interpretation of the employees involved in this regard. With advancement in mobile robots' capabilities in recent years, the interest in deploying robots on construction sites is increasing since they are able to navigate autonomously and acquire data. The robots can gather new kinds of on-site data that can be used for progress monitoring. One of the steps in mobile robot deployment on construction sites, is the autonomous navigation. Indoor and outdoor robot navigation can be improved with the building-related data namely Building Information Modeling (BIM) and Geographic Information System (GIS). The former can provide the building elements features and the latter would provide the surrounding site information of a construction project. BIM-GIS would provide semantic information that can be used for enhanced obstacle avoidance, improved path planning, and semantic navigation. The semantic navigation of mobile robots enables non-experts since they share their domain-specific knowledge. In this dissertation, we develop the following:

- A Systematic Literature Review (SLR) using novel methods of bibliometric analysis combined with qualitative analysis to identify the state-of-the-art and the gaps in using BIM and GIS for robot navigation.
- An Ontology-based approach to bridge the construction and robot navigation knowledge using established ontologies. The ontology is then used to retrieve the relevant information to be translated to the robotic system.
- A BIM-based path planner using IFC semantics integrated with robot navigation system using building elements geometries and semantics.

The building-related knowledge used in this research is gathered from different sources including detailed and thorough literature review, a case study and established standards of the robotic domain. We used experimental field test to validate our approach with an industrial partner. This research contributes to the field of robot deployment on construction sites to collect data that can be used for many applications such as progress monitoring, quality control and safety inspection. The developed solutions can be used for safer, easier and more intuitive mobile robot deployment on construction sites.

Keywords: BIM, GIS, IFC, mobile robot, ontology, path planning, data collection, navigation

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LIST OF ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
4D	Four Dimensional
AEC	Architecture, Engineering and Construction
AECO	Architecture, Engineering, Construction and Operation
AIA	American Institute of Architects
AMG	Automatic Multipatch Generation
ADE	Application Domain Extension
BIM	Building Information Modeling (or Model)
BIRS	Building Information Robotic System
CAD	Computer Aided Design
CityGML	City Geography Markup Language
COLLADA	Collaborative Design Activity
CORA	Core Ontology for Robotics and Automation
CR	Construction Robotics
DSR	Design Science Research
EKF	Extended Kalman Filter
ESRI	Environmental System Research Institute
GIS	Geographic Information System

GLANS	GIS Based Large-Scale Autonomous Navigation System
GPS	Global Positioning System
GUI	Graphical User Interface
HITS	(Hyperlink-Induced Topic Search)
IEEE	Institute of Electrical and Electronics Engineers
IFC	Industry Foundation Classes
i-GIT	Intelligent Generation of Indoor Topology
IMU	Inertia Measurement Unit
ISARC	International Symposium on Automation and Robotics in Construction
LiDAR	Light Detection and Ranging
LLR	Log-Likelihood Ratio
MDR	Map Data Representation
MEP	Mechanical, Electrical and Plumbing
OGC	Open Geospatial Consortium
OSA	Open-source Approach
OWL	Web Ontology Language
RF	Radio Frequency
RFID	Radio-frequency Identification
RGB	Red, Green, Blue
RGB-D	Red, Green, Blue - Depth

ROS	Robot Operating System
SLAM	Simultaneous Localization and Mapping
SLR	Systematic Literature Review
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
UWB	Ultra Wide Band
WLAN	Wireless Local Area Network
XML	Extensible Markup Language

INTRODUCTION

In many countries, the construction industry is considered an important portion of the economy since it involves a high number of workers and budget (Bogue, 2018). For this reason, increase in productivity of construction sector has always been an issue. According to Chen, de Soto & Adey (2018), automation of monotonous and repetitive tasks would significantly enhance construction efficiency. The authors argue that there are many ways for automating construction processes such as automation in design phase or use of robots on construction sites. Numerous studies indicated that deploying robots on construction sites would provide great opportunities for construction stakeholders in terms of productivity. For example, the article of (de Soto, Agustí-Juan, Hunhevicz, Joss, Graser, Habert & Adey, 2018) compares the performance of a concrete wall built by a robotic system to one built from conventional methods, and investigates the impact of digital fabrication (dfab) using a robotic platform. In this direction, Delgado, Oyedele, Ajayi, Akanbi, Akinade, Bilal & Owolabi (2019) have shown that automated robotic systems have the potential to *"revolutionise"* the construction industry by improving productivity in terms of cost and time. Bock & Linner (2015) argue that many construction methods has faced limitation in terms of implementation, therefore, it is now a necessity to employ robots in order to adopt new and innovative construction methods. In addition to the great advantages for the productivity of construction projects, automated robots can have positive impacts on the safety of construction labors (Castro-Lacouture, 2009). Despite the numerous benefits that automated robotic systems can bring to the construction projects, this industry is far behind compared to manufacturing in terms of adopting robots. Delgado *et al.* (2019) studied the challenges of robot adoption for construction project and they identified various challenges for robot deployment on construction sites. Inspired by the results of other studies, in this research, we focus on the use of an autonomous Unmanned Ground Vehicle (UGV) for automating data collection task for the purpose of progress monitoring of construction projects.

Progress monitoring of construction projects is a challenging task due to dynamic, complex and decentralized nature of construction processes (Tuttas, Braun, Borrmann & Stilla, 2017). To enhance the efficiency in this regard, the automation of progress monitoring is required as the projects evolve. To achieve this, the first step is to collect accurate and reliable data repetitively during the construction phase. Conventional methods of data collection for progress monitoring rely on periodic observation, manual data collection (which is mostly textual data), and individual interpretation of the construction state Álvares & Costa (2019)). These processes are error-prone, time-consuming and inefficient since the data collection is subjective in terms of interpretation (Teizer, 2015). A fundamental prerequisite in automated data collection using UGVs is the ability of the mobile robot to navigate the construction site autonomously and to capture the relevant and accurate data. In this respect, semantic navigation of mobile robots on construction sites has attracted the interest of construction stakeholders in recent years since it addresses the technical aspects of robot deployment for non-experts (Delgado *et al.*, 2019).

Building Information Modeling (BIM) is the digital representation of the building semantics and geometries in a data management environment (Eastman, Eastman, Teicholz, Sacks & Liston, 2011). BIM has a great number of applications for the Architecture, Engineering, Construction and Operation (AECO) industry, such as design-to-maintenance data management (Doumbouya, Guan, Gao, Pan et al., 2017), 4D simulation (Hatori, Satou, Onodera & Yashiro, 2020) and indoor path planning (Palacz, Ślusarczyk, Strug & Grabska, 2019). In parallel with BIM, Geographic Information System (GIS) has enabled the AECO experts to analyze the geo-spatial data of the surrounding environment at urban scale (Karan & Irizarry, 2015). Many applications of BIM-GIS integration are studied and are proposed to the construction stakeholders such as optimal location for tower cranes (Irizarry & Karan, 2012), energy consumption analysis (Afkhamiaghda, Mahdaviparsa, Afsari & McCuen, 2019), optimization of emergency response route (Tashakkori, Rajabifard & Kalantari, 2015), indoor-outdoor route planning (Teo & Cho, 2016). Numerous studies have investigated the indoor path planning problem for mobile robots using BIM semantics such as (Lin, Lin & Tserng, 2017; Hamieh, Deneux & Tahon, 2017; Palacz *et al.*, 2019). However, there are limitations in this field which are as follows:

- Studies investigating indoor robot path planning mainly focus on the geometry of building elements not on semantics.
- Some research papers address robot navigation using BIM; some using GIS. However, BIM-GIS integration application in robot navigation is yet to be studied.
- Semantic robot navigation during construction phase leveraging IFC data schema (integrated with ROS) is not studied.

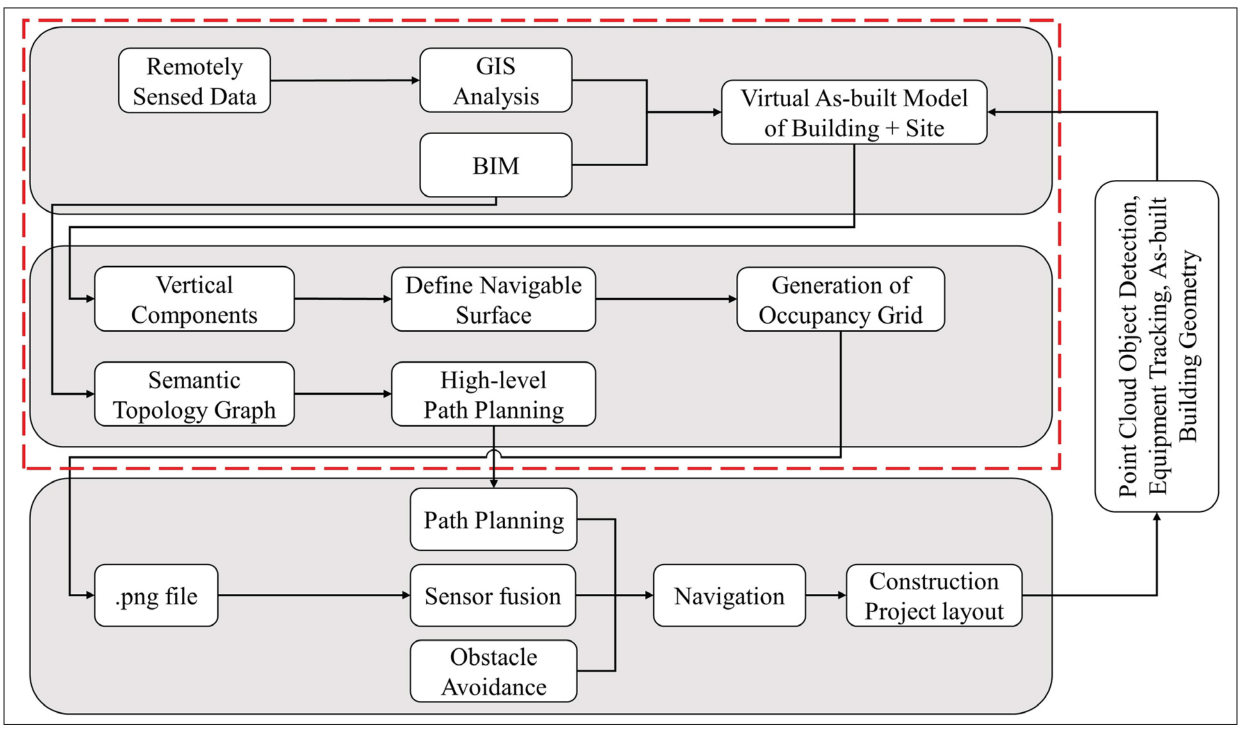

Figure 0.1 Overall Research Project and the portion covered in this thesis

As illustrated in Figure 0.1, The current thesis is part of a larger research project which aims at automated progress monitoring of construction projects. The red dashed rectangular shows the part covered by this thesis and its integration with the robot navigation system.

CHAPTER 1

RESEARCH METHODOLOGY

1.1 Research Process

This research integrates knowledge from the construction and the robotics domains and hence, an holistic methodology is needed to be able to successfully complete it. Thus, we follow design-science research methodology to develop the artifacts that are needed for the purpose of the current study. As illustrated in Figure 1.1, the main steps of design-science methodology adopted is as follows: *"Problem Identification"*, *"Knowledge Acquisition"*, *"Design Cycle"* and *"Evaluation"*.

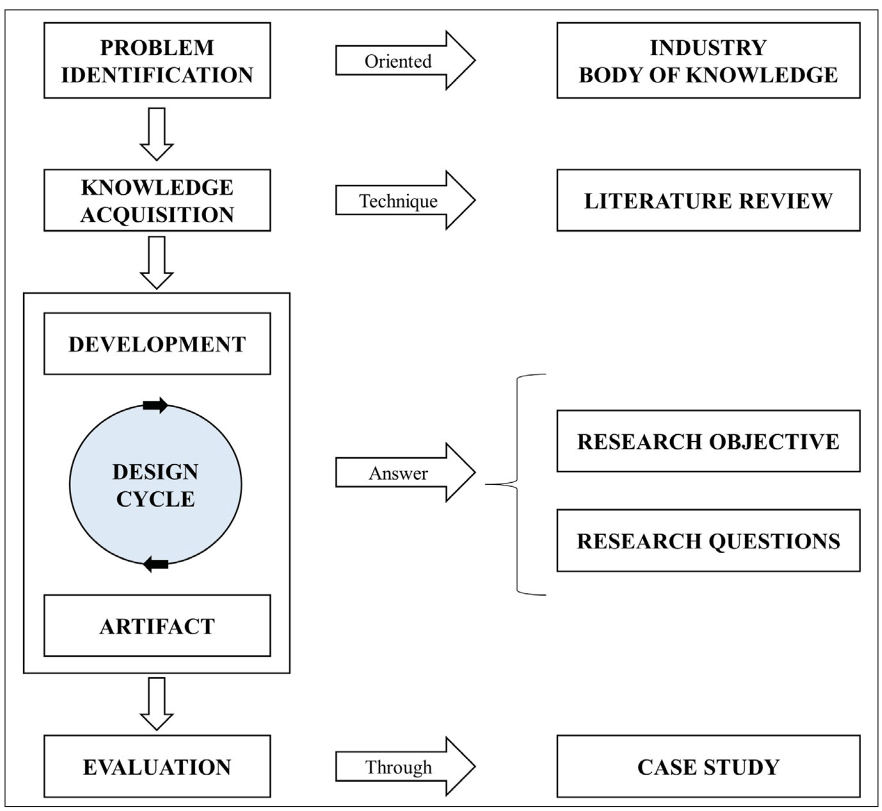

Figure 1.1 Overall Design-science Research Methodology
Adapted from Hevner & Chatterjee (2010, p. 16)

1.1.1 Problem Identification

Data used in any analysis need to be reliable and comprehensive. Progress monitoring in construction projects is not an exception. Therefore, there is a growing need in the AEC industry for accurate and automated data collection for progress monitoring, and robots (aerial or terrestrial) have the potential to help fulfilling this need. Unmanned Aerial Vehicles (UAV) are widely being used for outdoor environments, yet the major challenge remains for indoors. Hence, current research focuses on using Unmanned Ground Vehicles (UGV) to address the limitations in this regard.

To overcome the challenges in robot navigation, this research uses different techniques and algorithms. The state-of-the-art navigation strategy can be improved with building-related data. We propose the use of BIM and GIS for more efficient navigation, improved obstacle avoidance, and ultimately, more reliable data collection. According to Chapman, Butry & Huang (2010), the use of robotics in construction would have significant results including decrease in man-hour and cost as well as increase in productivity. However, little attention is paid to the use of robotic in data collection and progress monitoring while the few studies conducted in this regard lack the full integration with construction technologies. Hence, the AEC industry needs more research on deploying robots integrated with the use of BIM and GIS to reduce the errors and enhance efficiency. Therefore, the goal of this research is to collect data on construction sites using mobile robotic platforms in which the potential of integrated BIM-GIS semantics is used to enhance robot's navigation.

The motivation for this research is twofold: first, it is based on observation of the problems in the construction industry, and secondly, it builds on the existing body of knowledge. The construction industry is looking for new methods to collect accurate and reliable data that can lead to enhanced efficiency for progress monitoring. The conventional progress monitoring measures are error-prone and inaccurate. Therefore, there is a growing need in the AECO industry to use mobile robot platforms in order to autonomously track the projects progress.

1.1.2 Knowledge Acquisition

We reviewed a vast number of scientific works in the literature to profoundly enhance our understanding of the different approaches adopted for our problem. We identified the current practices to leverage BIM-GIS in robot navigation as well as the techniques used to address this problem. Our research uses, combines, extends previous studies in the robot navigation field and finally complements leveraging BIM-GIS by adding high-level building-related information to low-level navigation system in a full stack navigation.

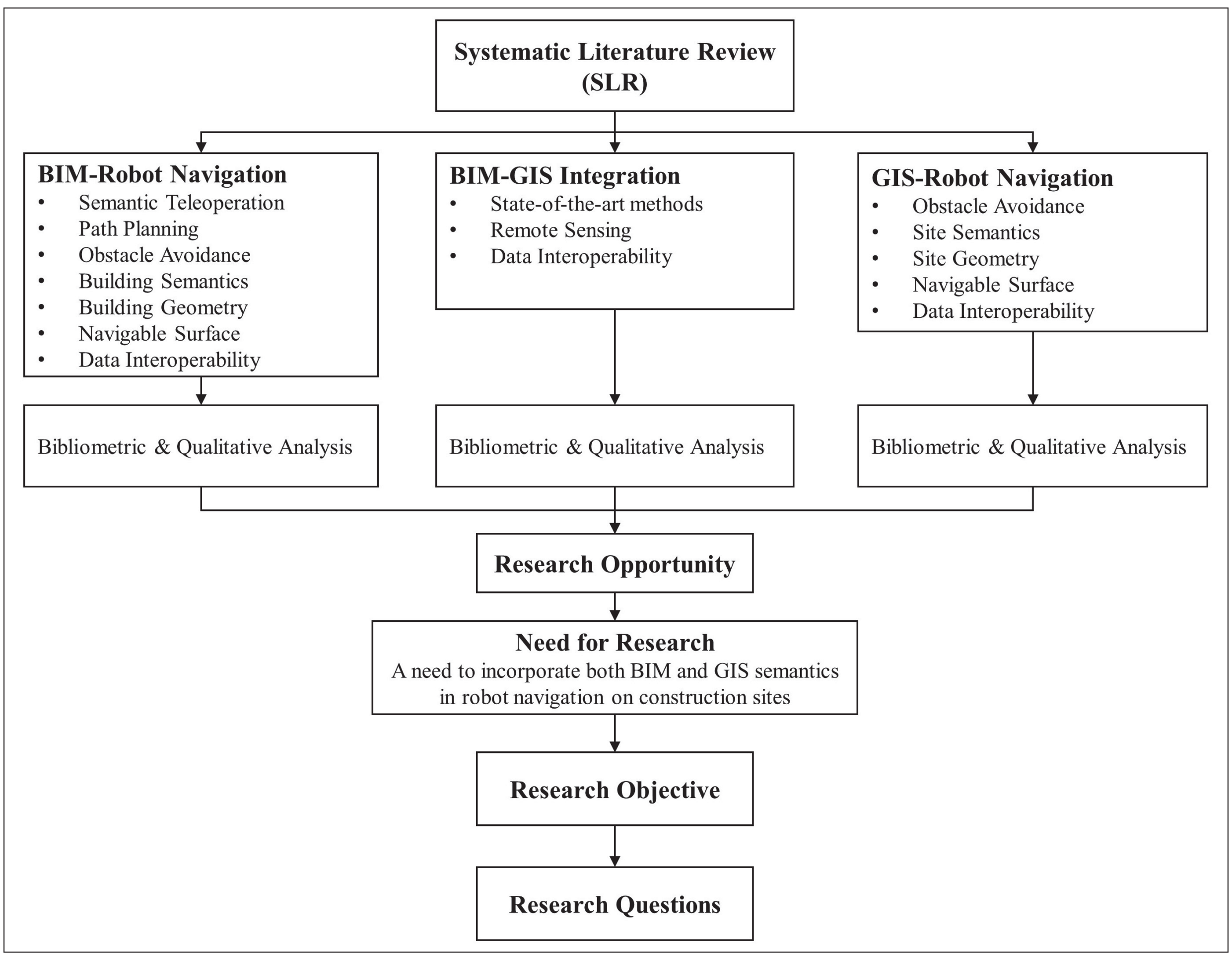

Figure 1.2 Workflow from Literature Review to Research Questions

Figure 1.2 illustrates the workflow followed from the Systematic Literature Review (SLR) to the research questions. In this direction, the existing body of knowledge is investigated using bibliometric and qualitative analysis methods in order to gain in-depth knowledge of the state-of-the-art in this regard. Since there was no study incorporating BIM-GIS semantic in robot navigation, we divided the literature review to three parts namely: BIM-Robot Navigation, GIS-Robot Navigation and BIM-GIS integration to study the opportunities, challenges and gaps in this field. The purpose is to identify what building-related data can contribute to the autonomous robot navigation that is provided by BIM and GIS. Therefore, the research opportunity is identified and consequently the research questions are formulated. More detail on the SLR is described in chapter 2.

1.1.3 Design Cycle

Design Cycle stage of the methodology has the biggest portion of the research process. As Hevner & Chatterjee (2010) argue, design cycle is the core concept of the design science methodology which iterates the development of the artifact to be evaluated in the next step. The requirements for developing the artifact are identified in the knowledge acquisition step (by conducting extensive literature review). However, the design cycle stage still collects data while the artifact is being developed. The design cycle is meant to answer the research objective and research questions which are formulated in section 1.1.3.1 and 1.1.3.2 respectively.

1.1.3.1 Research Objective

The current research project intends to develop an artifact that leverages BIM-GIS semantics in order to contribute to quicker, smarter and more precise autonomous robot navigation on construction sites for the purpose of data collection. The research objective is to **increase efficiency of data collection in construction projects**.

1.1.3.2 Research Questions

We formulated the research questions based on the problem identified from the industry and body of knowledge which are as follows:

1. What is the relevant information from BIM and GIS to be used in integration for robot navigation?
2. How the construction and robotic knowledge can come together to semantically transfer the building information to the robotic system?
3. How BIM-GIS data can integrate with the robot navigation system into a practical implementation enabling semantic navigation?

To answer the first question, we conducted a systematic literature review to identify the state-of-the-art for integration of BIM and GIS with robot navigation. In this direction, we extensively studied the scholarly papers to identify what building-related information can be leveraged for robot navigation. Chapter 2 is the published paper providing detailed information in this regard. The second paper (submitted) is an ontology developed to answer the second research question. In this paper, a Building Information Robotic System (BIRS) is developed to integrate the building data to the robot operating system (ROS). The ontology leverages the outputs of the first research question to facilitate data translation from BIM-GIS to ROS. Chapter 3 describes the procedure on the ontology development and its outputs. Finally, chapter 4 answers to the third research question by using the the semantic information (identified by the second paper) for indoor semantic path planning from IFC data.

1.1.4 Evaluation

The developed artifacts (BIRS and the semantic optimal path planner) produce results to address the research objective and answer the research questions. In the adopted design science methodology, the results need to be evaluated at the final step. In this direction, we evaluate the developed artifact using field experiment of a case study. More information in this regard is provided in chapter 3 where the BIRS ontology is evaluated; and in chapter 4 where the paper regarding the semantic optimal path planner is evaluated through a case study.

1.2 Thesis Outline

The current dissertation is a paper-based thesis and it is structured as follows: Chapter 2 is the paper published in Archives of Computational Methods in Engineering, in January 2021, entitled *Integration of BIM and GIS for construction automation, a Systematic Literature Review (SLR) combining bibliometric and qualitative analysis*. It explains the state-of-the-art in BIM-GIS integration and how it can be used for construction automation and more specifically, in mobile robot navigation. The authorship credits are as follows:

- **Sina Karimi:** Conceptualization; Data analysis, Investigation, Methodology, Software, Writing - original draft.
- **Ivanka Iordanova:** Guidance, Writing - review and editing.

Chapter 3 is the paper submitted to Journal of Information Technology in Construction, in February 2021, entitled *An Ontology-based Approach to Data Exchanges for Robot Navigation on Construction Sites*. It provides the details on how the ontology is formalized and how building-related data can be semantically translated to the robot. The authorship credits are as follows:

- **Sina Karimi:** Conceptualization; ontology development, Methodology, Software programming, Writing - original draft.
- **Ivanka Iordanova:** Guidance on Construction, Writing - review and editing.
- **David St-Onge:** Guidance on Robotics, Software programming, Writing - review and editing.

Chapter 4 is the paper submitted to IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), in February 2021, entitled *Semantic Optimal Robot Path Planning Using Building Information Graphs on Construction Sites*. It describes a novel path planning method using BIM/IFC semantics in robot navigation to increase accuracy and enabling semantic navigation of an autonomous robot. The authorship credits are as follows:

- **Sina Karimi:** Conceptualization; Optimal Path Planning Development, Software programming, conduct experiments, Writing - original draft (except for Experiment and Results sections).
- **Rafael Gomes Braga:** Hardware and software integration; Simulation; Graphical interface; conduct experiments, Writing (Experiment and Results sections)
- **Ivanka Iordanova:** Guidance on Construction, Writing - review and editing.
- **David St-Onge:** Guidance on Robotics, Software programming, Writing - review and editing.

Finally, conclusion presents a brief overview of the findings for research questions of this study, highlights the limitations of the research, and suggests directions for future studies.

CHAPTER 2

INTEGRATION OF BIM AND GIS FOR CONSTRUCTION AUTOMATION, A SYSTEMATIC LITERATURE REVIEW (SLR) COMBINING BIBLIOMETRIC AND QUALITATIVE ANALYSIS

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Article published in *Archives of Computational Methods in Engineering,* January 2021.

2.1 Abstract

For several decades now, the construction industry is suffering from low productivity, especially in comparison to manufacturing industries which have succeeded to benefit from digitalization of their processes. Furthermore, scarceness of qualified workforce is expected in the near future. Construction Automation is introduced as a solution to these challenges. The capabilities of construction robots are improving at an accelerated pace. They are starting to be used in non-laboratory contexts for automating processes ranging from infrastructure inspection to digital fabrication. One fundamental requirement of employing robots in construction is their autonomous positioning. Building Information Modelling (BIM) and Geographic Information System (GIS) are now a necessity for the construction projects. Integration between BIM and GIS provides holistic digital representation of the built environment that robots could potentially utilize for positioning purposes. Preceding this research, a number of reviews have been conducted on BIM-GIS integration, but none studied it from automation perspective. This research addresses this deficiency through a systematic literature review of the state-of-the-art on BIM-GIS integration with the purpose of robot positioning and navigation on construction sites.

Using software tools and "science-mapping" methods, 236 papers were explored. Trends, challenges, potentials, and deficiencies identified and mapped. Citation patterns of journal

articles along with the analysis of studies; visualized and analyzed. Bibliometric analysis is followed by a thorough qualitative analysis of the articles identified by the systematic methodology indicating limitations of current studies such as vertical navigation, inaccuracy, dynamics of construction sites, indoor-outdoor navigation. Requirements for robot positioning using BIM-GIS integration are defined.

Keywords: Construction Automation, Construction robots, Productivity, Building Information Modelling, BIM, Geographical Information Systems, GIS, Bibliometric, Science-mapping, Review.

2.2 Introduction

Productivity has always been an issue in construction industry (Chen *et al.*, 2018). According to Scape Group, 58% of construction suppliers and contractors identify scarceness of qualified workforce as the major challenge of improving the productivity of the construction industry in the near future (The Scape Group, 2016). Studies indicate that the construction industry is falling behind the overall global improvement in productivity (Bock & Linner, 2015). A great number of reasons have been identified, such as persistence of employing traditional methods, lack of implementing industrial approaches of construction processes, taking little benefit from the use of digital tools and communication technologies (de Soto *et al.*, 2018). Numerous studies, consequently, are carried out to tackle this issue. Barbosa, Woetzel & Mischke (2017) propose adaptation of technology, through leveraging cross-functional teams, and implementing brand new technology simultaneously with the training for it. Another study identifies the privileges of applying Scrum strategy from design to the construction phase (Streule, Miserini, Bartlomé, Klippel & De Soto, 2016). Agarwal, Chandrasekaran & Sridhar (2016) have developed a framework to better exploit and leverage current technologies namely, 'rapid digital mapping', 'Building Information Modelling' (BIM), 'collaboration within a digital workplace', 'Internet of Things' (IoT), and 'future-proof design and construction'. 'Future-proof design' is mainly referred to as future anticipation design and development methods not to detriment the future of the existing buildings (Rich, 2014). Some researchers propose that the construction industry should undergo a deep transformation in order to be able to adopt advanced technology. According to Bock & Linner (2015), the required change in construction industry comes from the current emerging technology referred to as “Industry 4.0”.

In that direction, Bowmaster & Rankin (2019) have recently modified the multidimensional framework proposed by Froese & Rankin (2014), with the purpose to examine the level of maturity of Canadian construction industry in respect to industry 4.0 technologies. The authors conclude that very little research has been carried out with regard to ‘construction-based’ automation and robotics in Canada causing a gap of ‘prototype development’ in ‘cyber-physical systems’ of navigating and positioning (Bowmaster & Rankin, 2019).

Performing research on one of the pillars of Industry 4.0, de Soto *et al.* (2018) investigate the productivity of digital fabrication in construction industry with a robot fabricating a complex concrete wall. The results show higher productivity when robotically fabricating a wall in comparison to a conventional method, and provide evidence that employing robots would enhance construction productivity.

Actually, a robot can be associated with every on-site inspection or digital fabrication practice, and a key part of the process is determining the robot’s position. Therefore, positioning of robots becomes a fundamental step in construction inspection or digital fabrication.

A virtual representation of the project and its environment can provide a holistic overview of the construction in relation to the existing infrastructures and the surrounding environment. Today, two well developed technologies namely Building Information Modelling (BIM) and Geographic Information System (GIS) provide the digital environment for facilitating the analysis and management of spatial and non-spatial data (Ma & Ren, 2017). BIM, basically, represents geometric and semantic functions of construction projects and provides a shared database enabling construction practitioners to collaborate effectively (Wang, Pan & Luo, 2019). BIM facilitates data management of buildings’ lifecycle including design, construction, operation, and maintenance of built assets (Doumbouya *et al.*, 2017). On the other hand, GIS provides location-related analysis along with spatial representation of built environment in various fields of science (Longley, Goodchild, Maguire & Rhind, 2005). Provided the capability of spatial data analysis by GIS, it is applicable to a broad range of practices including in construction industry (Wang *et al.*, 2019). In addition, several GIS-based simulation studies have been conducted for various purposes, which makes this field of knowledge more practical (Li, Quan & Yang, 2016).

Built environment stakeholders and geospatial specialists have investigated the integration of BIM and GIS in various research topics and practical applications, such as Smart City (Yamamura, Fan & Suzuki, 2017), urbanization (Tashakkori *et al.*, 2015), internet of things (IoT) (Brundu, Patti, Osello, Del Giudice, Rapetti, Krylovskiy, Jahn, Verda, Guelpa, Rietto et al., 2016), noise assessment (Deng, Cheng & Anumba, 2016a), energy consumption (Afkhamiaghda *et al.*, 2019), flood influence evaluation (Amirebrahimi, Rajabifard, Mendis & Ngo, 2016b), and environmental data analysis (Morris, 2003). Despite the great benefits of BIM and GIS integration, the process and methodology of such integration are challenging. Wang *et al.* (2019) argue that the different focuses of BIM and GIS causes the integration challenge. The former focuses on building components while the latter - on geospatial information and environment around the building. BIM is more concerned with the internal details of building projects forming micro-level data, whereas GIS is specialized in geospatial analysis. Nevertheless, BIM and GIS have great potential to be used together for the robot navigation and positioning. GIS would provide geo-referenced locations enabling robots to generate a navigation path, and BIM - semantic and geometrical information of the building or infrastructure, thus helping robots to detect obstacles and ultimately generating a navigable path.

This study is the first stage of a larger research project aiming at using BIM and GIS for robots' positioning on construction sites in order to reduce the complexity of the current navigation generating methods by using the common digital environment of the construction project. To be able to define the research focus, initially, current studies in BIM and construction robotics and their characteristics are investigated. Then, GIS and construction robotics are explored to examine how GIS can contribute to construction robots' navigation. In addition, the related works with regard to BIM and GIS integration are studied to examine the current solutions and to identify existing limitations. The research contributes to the scientific knowledge on robots' navigation on a construction site by systemizing the-state-of-the-art in the domain, and by identifying the requirements of robot's navigation on construction sites, integrated with BIM and GIS. The practical application of the projected results will make possible the automatic construction of more complex and 'real-life' building elements, integrating heterogeneous building systems. Ultimately, this has the potential to affect positively the productivity, health and safety on construction sites, as well as the quality and sustainability of a project.

2.3 Methodology

The methodology used in this study is Systematic Literature Review (SLR), which is defined as the identification, evaluation, and interpretation of a field of research that can be reproduced with the same protocol by other researchers (Kitchenham, 2004). The utilized SLR employs a combination of qualitative analysis (Moher, Shamseer, Clarke, Ghersi, Liberati, Petticrew, Shekelle & Stewart, 2015) and bibliometric network visualization referred to as "science mapping" (Van Eck & Waltman, 2014). The former focuses on qualitatively examining the papers collected through science mapping co-occurrence method, and the latter provides a comprehensive overview of the status in the field. Common methods studied in science mapping are "keyword co-occurrence," "citation relations," and "co-authorship relations." Bibliometric network visualization facilitates the analysis of a vast number of scientific networks by visualizing patterns systematically in bibliographical databases (Cobo, López-Herrera, Herrera-Viedma & Herrera, 2011).

Science mapping is capable of denoting the potentials of a specific field. In the context of the current study it is about the potentials of BIM and GIS integration in relation to construction robot navigation and positioning. Figure 2.1 illustrates the overall relationships between bibliometric analysis and qualitative analysis. Keywords co-occurrence is the mutual step in both analyses. Its results in bibliometric analysis is used in qualitative analysis in order to identify the most relevant articles.

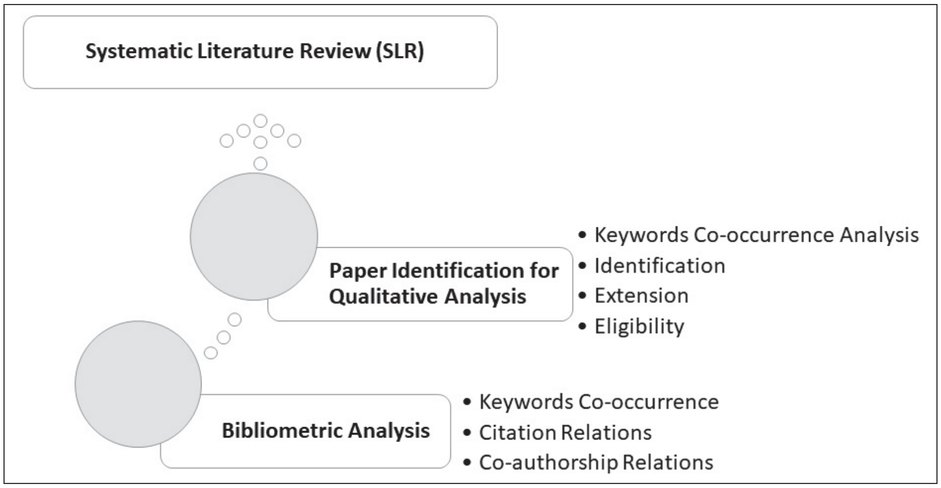

Figure 2.1 Overall Relationship of the SLR methodology with bibliometric and qualitative analyses

Figure 2.2 illustrates the overall methodology used to identify the most relevant papers to be investigated in the context of the qualitative analysis of this study. In the first phase, this methodology uses the keywords co-occurrence conducted in the bibliometric analysis.

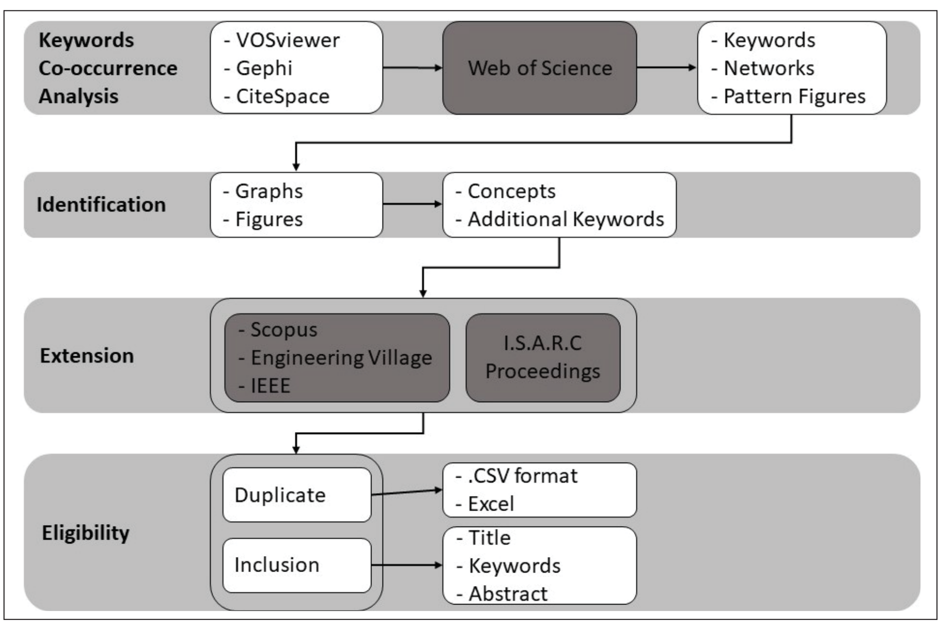

Figure 2.2 Context determination framework to search relevant scholarly journals

As presented on the Figure 2.2, the initial keywords co-occurrence analysis is performed on the Web of Science database. It allows for new keywords to be added to the paper identification process. This yielded 236 papers. At the next step, after having identified the journals whose focus is the closest to our target domain, the search is extended to include the following databases: Scopus, Engineering Village, IEEE and the ISARC proceedings, thus resulting 1730 papers. After eliminating the duplicated and the inclusions, we obtain 1021 papers. Their titles, keywords and abstracts are then carefully read to determine their relevance to the targeted domain. Thus, finally, 64 scholarly papers are qualitatively analyzed. The following points present in detail the methodology and the results of the science mapping part of this research.

2.3.1 Keywords co-occurrence analysis

The purpose of this analysis is to provide a holistic overview of construction robots' navigation and positioning employing BIM and GIS integration. The search strategy is initially to investigate robots' navigation with BIM-GIS integration together. It gave an empty result (0 papers). Hence, to attain the aforementioned goal, the bibliometric study is divided into 3 keyword clusters to investigate their relation with each other. In this step, each category is explored to include the most relevant papers for the qualitative analysis presented in section 2.4.2.

- **BIM and Construction Robotics:** (bim OR "building information model*") AND (automat* OR robot* OR "digital fabrication" OR dfab) AND (navigat* OR traject* OR path*)

As illustrated in Figure 2.3, the combination of BIM and construction robotics comprises various subdomains, which indicates the applications and the potentials of BIM in construction automation especially in construction robotics. Figure 2.3, also reveals various technologies employed for robots. It illustrates that "navigation" is a field of study that researchers work on, and suggests that the application of BIM in the construction industry can be related to robot navigation. Additionally, Figure 2.3 denotes adjacent subdomains around it, namely: "point cloud", "path planning", "indoor navigation", "indoor modeling". To explore the application(s) of BIM in Construction Robotics (CR), scholarly papers categorized under each subdomain

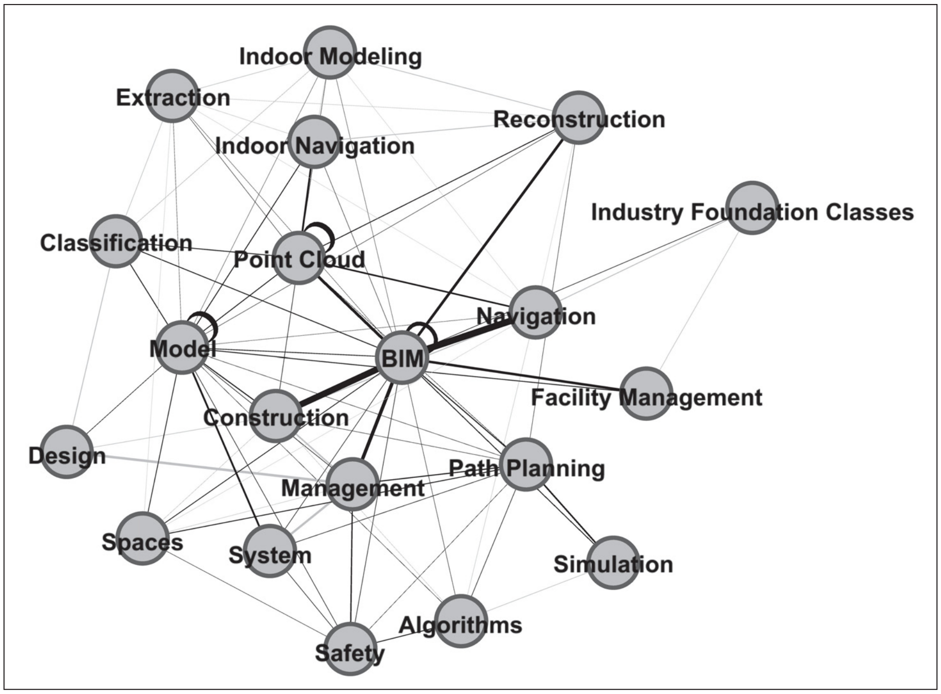

Figure 2.3 Keywords network of BIM and Construction Robotics

are identified and subsequently a qualitative analysis is conducted to investigate features and functions in this regard.

- **GIS and Construction Robotics:** (gis OR “geographic information system*”) AND (automat* OR “construct* robot*” OR “digital fabrication” OR dfab) AND (navigat* OR traject* OR path*)

Figure 2.4 demonstrates the hidden concepts of GIS and construction robotics and how GIS helps navigating and positioning robots. Similar to BIM and construction robotics keywords analysis, one important application of GIS in robotics is “navigation”. The other concepts such as “path planning,” “digital elevation models,” “algorithm,” “tracking,” “gps,” “remote sensing” play different roles in GIS and construction robotics domain. To understand the functions of each concept in navigating construction robots with GIS, detailed qualitative analysis is carried out (in section 2.4.2) to identify features and methods presented in the papers.

- **BIM and GIS:** (bim OR “building information model*”) AND (gis OR “geographic information system*”)

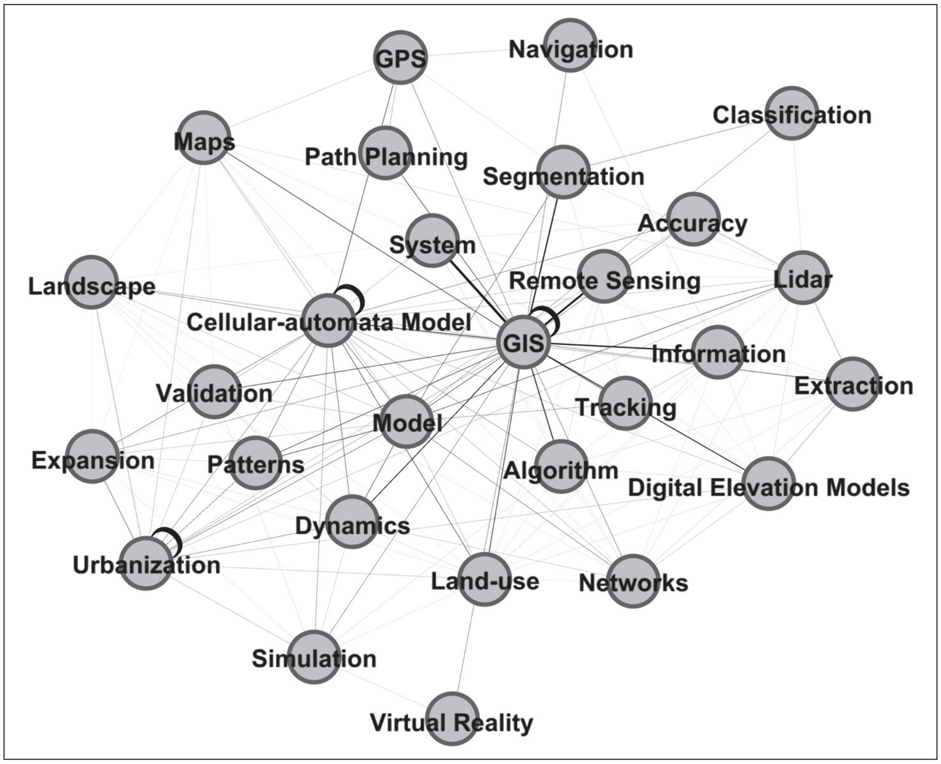

Figure 2.4 Keywords network of GIS and Construction Robotics

Many subdomains of the BIM and GIS interaction are revealed on Figure 2.5. The purpose of conducting this analysis is to collect data needed to integrate building information models and geographic information system in the desired research direction. Figure 2.5 indicates the current applications of such an integration. “facility management,” “layout,” “smart city,” “optimization,” “integration,” and “indoor” are some of those. It is also important to mention that IFC (Industry Foundation Classes) and CityGML (City Geography Markup Language) are open standard data model and exchange format for BIM and GIS respectively. Both appear in the keywords network as subdomains. As the two previous categories presented, journal papers categorized under each subdomain is studied qualitatively to provide a comprehensive understanding of current contributions and requirements of integrating them.

All the sets of data derived from Web of Science Core Collection, initially, are submitted to VOSviewer to construct a co-occurrence network of keywords, subsequently, are imported to Gephi to create customizable and detailed visualization and more importantly to run further

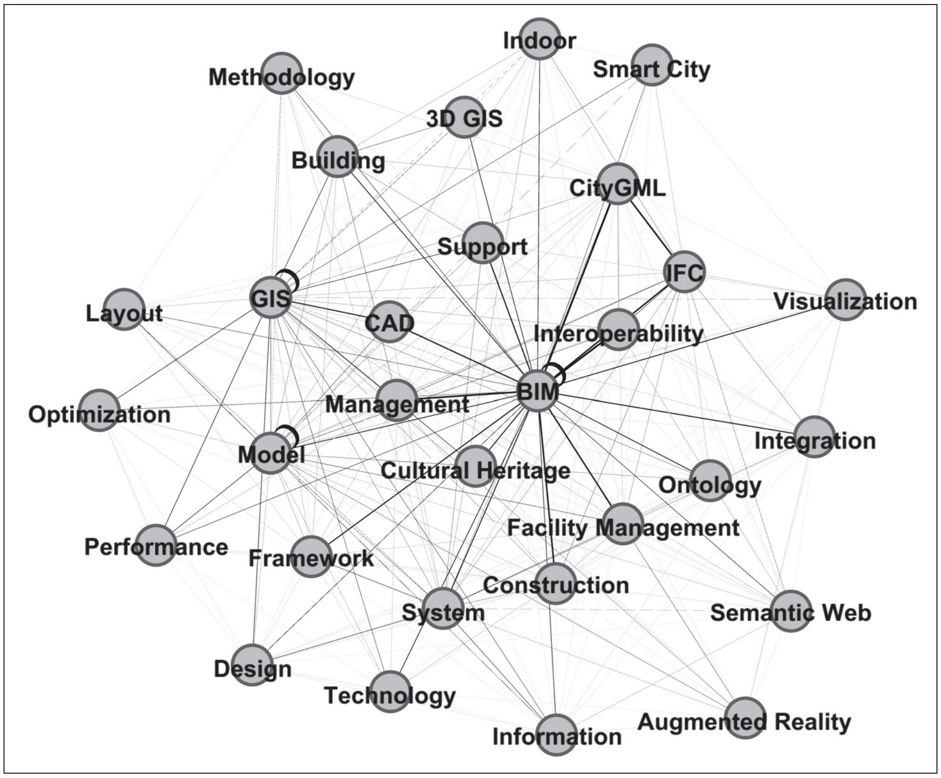

Figure 2.5 Keywords network of BIM and GIS

analysis. With Gephi computing tool, similar concepts such as "building information modelling", "building information modelling" and BIM are merged.

Cobo *et al.* (2011) provide a review of a number of available tools for the purpose of bibliometric analysis, namely: Bibexcel, CiteSpace, CoPalRed, IN-SPIRE, Leydesdorff's Software, Network Workbench Tool, Sci2 Tool, VantagePoint, VOSViewer. The authors conduct a survey to find the advantages and drawbacks of each of the above-mentioned tools. In addition, Van Eck & Waltman (2014) compare two "general network analysis tools" - Pajek (De Nooy, Mrvar & Batagelj, 2018) and Gephi (Bastian, Heymann & Jacomy, 2009) in order to analyze the visualize networks. The authors conclude that Gephi provides more tools on detailed customizable visualization compared to Pajek (Van Eck & Waltman, 2014). According to the above-mentioned analysis and for the purposes of this study, VOSViewer, CiteSpace, and Gephi are selected to perform the bibliometric analysis.

- VOSviewer is devised to constitute and map bibliometric data (Van Eck & Waltman, 2010).
- Gephi enables the researcher to carry out deeper analysis on mapped graphs and to make modifications to the networks (Cherven, 2015).
- CiteSpace analyzes the trends developing in a specific domain. It also manages to visualize various network layouts, detects clusters and analyzes within a given time period (Chen, 2014).

The Web of Science Core Collection is selected as the preliminary database to run keywords co-occurrence by VOSviewer due to its flexibility to search various combinations of terms, its thorough journals (Chen *et al.*, 2018) and its compatibility with VOSviewer computing tool. Furthermore, Web of Science Core Collection enables authors to investigate the peer-reviewed, high quality scholarly articles from all over the world. Other widely known databases such as Scopus, Engineering Village, IEEE, and I.S.A.R.C. (International Symposium for Automation and Robotics) proceedings are included later to make this research as thorough as possible (see section 2.3.3).

A keywords network is generated by running co-occurrence type of analysis on the dataset to constitute a graph based on the keywords. The nodes of the graph indicate the fields of research and the subdomains of which they consist. This is useful for identifying underlying concepts, adjacent topics and hidden links between themes; to illustrate the potentials and more importantly to determine the context of research for qualitative analysis. The fundamental step of bibliometric analysis is to determine the contexts of research, which are relevant to the objective of the survey. In other words, the choice of keywords for the search in the databases, models the entire bibliometric analysis (Cobo *et al.*, 2011).

2.3.2 Identification

Once the keywords network is formed, the subdomains and their keywords identified, the search proceeds a step forward and refines the context determination to the desired ones. Based on the procedure described in section 2.3.1, Web of Science Core Collection refinement provides the articles, which are the relevant ones to the scope of the study. It is noteworthy to mention that the identified papers are published by 2020. The papers collected by now are the only ones available in Web of Science Core Collection, but they still do not provide a comprehensive outlook to the field, so the search is extended to other databases.

2.3.3 Extension

To enable the literature to synthesize as many as possible related works, Scopus, Engineering Village, and IEEE (Institute of Electrical and Electronics) are added to the search. The I.S.A.R.C. (International Symposium for Automation and Robotics in Construction) proceedings are included too, as the papers published there represent the advances, contributions, and concerns of the researchers for all fields of construction with great concentration on Construction Automation, Robotics, IT, etc. (The International Association for Automation and Robotics in Construction, 2019).

2.3.4 Eligibility

Eligibility comprises two main steps, which are the identifications of duplicates and inclusion. The former identifies and subsequently removes the duplicated articles from the database and the latter only brings the papers which are precisely to the point of current study into consideration, which is the application of BIM and GIS integration in robots' positioning on construction sites. Although the number of scholarly papers remarkably increased in the extension phase, there are for sure many articles, which are duplicated in the different databases. To tackle this problem, all the databases' information is downloaded and is converted to .csv format in order for Excel to identify the duplicate ones and remove them. The I.S.A.R.C proceedings do not provide such export format so this procedure is done manually.

The final step is to submit only those articles studying, partially or thoroughly, the focus of the current research to qualitative analysis. To reach this objective, all the articles available so far are filtered based on their titles, keywords, and abstracts.

2.4 Findings

2.4.1 Bibliometric Analysis of BIM-GIS Integration

The Science mapping provided in this section is conducted on 236 papers of BIM and GIS from Web of Science Core Collection to provide a generic comprehensive overview of the field. The first study on Building Information Modeling and Geographic Information System occurred in 2008, carried out by Lapierre & Cote (2007), and is published by "URBAN AND REGIONAL DATA MANAGEMENT." As it is illustrated in Figure 2.6, from 2008 to 2019, there has been an important growth of the research in the field. In 3 years, during 2014 to 2017, a sharp increase has occurred which implies an exceptional interest of researchers in BIM and GIS together. It is also interesting to note that based on the forecasting line provided, it is predicted that this growth continues. New fields of BIM and GIS integration might emerge, or current solutions might be considerably improved.

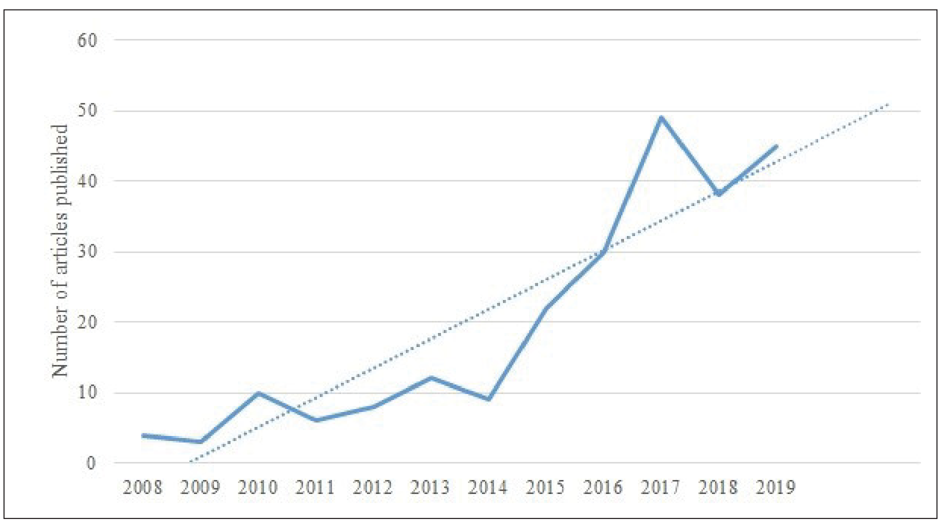

Figure 2.6 Distribution of papers over years
Adapted from Web of Science (2020)

2.4.1.1 Keywords co-occurrence analysis

Following publishers' requirements, the authors of scientific papers indicate their research focus through keywords. In bibliometric studies, the analysis of the keywords shows the width of the research domain, and draws the boundaries in that specific domain (Su & Lee, 2010). Graphs constituted by related keywords illustrate the relationships among subdomains existing in the studied field (Van Eck & Waltman, 2014). Hence, an analysis is performed based on the keywords co-occurrence method. Every couple of nodes (keywords) is linked via an edge and each edge carries a weight. The number of publications in which two keywords occur together is represented by weight metrics (Van Eck & Waltman, 2014).

In this research, VOSviewer software visualizes and shapes the networks of subdomain studies based on the data retrieved from Web of Science Core Collection. Gephi is employed in order to conduct further data analysis of the file exported from VOSviewer. Within Gephi environment, similar areas of studies (such as "geographic information system (gis)", "geographic information system", and "gis") are merged. The result is a graph comprising 30 nodes illustrated in Figure 2.7.

Gephi is capable of analyzing various statistics on a given network. The weighted degree of a node represents the weighted number relations (edges) it has (Opsahl, Agneessens & Skvoretz, 2010). In other words, the higher the number of weighted degree of a relation is, the more influential that domain is. A 'data laboratory' of Gephi consisting of the metric analysis of the graph on Figure 2.7 is presented in Table 2.1. Moreover, different layouts are available for different purposes in accordance with features of topologies (Gephi.org, 2019). The current analysis emphasizes the rankings of the research areas. The visualization of the data, therefore, is based on the ranking of the nodes.

Based on the information provided by bibliometric analysis, the following conclusions can be made:

1. The integration of BIM and GIS environments in construction has attracted a great amount of attention in recent years, but its potential applications in construction automation

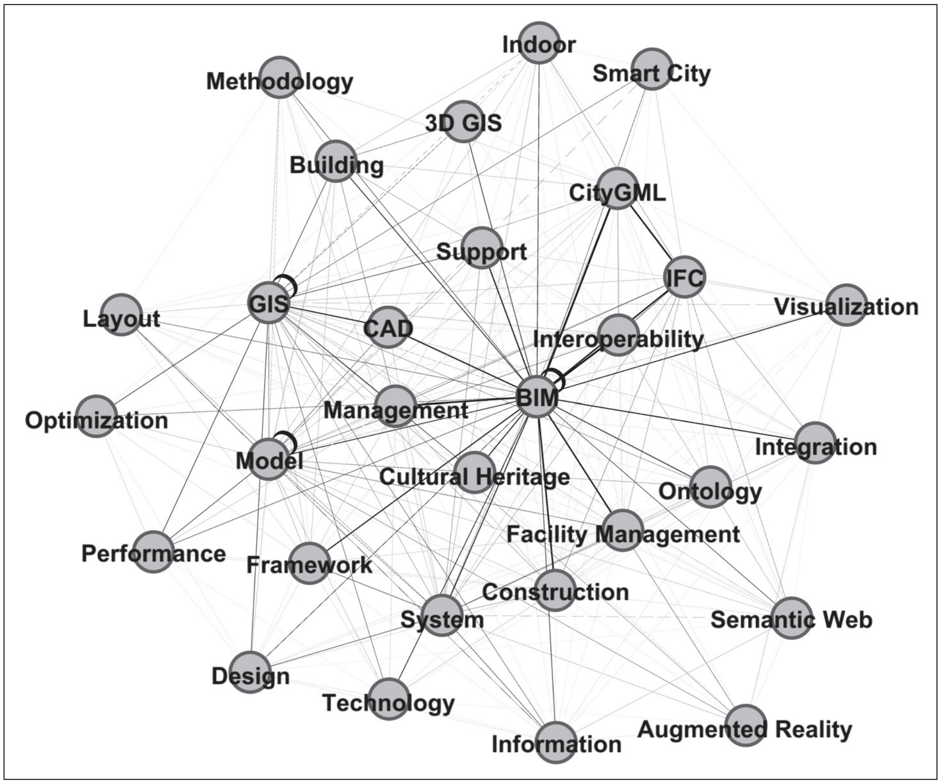

Figure 2.7 Core Research Focus - BIM and GIS

and construction robots' positioning has not been studied. As seen from the keywords subdomains table (apart from BIM and GIS, which are the focal fields of this literature review), "citygml", "management" and "interoperability" attracted higher attention. In addition, analysis of the node weighted degree reveals that these three research areas have much higher relative importance compared to all the others. On the other hand, less attention has been paid to "cultural heritage", "methodology", and "smart city" indicating that researchers investigated these research areas less frequently within the body of the existing literature. More importantly, Figure 2.7 and Table 2.1 denote that construction automation is not one of the studied sub-domains and hence, requires more attention from researchers.

2. The research areas which are in the middle of Table 2.1 depict the potential areas in BIM & GIS integration. "Augmented Reality", "Facility Management", and "layout" are examples

Table 2.1 Ranking of the subdomains in relation to BIM-GIS integration

Label	**Degree**	**Weighted Degree**
BIM	31	52.96
GIS	31	16.38
CityGML	21	15.33
Management	23	12.98
Interoperability	19	12.21
Model	29	11.93
Construction	23	11.48
IFC	15	11.11
Facility Management	19	10.32
Support	20	9.49
System	21	9.37
Framework	18	9.00
CAD	9	7.00
Information	17	6.66
Semantic Web	19	6.50
Design	17	6.40
Integration	17	6.35
Ontology	14	6.35
Performance	9	5.82
Technology	12	5.52
Building	10	5.21
Visualization	13	4.96
Indoor	16	4.77
3D GIS	8	4.49
Layout	13	4.34
Augmented Reality	14	4.26
Optimization	9	4.05
Cultural Heritage	7	4.00
Methodology	10	3.09
Smart City	8	2.76

of such potentials. However, other areas, which are not listed in Table 2.1 are either not investigated or received much less attention, which shows the research gaps in this field. Other finding of this scientometric analysis reveal that a great deal of research is directed towards the “management” aspect of construction projects. Table 2.1, however, denotes that many authors have contributed to the domain by investigating “interoperability” of BIM and GIS, indicating one of the obstacles for the integration of the two digital environments. On the other hand, the “smart city” facet of BIM and GIS integration has one of the lowest weighted degrees (see Table 2.1) revealing that applications of BIM and GIS integration have been more studied in “building” projects rather than in “city planning” even though it could be utilized for both small and large scale projects.

3. As shown on Figure 2.7, “ifc (Industry Foundation Classes)” and “citygml (City Geographic Markup Language)” are two data schemas being used for BIM and GIS integration. The former is the open-format standard data schema for BIM and the latter has been developed for GIS interoperability. The bibliometric visualization of the literature database denotes that every region, where several nodes are located close to each other, establishes relationship within the area. For instance, “integration,” “interoperability,” “ifc”, “citygml” and “semantic web” are located close to each other within the network (see Figure 2.7) indicating that authors used semantic web technology to enable integration of BIM and GIS with IFC and CityGML schemas.

2.4.1.2 Document co-citation analysis

The document co-citation method reveals citation patterns among research studies and provides information regarding the intellectual structure of the studies (Chen, Ibekwe-SanJuan & Hou, 2010). Creating a network of document co-citation analysis is a common approach for providing this kind of information via science mapping (Chen *et al.*, 2010). CiteSpace is the selected software to conduct this analysis by creating citation clusters which is the most common method for network of co-citation analysis (Hosseini, Martek, Zavadskas, Aibinu, Arashpour & Chileshe, 2018). Figure 2.8 visualizes the paper clusters computed by CiteSpace, using the Log-Likelihood Ratio (LLR) algorithm. In statistical analysis, a log-likelihood ratio is a test to identify a null model against an alternative model (Dunning, 1993). LLR algorithm is mainly used to calculate p-value to decide on rejection of a null model (Dunning, 1993). In this regard, after using “filter out small clusters”, eight clusters (out of 61) are detected as the main research areas where cluster 0 is the largest in terms of size, indicating that this cluster contains the largest number of publications, while cluster 8 is the smallest cluster of the important ones. The labels attached to clusters of Figure 2.8 are proposed by CiteSpace. It should be mentioned that CiteSpace focuses on formation of clusters rather than on the underlying contents in the given clusters (Chen *et al.*, 2010).

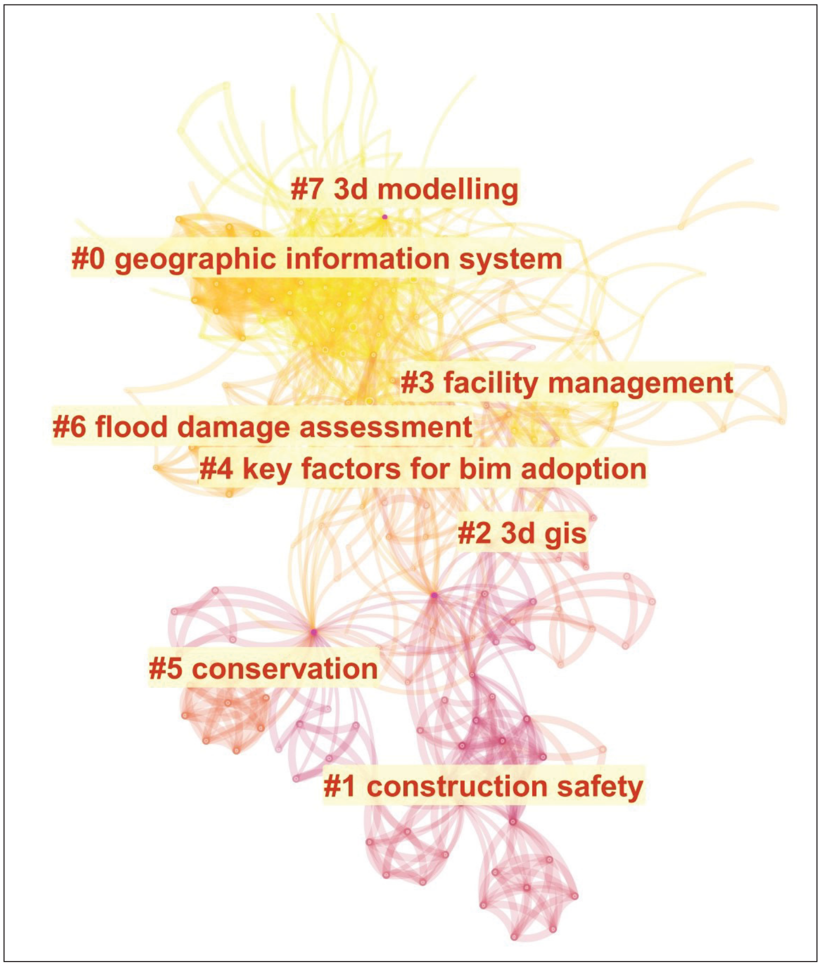

Figure 2.8 Clustering structure of BIM and GIS integration

Metrics evaluated by CiteSpace computing tool are Modularity Q = 0.7127 and Mean $Silhouette$ = 0.5206. The metric modularity ($0 < Q < 1$) indicates to what extent a network is capable of being independent (Shibata, Kajikawa, Takeda & Matsushima, 2008). The amount of modularity represents the quality of a network's structure meaning that modularity close to 1 indicates a network is well-structured while modularity close to 0 illustrates unclear

Table 2.2 Core clusters of document co-citation analysis if BIM and GIS

Cluster ID	Size	Silhouette	Mean Year	Focus of Cluster
0	89	0.705	2014	Geographic Information System
1	29	0.918	2006	Construction Safety
2	29	0.838	2008	3D GIS
3	28	0.845	2013	Facility Management
4	28	0.800	2011	Key Factors for BIM Adoption
5	27	0.954	2008	Conservation
6	22	0.870	2010	Flood Damage Assessment
7	15	0.857	2014	3D Modelling

cluster boundaries within a network (Chen *et al.*, 2010). Table 2.2 illustrates the details of clusters retrieved from CiteSpace.

The other metric "Silhouette" represents the uncertainty of a given cluster and is ranged from -1 to 1, meaning that a silhouette close to 1 indicates a cluster well separated from other clusters, whereas a silhouette close to -1 introduces heterogeneity of members within a given cluster (Rousseeuw, 1987). By interpreting aforementioned information of the study (Figure 2.8; Table 2.2), the following results can be formulated:

4. By applying document co-citation analysis, the number of articles considered for the clustering are more than the number of articles in the database indicating the fact that there are some that appear in more than one cluster. This indicates that the studies have high integrity and research endeavors took benefit from the previous ones meaning that the research in BIM-GIS integration is built on the studies conducted before. Results of studies conducted in the field of BIM and GIS reflect that researchers exchange their ideas and focus on the field. However, investigators have not studied potentials of BIM and GIS integration in relation to construction automation, which needs to be investigated.
5. An overview on the Mean Year indicates on what subdomain researchers focused during the years. Document co-citation analysis of BIM-GIS integration reveals that the recent attempts are mainly slanted towards Geographic Information System, 3D Modelling and Facility Management. Also, construction safety appears as the one of the earliest applications of BIM-GIS integration studied by researchers. Other research focuses are also complied in

the list on Table 2.2. Citation patterns of BIM and GIS integration (see Figure 2.8) reveal that authors of existing literatures have not investigate the construction automation relations with BIM-GIS integration domain and there exists a lack of exchange of ideas between these two domains.

6. Given the structure of the clusters demonstrated in Figure 2.8, BIM-GIS studies indicate a relatively high structural integrity. Silhouette values indicated in Table 2.2 show that clusters of the visualized network are connected through citations inside and outside of their clusters. As Hicks (1999) argues, such structure of clusters occurs when authors cite studies from other clusters, which creates a well-formed citation pattern of a given field. Therefore, as BIM-GIS forms well-structured clusters, this draws a promising future of the field.

2.4.1.3 Direct citation of sources

Direct citation of sources indicates prominent journals in a field of study (Van Eck & Waltman, 2014). Identification of prominent journals is beneficial to readers, authors, and editors. It enables readers to select which journals are focused on their field of study in order to find creditable articles, and it indicates to authors where to publish their studies in order to reach more potential readers in their field (Guidry, Guidry Hollier, Johnson, Tanner & Veltsos, 2004).

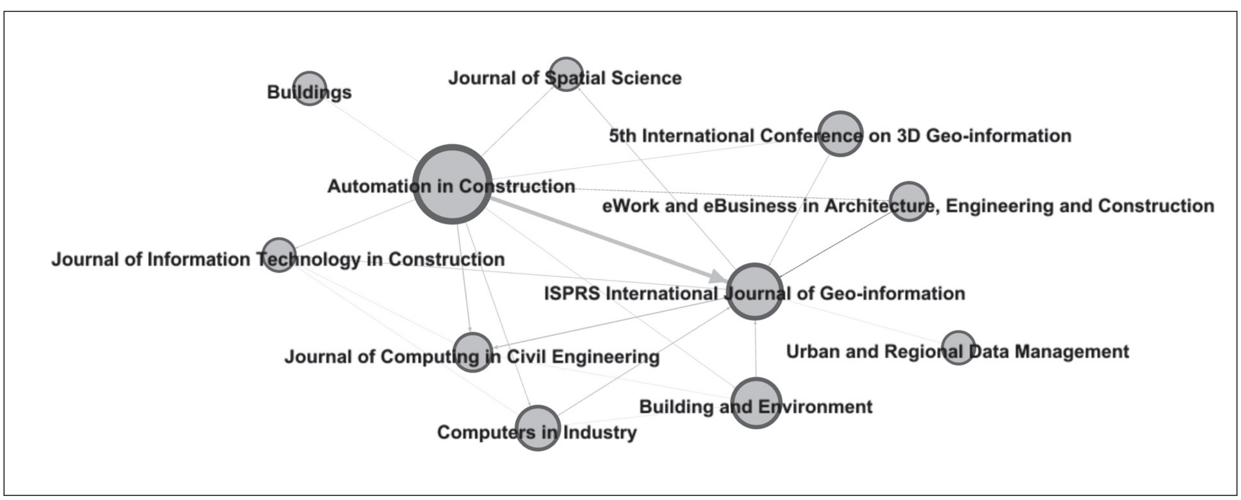

Figure 2.9 Graph of prominent journals in BIM & GIS

Among Gephi's statistics, HITS (Hyperlink-Induced Topic Search) algorithm is capable of rating web pages (Gephi, 2019). The HITS metric calculates two values for a web page; authority and hub value. By estimating "authority" Gephi provides each node (journal) a score indicating the value of the content within the journal. It also provides a "hub" value for outgoing links of each node (journal) indicating the value of links (Khokhar, 2015). Figure 2.9 illustrates 10 prominent journals in the field of BIM and GIS integration ranked based on the score calculated by Gephi using the HITS algorithm.

Table 2.3 also illustrates the top journals of the field accompanied by their rank, "authority" value, "hub" score, and the main research areas of each one. The most important outlet of the field is by far "Automation in Construction" with highest hub score (0.772) and highest weighted out degree (71.0). To provide better insight of each journal's research areas, their subdomains are also listed in the table. This helps authors and readers to refine their choice of journals to either publish their work or to read about their field of research. The HITS analysis in Gephi shows the following results:

The analysis of the network in Figure 2.9 can be interpreted as follows:

7. The majority of the articles in BIM and GIS integration are published in two journals namely, Automation in Construction and ISPRS International Journal of Geo-information. It is worthy to note that comparison between "weighted out degree" values of these journals shows that flow of information begins from Automation in Construction rather than ISPRS International Journal of Geo-information with a high difference (see Table 2.3).
8. The investigation of BIM and GIS integration with regard to construction automation is a focus of study of none of the journals. This fact corroborates the findings of current literature in previous sections that potentials of BIM and GIS integration from construction automation view has not been studied sufficiently. This fact confirms that more attention needs to be paid for applications of BIM-GIS in construction automation.

Table 2.3 Prominent journals of BIM and GIS

Rank	Journal	Weighted out Degree	Authority	Hub	Research Areas
1	Automation in Construction	71	0.043792	0.772793	Construction Building Technology, Engineering
2	ISPRS International Journal of Geo-information	22	0.486019	0.379324	Physical Geography, Remote Sensing
3	Building and Environment	9	0.222176	0.358016	Construction Building Technology, Engineering
4	Computers in Industry	8	0.325105	0.267654	Computer Science, Engineering
5	5th International Conference on 3D Geo-information	8	0	0.152319	Image Science Photography Technology, Physical Geography, Remote Sensing
6	eWork and eBusiness in Architecture, Engineering and Construction	6	0.222176	0.139729	Computer Science, Construction Building Technology, Engineering
7	Journal of Computing in Civil Engineering	1	0.434159	0.127924	Construction Building Technology
8	Buildings	0	0.222176	0	Computer Science, Engineering
9	Journal of Information Technology in Construction	0	0.444958	0	Engineering
10	Journal of Spatial Science	0	0.33123	0	Physical Geography, Remote Sensing
11	Urban and Regional Data Management	0	0.109054	0	Remote Sensing, Engineering

2.4.1.4 Co-authorship analysis

Conducting a co-authorship analysis enables researchers to explore and investigate the collaboration networks of pioneer researchers, institutions, and countries to acquire more profound knowledge of the field, develop expertise, increase productivity, and decrease isolation (Ding, 2011). Additionally, it would be worthy to the scientist who are carrying out research in a specific field to identify the prominent researchers, institutions, and countries to keep track of innovations, novel approaches, or recently developed ideas. Luwel (2004) argues that co-authorship analysis provides thorough investigation of scientific collaboration which ultimately leads to higher productivity of the work, higher citation, and attraction of attention. Based on what is discussed above, the following part of the literature analysis is divided into 3 sections namely, pioneer researchers, pioneer institutions, pioneer countries with regard to BIM and GIS integration.

- **Pioneer Researchers**

As Figure 2.10 illustrates, there are two major clusters of collaborating researchers in the reference field. Each of the clusters introduces, directly or indirectly, prominent authors in BIM and GIS integration. Direct indication of co-authorship refers to papers the authors published in collaboration, while indirect co-authorship refers to having mutual co-authors. Additionally, HITS algorithm is run to rank the prominent authors through applying authority scores (Khokhar, 2015). Quality of the connected nodes with link to other influential nodes of the graph constitutes the authority score (Lu & Feng, 2009). Gephi ranks the nodes with authority score to visualize the prominent researchers in terms of their influence to the field. Thus, the following interpretation can be made of the results shown on Figure 2.10:

9. The majority of the BIM and GIS integration researchers collaborate. However, an integral network of collaboration is far to be present. Some isolated authors should identify the collaboration networks in order to be able to enhance their productivity. Nearly 40% of the authors have established a strong relationship working in BIM and GIS, which provides prospects for improving productivity of the field in future. Nevertheless, there are a few authors who do not belong to any cluster reflecting the fact that those authors of the network (Figure 2.10) are carrying on the research in isolation.

- **Pioneer Institutions**

Similar to individuals' collaboration in the BIM and GIS domain, a network of institutional collaboration can be created to identify the prominent universities and institutes around the world.

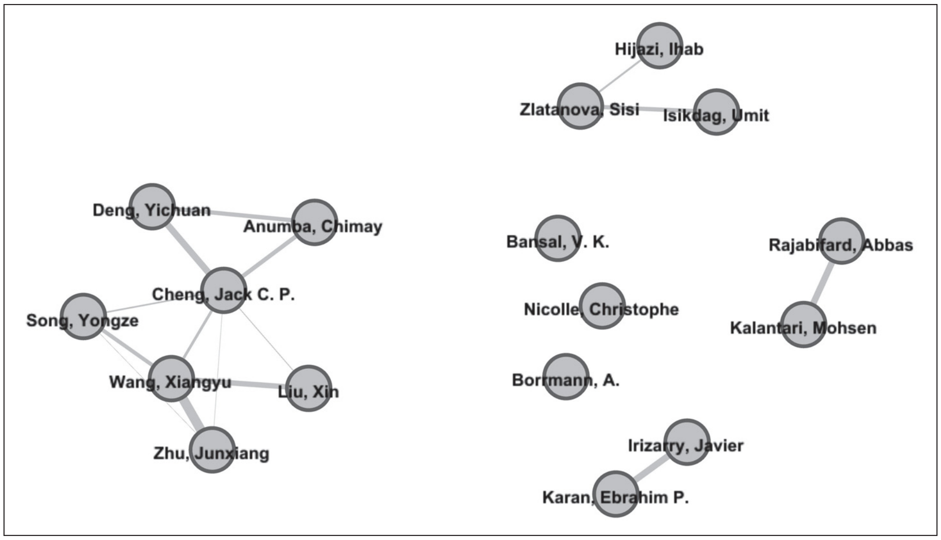

Figure 2.10 Prominent researchers in BIM and GIS

As Figure 2.11 illustrates, the HITS algorithm ranks the institutions based on the "hub" score to show the influence of the nodes' actors (Khokhar, 2015). The size of the nodes represents the "hub" score showing the influence of the institution on others. Interpretation of the HITS algorithm analysis along with the network demonstrated in Figure 2.11, shows that:

10. Apart from the four isolated ones, the majority of the institutions working on BIM and GIS collaborate. However, this collaboration does not establish a strong relationship among them (visualized by the low number of connections). This indicates one of the problems in the field. Solving this lack of collaboration has the potential to result in significant progress and productivity improvement of the BIM and GIS integration field.

- **Pioneer Institutions**

Following a procedure similar to the one identifying prominent researchers and pioneer institutions, Gephi reveals the influential countries in the BIM and GIS integration domain. Directed and undirected edges map the flow of information and closeness among countries (as shown on Figure 2.12). Co-authorship analysis of countries can contribute to redefine strategies and to establish policies to improve productivity. Based on the statistical analysis and the graph illustrated in Figure 2.12, the results can be interpreted as follows:

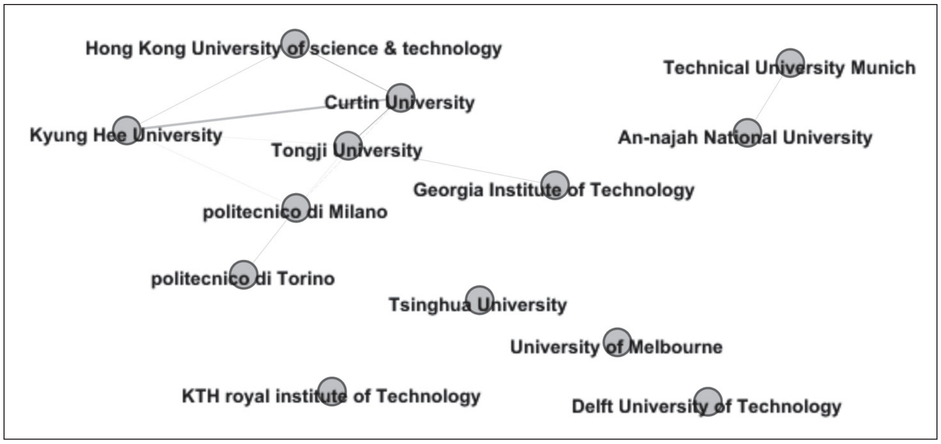

Figure 2.11 Pioneer institutions of BIM and GIS

11. Taiwan is the only country, which does not work in collaboration with other prominent countries, while the United States connects with all countries. In addition, the flow of information correlates with the USA, which is the most prominent country in BIM and GIS integration.
12. According to the average degree values calculated by Gephi, Canada can be categorized as a country where BIM and GIS integration has not been greatly studied. About 5% (13 out of 236) of the investigated articles are developed in Canada. The names and affiliations of the authors with more than 2 published papers are listed in Table 2.4:

Table 2.4 Prominent researchers of Canada in BIM & GIS integration

Author	**Affiliation**	**Number of publications**	**Publication Year**
Hammad. A.	Concordia University	2	2016, 2017
Salimzadeh. N.	Concordia University	2	2016, 2017
Pottinger. R.	University of British Columbia	2	2017, 2018
Staub-French. S.	University of British Columbia	2	2017, 2019
Zadeh. PA.	University of British Columbia	2	2017, 2019

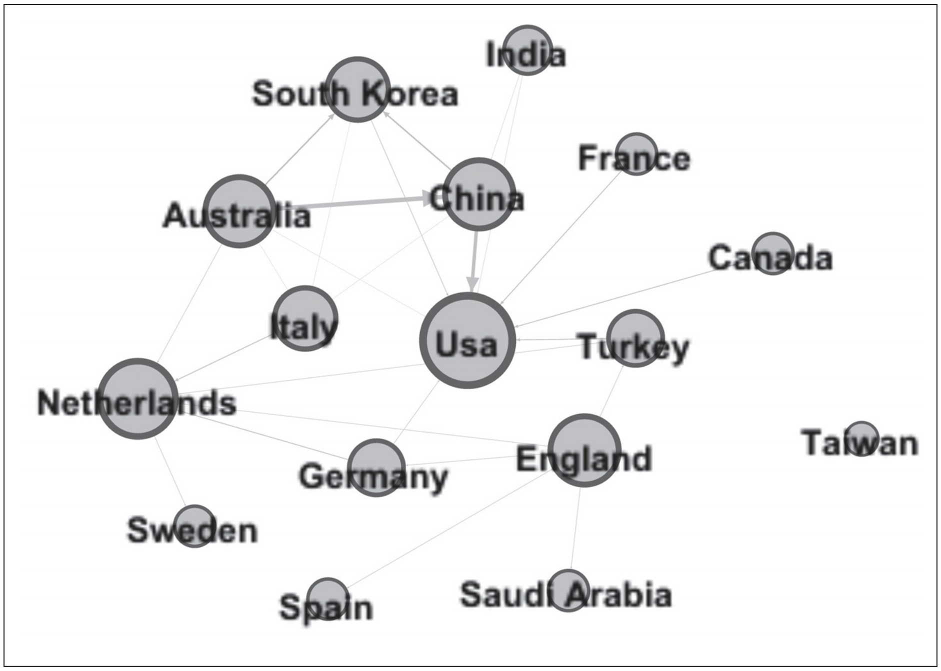

Figure 2.12 Pioneer countries in research on BIM and GIS integration

The data on Table 2.4 implies that BIM and GIS integration field has not been broadly studied in Canada, so more investigations needs to be carried out in this domain.

2.4.2 Qualitative Analysis

Section 2.4.1 of the current literature review adopted bibliometric analysis to investigate the integration between BIM and GIS. The systematic literature review identified the most relevant articles to the research topic to study in depth the contributions to the field. In what follows, these papers are classified into three categories for explicit distinction between different subdomains, namely: BIM and robotics, GIS and robotics, and BIM and GIS in relation to robots' positioning and navigation on construction sites.

2.4.2.1 BIM and Robotics

The purpose of the current literature review is to investigate the potentials of BIM-GIS integration in relation to construction automation especially in robot's navigation on construction sites.

After having a comprehensive bibliometric analysis of the BIM and GIS integration domain, this section is to qualitatively investigate, in depth, the previous contributions of researchers regarding the applications of BIM in robots' navigation. The application of GIS is investigated afterwards. This section describes the previous research attempts followed by the interpretations of the studied papers.

Delbrügger, Lenz, Losch & Roßmann (2017) have developed a BIM-based navigation framework for digital twins of factories. It comprises of building information model and factory equipment classified as fixed and dynamic. In addition to BIM, the proposed framework incorporates path-finding technology. The authors have developed a navigation core utilizing two approaches namely, corridor map method and navigation mesh. The former refers to convex polygons covering navigable surfaces, which are mainly triangles (Arkin, 1987) and the latter represents edges as navigation corridors with a free space for collision-avoidance provided by a sphere (Geraerts & Overmars, 2007). The navigation framework for digital twins of factories improves the IFC-format imported files by initially importing the ifcXML file to IFC Engine (EDF ltd, 2019) and subsequently submitting the file into VEROSIM (Delbrügger *et al.*, 2017). VEROSIM supports IFC and CityGML files to run simulation for spatial analysis (Verosim Solutions, 2019). Delbrügger *et al.* (2017) classify building components as navigable surfaces and objects as either obstacle or agent. Obstacles can be either static or dynamic. They have also developed a scene content containing all the possible components in factories and mapped each element to navigation criteria.

Ibrahim, Roberts, Golparvar-Fard & Bretl (2017) have developed interactive model-based path planning for Unmanned Aerial Vehicles (UAV) to capture data on construction sites. They use a semi-automated approach with a drone to capture visual data on construction sites. Interoperability problems have been eliminated using a web platform technology. With a mobile application, used to plan the flight, the proposed system integrates web platform with visual model derived from the UAV's camera to compare the construction progress with the schedule. A BIM model is used to plan the aerial trajectory in order to inspect the related sectors of the construction sites.

Darwish, Li, Tang, Li, Chen et al. (2019) have created a framework in which RGB and depth (RGB-D) sensors are used to visualize indoor environments, taking structural constraints into account. They propose two main purposes of the RGB-D sensors namely, robot collision avoidance within indoor environment (Endres, Hess, Sturm, Cremers & Burgard, 2013) and 3D model reconstruction (Tsai, Chiang, Chu, Chen, El-Sheimy & Habib, 2015). Darwish *et al.* (2019) focus on the latter application in their proposed framework, which considers all the features in RGB and depth images to reconstruct an indoor environment.

Nahangi, Heins, McCabe & Schoellig (2018) present a method with which UAV localization and navigation can be tackled in GPS-denied indoor construction environments. The proposed method uses connected coordinates of BIM model with AprilTags. With UAV's camera, the data of tags are captured and are transformed so that the UAV can localize. The authors confirm that the Global Positioning System (GPS) is accurate and reliable for outdoor environments, but inefficient for the indoor ones. AprilTags is a visual fiducial system in which the tags can be ordinarily printed. The coordinates of the tags correspond with those in a BIM model so that the UAV is able to localize itself in global coordinate system (Nahangi *et al.*, 2018). In order to localize the UAV, an on-board camera is employed to detect the AprilTags.

Lin *et al.* (2017) have developed a method for automatic generation of indoor environment employing BIM and GIS at geometry level. With integration of BIM, GIS and i-GIT algorithm, they generate several possible routes for navigation purposes. To accomplish the automatic indoor navigation, they have developed a collective algorithm named Intelligent Generation of Indoor Topology (i-GIT) which supports IFC schema and automatically generates space boundaries for vertical and horizontal navigation. A set of algorithms are employed to generate floor-level paths and non-planar paths and to reduce the complexity and redundancy of path nodes. The former refers to horizontal navigation while the latter responds to vertical navigation needs. ESRI ArcScene is utilized to identify space boundaries of the IFC file and the algorithms were run in that environment.

Siemiatkowska, Harasymowicz-Boggio, Przybylski, Różańska-Walczuk, Wiśniowski & Kowalski (2013) adopt a semantic approach based on a BIM model for robot delivery indoor navigation. They have developed a hierarchical action planning to incorporate time-optimized robot navigation including two technologies namely, object detection based on point cloud and object detection based on image. Both horizontal and vertical navigation are taken into account and are tested within dynamic environment. They employ BIM to extract semantic information and indoor topology in order to be able to run the hierarchical action planning. Hamieh *et al.* (2017) have developed BIM-based indoor path planning method named BiMov using four definition phases. The first phase identifies all possible paths within a space using algorithms run on an IFC file. The second phase reduces the number of paths by discriminating between a mobile object, a person, or a bulky equipment. The possible paths within a space are further refined in third phase based on the content of the path, which can be influenced by the presence of machinery or restricted areas. Phase 4 considers number of paths affected by real-time situation or building's passages. Although the authors presented four-stage planning regarding robot navigation within indoor environments, they put emphasis only on the first two phases.

Quintana, Prieto, Adán & Bosché (2018) have developed a method using BIM, 3D laser scanner, and a color camera to detect 3 positions of a door within indoor environment. To attain this goal, they integrate geometry and color information obtained from the environment to detect the angle of a given door, and identify it as open, semi-open, and closed. Their system also provides an accurate position of the door in the world-coordinate-system.

Kayhani, Heins, Zhao, Nahangi, McCabe & Schoelligb (2019) assess the Extended Kalman Filter (EKF) to improve indoor localization using AprilTags. They use that improvement to navigate Unmanned Aerial Vehicle (UAV) within an indoor environment. They adopt a probabilistic approach towards data fusion in order to improve pose estimation accuracy. In this method, the authors employ BIM to identify coordinates of fiducial markers with a UAV equipped with camera to identify the relative pose. All the information is ultimately put together to calculate the coordinates in the global coordinate system. They use EKF to consider uncertainty, which is the characteristic of construction sites. BIM, in this approach, is specifically used to help the drone to identify the 3D coordinates of the AprilTags.

Neges, Wolf, Propach, Teizer & Abramovici (2017) have developed a system based on the Bluetooth Low Energy (BLE) to improve the quality of indoor location tracking on construction sites and for facility management purposes. The authors classify the work spaces systematically using a building information model and, then, place BLE beacons on different locations. The result of the study shows that the functionality of the proposed method is limited. The experiment also indicates that the signal strength and method robustness is greatly affected by the dynamic nature of construction sites and facilities.

Palacz *et al.* (2019) propose a method to navigate indoor mobile robots using the IFC schema of BIM and a graph, combined with artificial intelligence. They argue that the structure of buildings and the semantics of building components have great influence on the possible routes between two points. This graph-based navigation approach assigns attributes to graph nodes and graph edges. The former contains semantics of building elements and the latter stores the cost of navigation between spaces dependent on different variables namely, opening width, lift existence, space distance, and door types. The authors argue that the information derived from IFC schema only includes construction elements, while other elements such as chairs, anything left on the floor, etc. should be considered. Hence, an additional algorithm could the robot navigation for passing obstacles. This contribution assumes the robot has such algorithm built in (Palacz *et al.*, 2019).

Kim, Chen, Kim & Cho (2018) have provided a method in which a mobile robot collects spatial data specifically developed for construction sites with many uncertainties. The proposed system uses Simultaneous Localization and Mapping (SLAM) techniques to build a map of construction site for navigation through point clouds. However, the SLAM technique does not provide obstacle-awareness for a mobile robot so that kinematic modelling of the robot is analyzed. The authors, then, develop an algorithm based on fuzzy control to navigate the mobile robot in unknown environments with obstacles. In this method, real-time 3D environment reconstruction based on laser scanning is used instead of a building information model (Kim *et al.*, 2018).

Based on the literatures reviewed the following findings are presented:

1. Many indoor navigation and localization methods are introduced and investigated especially with integration to BIM. Indoor localization methods can be classified in three main categories (Ibrahima & Moselhib, 2015):
   - Wave-based propagation: comprising devices receiving waves of two frequency ranges, namely: ultrasonic and sound waves. Different types of receivers are also presented - such as radio frequency (RF), ultra-wideband (UWB), and wireless local area network (WLAN) (Caldas, Torrent & Haas, 2006; Goodrum, McLaren & Durfee, 2006; Jang & Skibniewski, 2008). Nonetheless, researchers studying the abovementioned techniques have reported several limitations with regard to accuracy. Infrared accuracy is reported at room-level (i.e. its accuracy is limited and it would not be a functional option for larger spaces) and its performance is disrupted by sunlight. WLAN and RFID accuracy is insufficient and varies from 4-9 m. UWB, in contrast, provides 9 cm accuracy but it is expensive and requires complicated deployment of transmitters, which makes it inefficient.
   - Image-based localization: relies on computer vision techniques and image matching. Computer vision techniques, itself, are categorized into two methods: Global and Local. The former refers to detecting edges and recognizing features, whereas the latter detects landmarks with the help of tags and images. The reported studies indicate that these methods suffer from lack of precision and, more importantly, are not appropriate for dynamic environments such as construction sites.
   - Inertia-based localization: this method uses an initial location and navigates through accelerometers, inertia measurement units (IMU), and other motion detectors. Ibrahima & Moselhib (2015) have developed a localization technique, which combines IMU and Kalman Filter. Their method produce a higher accuracy compared to ultrasonic and sound waves, but it remains yet inefficient due to the very demanding computational calculations.
2. Researchers use algorithm-based approaches to navigate mobile robots. Taneja, Akinci, Garrett Jr & Soibelman (2016) categorize them into three major classes namely: center-line

based, metric-based, and visibility-based. Center-line based algorithms select the medial axis of an indoor space, metric-based algorithms move along the navigable boundaries of a given space, and visibility-based algorithms are comprised of nodes and edges representing the end points of a path and the visible lines of a given indoor environment respectively. The limitation associated with these algorithms is that they do not consider the dynamic objects and furniture of an indoor environment to which construction sites are subject.

2.4.2.2 GIS and Robotics

This section of the literature review studies qualitatively the applications of GIS in robots' navigation on construction sites independent from BIM. In this part, the papers identified in the methodology section are investigated in depth to have a comprehensive overview of GIS and robots' positioning on construction sites. In what follows, the papers are described and later, discussed.

Mangiameli, Muscato, Mussumeci & Milazzo (2013) have developed a method based on GIS for generation of raster maps showing obstacles in urban areas. The authors develop this method to enable flight planning of an UAV. Their approach first represents the building data as a vector data shapefile, and then, converts it to raster to be able to use GIS. The authors use Spline algorithm to extract buildings' height for the raster map, identification of possible path within urban environment, and conversion of the path identified to waypoints for navigation of UAV. The possible obstacles are determined and subsequently are georeferenced in order to be avoided.

Zaki & Dunnigan (2017) identify three challenges to navigate autonomous robots, namely: representation and schemes, planning algorithm, and the integration architecture of both. They combine GIS modelling and description logic for representation and schemes, modify and fuse algorithms, and ultimately introduce a navigation architecture. GIS and ontology are used to constitute digital representation of dynamic data. The proposed framework does not consider neither vertical navigation nor moving obstacles.

Yang, Wang, Kwan & Yang (2015) propose a GIS platform in which the GIS database is modified. The authors introduce properties such as road width, lane number, lane info, and if-traffic to be able to describe the environment of the Unmanned Ground Vehicle (UGV). In addition, they redefine road models and turning strategy to generate a cost map navigating system for UGV navigation in urban environments.

Fernández-Caramés, Serrano, Moreno, Curto, Rodríguez-Aragón & Alves (2016) introduce a method for integration of indoor localization approach and GIS for the purpose of real-time navigation. They employ GIS to analyze indoor spatial data and develop a method that detects a door within indoor environment with data fusion of laser and vision sensors. Extended Kalman Filter is used for path finding.

Tur, Zinggerling & Murtra (2009) have developed a map-based navigation system in urban environments using GIS. The proposed system enables a robot or a team of robots to navigate within urban environments with prior assumption that an understandable navigation map is available. In this system, robots can connect to the map and navigate based on it. The authors highlight communication protocols and cooperation issues as the important aspects of the work.

Sun, Yang & Liu (2018) have proposed GLANS (GIS Based Large-Scale Autonomous Navigation System) for robot navigation in urban settings. They argue that current simultaneous localization and mapping (SLAM) techniques cannot be utilized for large-scale environments. In this method, a GIS database suggests a topological path on which the mobile robot can navigate, detect obstacles and consequently modify the path. Moreover, the adjustment results can be shared with other mobile robots so that the navigation and localization process is optimized. Their method is independent of the Global Positioning System (GPS).

Park, Kim & Lee (2013) have developed a GIS-based method to analyze trafficability of terrain for autonomous robot navigation. In this method, GIS is employed to analyze the possibility of having a piece of terrain under traffic of unmanned ground vehicles by generating grid maps. The GIS database analyzes the spatial data of a given environment and assigns a cost to each grid. Once all the grids are assigned with a cost value, a path can be generated to navigate the mobile robot.

Rackliffe, Yanco & Casper (2011) have developed a GIS-based approach with which UAV can be landed and UGV can be navigated. In this method, they integrate GIS with sensor data of the vehicle in urban settings.

The literature review conducted on robot navigation using GIS technology indicated that algorithms and the implementation play a key role in this regard.

3. The majority of the research on robot navigation with Geo-referenced locations focuses on algorithms and computational issues. However, there are some uncertainties associated with a given space that should be considered. Construction sites, for instance, are dynamic and are associated with many uncertainties. Dealing with uncertainties, is one issue that cannot be addressed by predetermined algorithms so that other approaches should be included.
4. Zaki & Dunnigan (2017) argue that algorithms applicable to path planning are different from the ones for motion planning. They define "path planning algorithms" as "seeking the most appropriate path to a given point", and "motion planning algorithms" as "robot's actual movement." Thus, they classify motion-planning algorithms into eight categories namely, 1) "Bug Algorithms," "Roadmap," 2) "Cell Decomposition," 3) "Potential Fields," 4) "Sampling-based motion planning," 5) "Kalman filtering," 6) "Heuristic Approaches" and, 7) "Mathematical programming." The common characteristics of all the above-mentioned algorithms is that they are not mutually exclusive, thus combinable.

   Moreover, path planning algorithms are divided into five categories namely, 1) "sampling-based algorithms," 2) "node-based optimal-based algorithms," 3) "mathematical model based algorithms," 4) "bio-inspired algorithms," and 5) "multi-fusion based algorithms" (Zaki & Dunnigan, 2017).

2.4.2.3 BIM and GIS (in respect to construction automation)

The main objective of this section is to identify the requirements of BIM and GIS integration for the purpose of construction robot navigation and positioning. To attain this goal, first, the tools and methods for integration of BIM and GIS are presented. Then, a comparison of the different methods and tools will determine whether one of them is appropriate for the future purposes of this research, or a novel approach should be developed to assist construction robot navigation and positioning.

Hwang, Hong & Choi (2013) have created a roadmap to develop a prototype of interoperable framework to facilitate BIM and GIS integration. In this direction, they employ IFC format of a BIM model to integrate it into GIS environment.

Liu, Li, Zlatanova & Liu (2018) explore BIM as a technology facilitating collaborations between construction stakeholders and management of building components data. They bring IFC into consideration as interoperable data format of BIM containing spatial information of building components. They also perceive GIS as a platform to provide further spatial analysis on the information provided by IFC. The authors focus on identifying the requirements for “a generic 3D indoor framework” and identify four of them to be relevant for indoor spatial analysis, namely (Liu *et al.*, 2018): “Generation of a vector map,” “Management of data,” “Analysis of environment,” and “Management of safety.”

Irizarry & Karan (2012) employ GIS to conduct spatial data analysis to find the best location and number of cranes on construction sites. To do this, they need semantic information with regard to the building elements, and they find BIM as a response to this need. To overcome the challenges of the integration of BIM and GIS, they combine an “optimal algorithm”, GIS, and BIM to create a model, optimizing the location and the number of tower cranes (Irizarry & Karan, 2012).

Zhu, Wang, Wang, Wu & Kim (2019b) have developed an open-source approach (OSA) to integrate BIM and GIS using IFC and shapefile format respectively. They utilize IFC-Tree as the spatial structure of IFC to export data into shapefile format through developing and implementing Automatic Multipatch Generation (AMG) algorithm. Their work needs to be improved in terms of efficiency so their next contribution is built upon.

Zhu, Wang, Chen, Wu & Kim (2019a) introduce an enhanced open-source approach (E-OSA) to integrate geometric data derived from IFC into shapefile in order to contribute to BIM and GIS integration. The authors improve the efficiency of their previous contribution which is open-source approach (OSA). In this enhanced approach, Brep, swept solid, mapped representation and clipping are successfully transformed into Brep within a shapefile format using an algorithm. It is also discussed that CityGML and Shapefile as the most prominent data exchange formats with their pros and cons (Zhu *et al.*, 2019a).

Wang *et al.* (2019) consider BIM as the digital representation of a shared database of construction projects to enable construction practitioners collaborate throughout the project lifecycle. The authors take GIS into account as geographical, cartographical, and remote sensing technology, which comprises spatial data and classify key applications of BIM and GIS integration into 1) integration of data, 2) projects' lifecycle applications 3) management of energy, and 4) management of urban environments. Additionally, data integration is identified as the fundamental and the most challenging step in this regard.

Hong, Hwang & Kang (2012) have studied the correlation of IFC and CityGML as the most prominent data format with regard to BIM and GIS respectively. They identify features of the two, prior to mapping the IFC to CityGML at various level of details (LoD), from LoD0 to LoD4. The authors consider their contribution as the foundation of BIM and GIS of indoor and outdoor environment (Hong *et al.*, 2012).

Adouane, Stouffs, Janssen & Domer (2020) have developed a model-based approach to facilitate IFC data conversion into CityGML. They encounter semantic and geometry as the main challenges in this regards. In this direction, they have also developed a series of additive algorithms to overcome the issues occurred in the project. Their work indicates that the semantical and geometrical issues occurring when converting IFC into CityGML, could be handled by a set of algorithms (Adouane *et al.*, 2020).

Zhu, Wright, Wang & Wang (2018) assess integration of BIM and GIS at data level. They conduct literature review on scholarly papers to investigate data models in terms of relevance and features, examine other potential data models for BIM and GIS integration, and provide roadmap for future works. BIM and GIS are considered as well-developed technologies where BIM is employed throughout a building lifecycle, while GIS mostly correlates with location issues and spatial data analysis in various domains. They have identified the challenges and the methods to integrate BIM and GIS.

Isikdag, Zlatanova & Underwood (2013) have developed BO-IDM based on building information for indoor navigation purposes. They determine the requirements for BIM and GIS integration and they attain this goal through simplifying BIM models (Isikdag *et al.*, 2013). Even though the proposed framework is practical, it shows important limitations such as removing a void for the sake of simplicity, thereby making it insufficient for the purposes of automation in construction.

Based on the scientific works mentioned in this section, the following conclusions can be drawn:

5. BIM and GIS integration occurs at different levels. Researchers defined several levels of integration with regard to BIM and GIS integration so a common definition with consensus on it is not available. BIM and GIS could integrate mainly on two levels, which interrelate fundamental level and application level (Irizarry, Karan & Jalaei, 2013). Fundamental level refers to data exchange and interoperability of BIM and GIS, while application level refers to developing new software tools to benefit from BIM and GIS advantages. Another classification comprises 5 categories namely, "schema-based," "service-based," "ontology-based," "processes-based," and "system-based" (Kang & Hong, 2015). A third classification comprises of three levels namely, data, process, and application (Amirebrahimi, Rajabifard, Mendis & Ngo, 2016a). Data level incorporates extending current data schemas or modifying data formats to fit other software. Process level refers to cooperation of data schemas, while at the application level, new software is developed to incorporate BIM and GIS privileges. Although the aforementioned classifications define different levels of integration, much of the research attempts are being carried out on data level. In this

direction, Zhu *et al.* (2018) have extended the data level into two sub-levels, which are geometry level and semantic level. The former focuses on geometry transformation of data, whereas the latter concentrates on full attribute data translation.

6. Many researchers have identified various data exchange formats for both BIM and GIS. The former comprises less formats in terms of quantity compared to the latter. There is a consensus among the researchers, however, that IFC is the promising data schema representing BIM (Adouane *et al.*, 2020; Liu *et al.*, 2018; Irizarry & Karan, 2012; Zhu *et al.*, 2019b,a). BuildingSMART (formerly the International Alliance for Interoperability) developed IFC as an EXPRESS-based tool (Mignard & Nicolle, 2014). IFC uses three types of geometrical definitions to represent 3D models: boundary-representation (b-rep), constructive solid geometry (CSG), and sweep volumes (Donkers, Ledoux, Zhao & Stoter, 2016). B-rep uses the object's boundary surfaces to represent a 3D complex object (Wu & Hsieh, 2007), CSG applies a set of Boolean operators namely, union, intersection, and difference on primitive shapes such as spheres, cones, pyramids, or cylinders (Wyvill, Guy & Galin, 1999), and sweep volumes uses a path to extrude 2D objects in order to create solid shapes (Zhu *et al.*, 2018). American Institute of Architects (AIA) defined IFC Levels of Development (LOD) from lowest to highest amount of information they contain. The five levels are LOD100, LOD200, LOD300, LOD400, and LOD500. The BIMForum have developed LOD350 in addition to the aforementioned levels as there was a need for a Level of development between LOD300 and LOD400 in order to detect/avoid clashes, layout, etc. (Zhu *et al.*, 2018). BuildingSMART have also developed other IFC schemas such as XML-based IFC standard and ifcXML in addition to EXPRESS-based IFC standard (Deng, Cheng & Anumba, 2016b) which can be used for BIM-GIS integration.
7. Contrary to the case with BIM, researchers have not reached a consensus regarding GIS data exchange format. City Geographic Markup Language (CityGML) and Shapefile are two primary formats in terms of data exchange schema in GIS. The Environmental System Research Institute (ESRI) has developed Shapefile as an open data schema containing attributes and spatial features (Environmental Systems Research Institute, Inc., 1997). On the other hand, CityGML is an XML-based standard. The Open Geospatial Consortium

(OGC) has approved it as the standard open data schema representing 3D models of cities and landscapes (Deng *et al.*, 2016a). Although Shapefile data schema is the native format of GIS and can be exported to non-GIS software tools such as Collaborative Design Activity (COLLADA), SketchUp, and 3D Studio Max (Environmental Systems Research Institute, Inc., 2008), CityGML is more suitable for BIM and GIS integration. This is because Shapefile is a non-semantic data model while CityGML is. Moreover, CityGML can provide bidirectional data transformation for BIM and GIS integration while Shapefile only allows transforming data from BIM to GIS (Zhu *et al.*, 2019a).

8. CityGML is defined based on the Levels of Detail (LoD) provided in a 3D model from LoD0 to LoD4 (Zhu *et al.*, 2018). CityGML also uses boundary representation (b-rep) to visualize 3D models and it allows users to extend it through application domain extension (ADE).

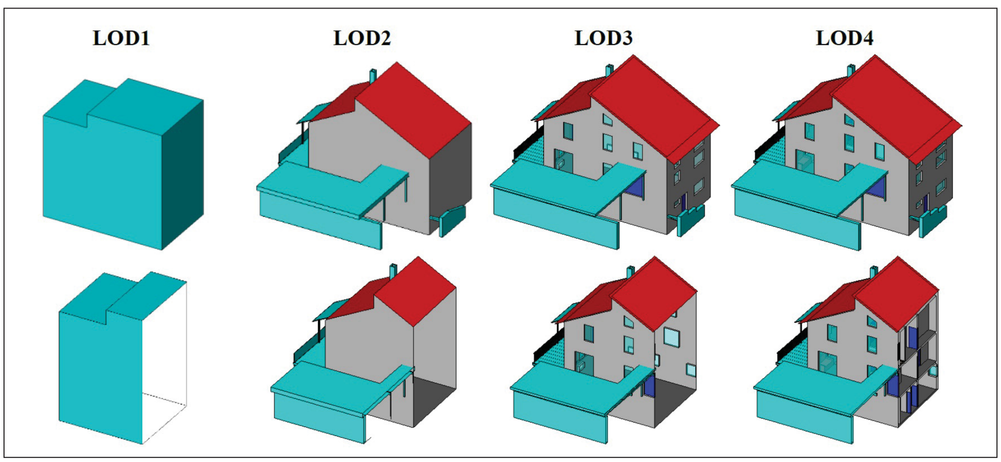

Figure 2.13 Levels of details on a residential house
Taken from Gröger *et al.* (2012, p. 67)

Figure 2.13 illustrates various levels of detail on a residential house. LoD0 is just the footprints of the house in 2 dimensional environments, while LoD1 represents in solid shapes with a flat roof. LoD2 becomes more advanced in terms of showing details compared to LoD1. LoD3 and LoD4, both, demonstrate the openings of the building but LoD4 incorporates interior spaces and components such as interior walls, and doors.

2.5 Discussion

The current study is a systematic literature review (SLR) combining scientometric analysis and qualitative analysis. The former is used to investigate a large dataset of articles on BIM and GIS integration, which is difficult to conduct with conventional methods, and the latter is utilized to deeply explore the field with relation to robot navigation for construction sites. The literature review methodology adopts a systematic approach in order to be able to investigate the field comprehensively. It extends earlier review works and examines the domain of BIM-GIS integration from a new – automation in construction - perspective in order to address the existing limitations and to reduce complexity.

This SLR testifies that the current solutions relying on BIM with developed localization methods show many limitations such as lack of vertical navigation (i.e. from one floor to another floor), inaccuracy, not considering the dynamic nature of construction sites, etc. Therefore, more research needs to be performed in this regard or new approaches needs to be developed. The current study, which is part of a larger research project aimed to provide digital framework for robot navigation on construction sites, investigates the BIM-GIS domain to find its potential for improving robot navigation.

GIS, on the other hand, enables researchers to develop methods for robot navigation both for indoor and outdoor applications through applying various algorithms. The reported contributions are associated with high complexity and are unsatisfactory, as they do not consider construction sites uncertainties such as constant changes. Additional complexity comes from the analysis of data obtained from robot sensors. In this direction, complexity could be reduced exponentially through defining navigable surfaces in which building components are excluded.

BIM and GIS technologies are becoming omnipresent in construction projects and provide great benefits to the project stakeholders. However, due to their intrinsic differences, specifically in terms of focus, the integration of BIM and GIS is somewhat challenging and still under investigation. A number of research attempts are carried out to tackle navigation issues with either BIM or GIS for indoor environments, but they are still incompatible with construction sites' characteristics. BIM and GIS integration shows great potentials to be employed for robot navigation purposes as several research studies confirm it. GIS can be utilized to identify optimal path so that construction robots would be able to navigate and localize properly. BIM can also be used in this regard. BIM can provide a priori obstacle detection to robot through geometry and semantics of 3D models. Integration of BIM and GIS has the potential to considerably reduce the complexity of conventional navigation methods beside other opportunities it provides. Moreover, other methods should be incorporated to detect objects on construction sites, and react to its dynamic context.

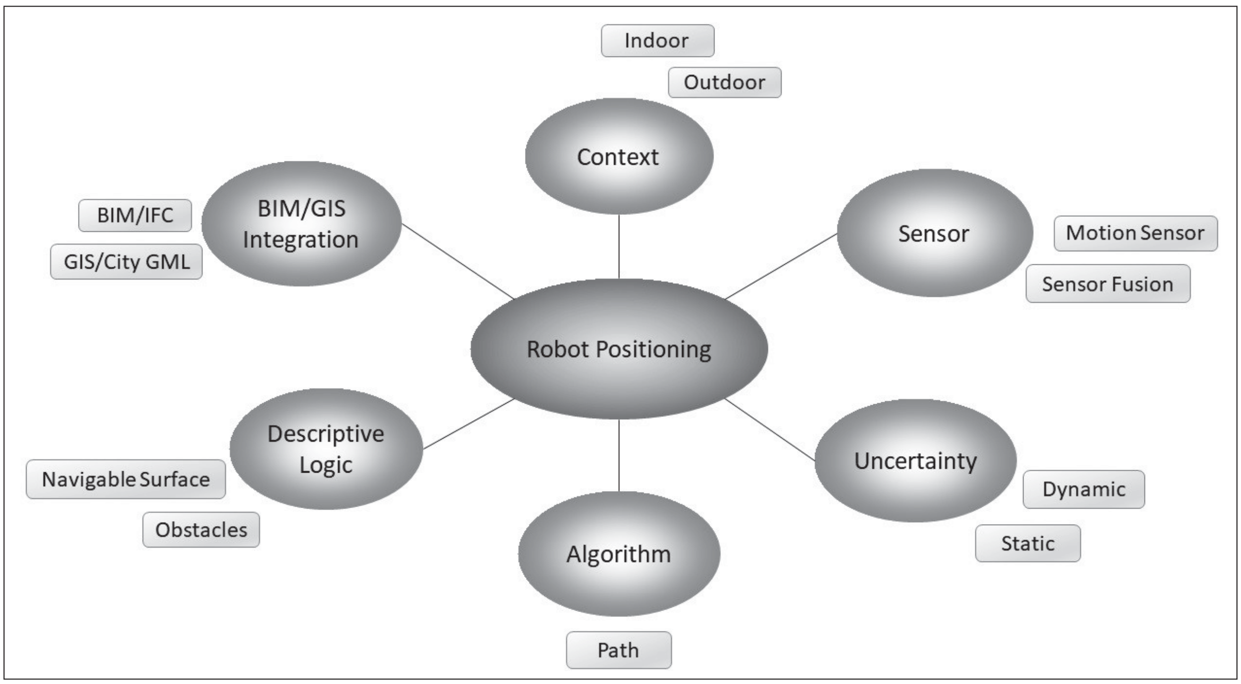

Figure 2.14 Requirements of BIM-GIS integration for robot navigation

Figure 2.14 illustrates the identified requirements for a digital framework for robots' positioning on construction sites. Having identified the requirements, our future research will seek to propose a novel approach to construction robots' navigation, integrated with BIM and GIS to cover the limitations of previous attempts and to decrease the complexity substantially.

2.6 Conclusion and future work

Studies have indicated that construction industry is suffering from low productivity, compared to other industries; also, scarceness of qualified workforce is foreseen in near future. Construction automation is introduced as one possible solution to these challenges. It is comprised of many aspects and practices but one of its functionalities is Digital Fabrication (Dfab). To enable construction robots to accomplish the assigned tasks perfectly, they need to be precisely positioned on the intended place. BIM and GIS have indicated great potential in this regard. Since BIM and GIS are already being used for other purposes in construction projects, relying on them for robots' navigation would reduce the complexity and the amount of time spent to implement other methods. However, BIM-GIS integration is challenging due to their different intrinsic focus. Hence, the current study adopts a Systematic Literature Review (SLR) to thoroughly review the research in the domain. In addition, scientometric analysis is used to investigate 236 articles. To deeper understand the challenges of the BIM-GIS integration in respect to robot navigation, qualitative analysis is carried out on the topics derived from keywords' co-occurrence method. Based on the qualitative analysis, challenges, gaps, and limitations of current solutions are investigated and the requirements to address limitations are determined. More importantly, this research aims to propose a novel approach using BIM and GIS integration for construction robots' navigation. Future work can also incorporate non-scholar sources such as texts and articles on websites in order to be investigated.

CHAPTER 3

AN ONTOLOGY-BASED APPROACH TO DATA EXCHANGES FOR ROBOT NAVIGATION ON CONSTRUCTION SITES

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Article submitted to *Journal of Information Technology in Construction*, February 2021.

3.1 Summary

As-built modeling and reconstruction require data of high quality from spatial structure environment and the surrounding site in construction projects, in terms of both frequency and accuracy. As-planned information can be acquired for indoor structure through Building Information Modeling (BIM) and for outdoor environment from Geographic Information System (GIS). These data should be collected in different phases of a facility life cycle, thereby making this essential task repetitive and monotonous. For this reason, the use of autonomous Unmanned Ground Vehicles (UGV) has attracted construction stakeholders' attention in recent years. However, the tools of both industries are yet to be integrated in a coherent deployment infrastructure. Specifically, there is no standard format for data exchanges between the construction and robotic domains. Hence, the semantics of BIM-GIS cannot be automatically integrated by any robotic platform. To enable semantic data transfer across domains, semantic web technology has been widely used in multidisciplinary areas for interoperability. We exploit it to pave the way to a smarter, quicker and more precise robot navigation on construction sites. This paper develops a semantic web ontology integrating robot navigation and data collection to convey the meanings from BIM-GIS to the robot. The proposed Building Information Robotic System (BIRS) provides construction data that are semantically transferred to the robotic platform

and can be used by the robot navigation software stack on construction sites. To reach this objective, we first need to bridge the knowledge representation between construction and robotic domains. Then, we develop a semantic database to integrate with Robot Operating System (ROS) which can communicate with the robot and the navigation system in order to provide the robot with semantic building data at each step of data collection. Finally, the proposed system is validated through a case study.

Keywords: BIM, GIS, ROS, mobile robot, ontology, navigation, data exchange

3.2 Introduction

Progress monitoring of construction projects needs accurate and comprehensive data collection to increase productivity and support risk management. Manual data collection is inefficient due to its high cost, inaccuracy, error-prone nature (Rebolj, Pučko, Babič, Bizjak & Mongus, 2017). Among different propositions such as implementation of new technologies by leveraging cross-functional teams (Barbosa *et al.*, 2017) and Scrum strategy deployment in various phases of construction (Streule *et al.*, 2016), the use of autonomous robots has shown great potential to achieve efficiency and high precision of data collection (Ardiny, Witwicki & Mondada, 2015). The fundamental requirement of automated data collection is for the robot to be able to (1) navigate autonomously in a dynamic environment and (2) acquire relevant and accurate data. With the growth of mobile robots' capabilities in recent years, the interest in having high-level semantic information integrated within the robot is increasing: it is expected to ultimately make the robots easier to deploy (Crespo, Castillo, Mozos & Barber, 2020). Robots with semantic representation and recognition (association of location-semantic) of their environment are more intuitive to operate for non-experts, because they share conceptual understanding (Kostavelis & Gasteratos, 2017). Among the various challenges to implement semantic navigation, one is the association of high-level information with the geometry of the environment, such as discrete maps often referred to as occupancy grids. To achieve this, one needs to develop a knowledge representation (Crespo *et al.*, 2020), for which domain-specific ontologies are well suited (Gruber, 1995). Therefore, this study intends to facilitate data exchange between construction and robotic domains by developing an ontology which supports formal representation of the domains' knowledge. The resulting ontology then becomes a base structure for data extraction of BIM-GIS; relevant to robot navigation.

BIM is used throughout the entire life cycle of a facility in many aspects, for instance to track its state from design to maintenance (Doumbouya *et al.*, 2017), for smart city integration (Afsari, Florez, Maneke & Afkhamiaghda, 2019), 4D simulation (Hatori *et al.*, 2020), and clash detection (Savitri, Pramudya et al., 2020). In a similar way, GIS has enabled Architects, Engineers, Contractors (AEC) to acquire geo-spatial data with regards to surrounding site conditions and topographical information of a construction site (Karan & Irizarry, 2015). The integration of BIM and GIS grants new opportunity in construction projects such as finding the optimal location for tower cranes (Irizarry & Karan, 2012), assessing the occupants behaviour impact on energy consumption (Afkhamiaghda *et al.*, 2019), assessing urban energy performance (Yamamura *et al.*, 2017), helping with emergency response route (Tashakkori *et al.*, 2015), merging indoor-outdoor combined route planning (Teo & Cho, 2016) and pre-construction planning (Karan & Irizarry, 2015). Integration of BIM-GIS data provides a holistic overview of digital built environment including the facility and the environment around it at urban scale that can be used for robot navigation on construction sites for data acquisition of the existing condition. However, the construction and robotic worlds need to share a common semantic interoperability.

Semantic web technologies provide high-level data exchange among various domain knowledge representations enabling interoperability through attachment of decentralized data with semantics to different concepts (Kalfoglou, 2009). In an ontology, concepts, semantics and their relations with one another are defined through taxonomies (hierarchical structure of data) and relationships (Van Rees, 2003), thereby providing a machine-understandable structure in which concepts and knowledge are represented (El-Diraby, Lima & Feis, 2005). Ontologies can be categorized into three levels based on their components and level of detail namely: top-level (or upper), domain and application ontologies. Top-level ontologies formalize a generic ontology across all domains whereas domain ontologies provide knowledge representation which is formal, reusable and shareable across a specific domain. Application ontologies aim to create focused ontology for a given application (Karan, Irizarry & Haymaker, 2016).

The Institute of Electrical and Electronics Engineers published a standard (IEEE 1872-2015) (708, 2015) for Robotics and Automation ontologies based on the Core Ontology for Robotics and Automation (CORA). In this paper, we leverage IEEE 1872-2015 in order to bridge it with construction-based knowledge. This standard provides formal and shareable representation of the robotics and automation domain along with the definition of concepts and the relationships between concepts, attributions and constraints. The proposed ontology is a domain ontology that needs to be derived into specific implementations. Since some of the concepts discussed in the CORA are not thoroughly defined, CORAX (CORA's extension) was proposed to cover these gaps (708, 2015). The other standard we leveraged is the IEEE 1873-2015 (730, 2015). Robot Map Data Representation for Navigation (MDR) standard focuses on the interoperability between robots, humans, and machines in terms of 2D metric and topological maps rather than 3D or semantic maps. Hence, the current study intends to bridge the semantic information of BIM and GIS using some of the concepts in MDR in order to enrich map representation for human-robot data exchange.

The current study's objective is to enable semantic interoperability between BIM, GIS, and robot navigation system to translate semantic data from BIM and GIS to the Robot Operating System (ROS). Since there is no standard format to translate data between BIM-GIS and ROS, the semantics of the IFC and CityGML is not understood by the robotic platform, thereby making it essential for the robot to be able to "call" for the semantic information. Building elements' semantics can be provided to the ROS so that different information would be accessible to the robot when and where it is needed. The proposed bridging ontology is based on the extension of IEEE 1872-2015 and IEEE 1873-2015 standards. To reach this objective, we develop a Building Information Robotic System (BIRS) which conveys semantic data to ROS. The current study's contributions are:

- An ontology bridging BIM-GIS data to IEEE 1872-2015 and IEEE 1873-2015 standards.
- Cross-domain data structure enabling exchanges between construction and robotic domains.

- A practical implementation of the proposed ontology and data structure to deploy it on an autonomous mobile robot navigating a construction site.

The remainder of this paper is structured as follows: Section 3.3 describes other scientific works related to the studied domain to provide a background of what has been achieved so far as well as their contribution. Section 3.4 provides a detailed explanation of the methodology and how our ontology is developed to facilitate data exchange. Section 3.5 presents how the ontology can be used as well as the results from a case study. Finally, section 3.6 concludes the research carried out with the limitations of the proposed system as well as some future research directions.

3.3 Related Work

Even though the growth of World Wide Web has resulted in incredible increase of the information coming from heterogeneous data sources, users are able to navigate through the information easily. This implies the power of semantic web in a way that is understandable by humans and machines (Berners-Lee & Hendler, 2001). The implementation of semantic web requires formal knowledge representation of domains (ontologies) in which the concepts and the relationships between them are explicitly described. Ontology is defined in different ways in the various domains. Guarino (1995) defines ontology as *"an artefact constituted by a specific vocabulary used to describe a certain reality, along with a set of explicit assumptions related to the desired meaning of the vocabulary"* in the context of Artificial Intelligence. Studer, Benjamins & Fensel (1998) define ontology at a higher level: *"a formal, explicit specification of a shared conceptualization."* When it comes to developing an ontology, vocabulary does not suffice to convey the intended meaning. In order to make an ontology efficient and functional, other parameters are taken into account namely the concepts (terms which are mainly abstract and are aligned to the taxonomies), relationships (the semantic connection between concepts), instances (an existing entity representing features of concepts) and axioms (defined rules across the domain which is valid) (González, Piñeiro, Toledo, Arnay & Acosta, 2020). The potentials of ontologies have resulted in the increase of interest in using them and therefore, novel forms of knowledge representation are created. In this direction, the World Wide Web Consortium (W3C) developed the Resource Description Framework (RDF) to function as a *"standard model for data interchange on the Web"* (World Wide Web Consortium (W3C), 2014).

In the construction industry, the earliest studies on semantic web technologies aimed at achieving a higher level of efficiency for the federated information through adopting ontological approach to retrieve the *"related concepts"* to manage on-site problems (Elghamrawy & Boukamp, 2008). Another study uses ontology to search and extract the construction data because the AEC data are numerous and somewhat hard to retrieve (Staub-French & Nepal, 2007). Sensing data integration for construction management through semantic web was also subject to several earlier contributions. (Elghamrawy & Boukamp, 2010) developed an ontology in which Radio-frequency identification (RFID) technology is used to archive and retrieve construction document information. Liu, Li & Jiang (2016) use ontology for cost estimation of construction projects in China. Barbau, Krima, Rachuri, Narayanan, Fiorentini, Foufou & Sriram (2012) developed a plugin for a software tool supporting ontology development (i.e. Protégé) to translate the STEP's EXPRESS schema into Web Ontology Language (OWL). Farias, Roxin & Nicolle (2015) propose a framework to create an OWL ontology for COBie, a standard in BIM for Facility Management. González *et al.* (2020) describe the development of an ontology to support indoor navigation which is based on IfcOWL ontology translating IFC schema into OWL. Venugopal, Eastman & Teizer (2015) develop a model for data exchanges using IFC schema based on ontologies. Ontological approaches are also suggested for information exchanges in precast concrete (Venugopal, Eastman & Teizer, 2012). The literature shows that ontologies are nowadays common for information exchanges across the AEC industry but they do not fully take advantage of established ontologies in other domains such as robotics. Therefore, we propose a bridging ontology between construction and robotic domains to cover this gap.

Many other fields have leveraged ontologies to extend interoperability across other domains. In the AEC industry, the nature of the information is decentralized and fragmented (Atazadeh, Kalantari, Rajabifard, Ho & Ngo, 2017) which results in obstruction for interoperability purpose. The data from different sources come with different formats and they follow different ontologies. Each of those ontologies are designed for different needs, therefore, it may obstruct interoperability in the AEC industry (Aziz, Anumba, Ruikar, Carrillo & Bouchlaghem, 2006). Hence, there has been a considerable number of attempts to provide open source data schema for BIM interoperability such as BIMXML and COINS (Zhu *et al.*, 2018). However, Industry Foundation Classes (IFC) is the primary open-source, EXPRESS-based data schema being used across the AEC domain (Mignard & Nicolle, 2014). IFC schema is comprised of four layers namely: resource layer, core layer, interoperability layer and domain/application layer (Terkaj & Viganò, 2017). IFC is a hierarchical data schema in which classes inherit the properties of upper layers (González *et al.*, 2020). Furthermore, many papers address the challenges of BIM and GIS integration in which some studies adopt ontological approach. More information in this regard and the requirements for utilizing BIM-GIS integration in robot navigation can be found in the review by (Karimi & Iordanova, 2021).

There also is a number of ontology-based deployment in robotics outside of the construction domain. One of the first studies which uses ontology is KnowRob (Knowledge processing for Robots) (Tenorth & Beetz, 2009). KnowRob ontology provides an open-source knowledge system for service robots managing uncertainties such as sensors' noise. In KnowRob ontology, the authors argue that controlling an autonomous robot requires several factors such as representing more fine-grained action. In another study (Beetz, Beßler, Haidu, Pomarlan, Bozcuoğlu & Bartels, 2018), the authors extend The KnowRob ontology to retrieve experimental knowledge (*"narrative enabled episodic memory"*). OpenEASE is a service, based on the web knowledge using KnowRob to retrieve, store, supervise, and visualize the robot knowledge (Beetz, Tenorth & Winkler, 2015). KnowRob also uses RDF to represent the knowledge. RObot control for Skilled ExecuTion of Tasks in natural interaction with humans; based on Autonomy, cumulative knowledge and learning (ROSETTA) uses a set of ontologies to constitute a model in order for the manufacturing robots to be adopted (Olivares-Alarcos, Beßler, Khamis, Goncalves, Habib, Bermejo-Alonso, Barreto, Diab, Rosell, Quintas et al., 2019). ROSETTA ontology is based on CORA ontology, itself based on SUMO ontology. Although CORA is using SUO-KIF language, ROSETTA is written in OWL. Persson, Gallois, Björkelund, Hafdell, Haage, Malec, Nilsson & Nugues (2010) develop a *"knowledge integration Framework"* which establishes relationships between different segments of ROSETTA. OROSU (Ontology for Robotic Orthopedic Surgery) is yet another ontology developed based on IEEE 1872-2015 Standard Ontology for Robotics and Automation, uses OWL to retrieve information of the knowledge-based framework for surgical robotics (Gonçalves & Torres, 2014). (Diab, Akbari, Ud Din & Rosell, 2019) propose Perception and Manipulation Knowledge (PMK) ontology for representing and reasoning knowledge in task and motion planning. In PMK ontology, the authors implement from OWL the ontology using again CORA and SUMO as the base ontologies (Olivares-Alarcos *et al.*, 2019).

In the sub-domain of semantic knowledge for robot navigation, Kollar & Roy (2009) adopt an ontological approach to enable human-robot interaction, specific to the task of search and find. Galindo, Saffiotti, Coradeschi, Buschka, Fernandez-Madrigal & González (2005) propose a multi-hierarchical approach for semantic navigation comprising of spatial and conceptual hierarchies. The former describes conventional metric approach of the building spaces and the latter incorporates semantic information of the environment. However, the BIM semantics still remains neglected even if it can add more semantic information to robot navigation. With great contribution to semantic navigation, none of them studied the necessity of incorporating BIM semantics to robot navigation during and/or after construction phase. There are also already several works addressing BIM usage for robot navigation. Delbrügger *et al.* (2017) developed a framework for digital twin factories supporting human and robot indoor navigation. Ibrahim *et al.* (2017) studied the use aerial robots to capture data from construction sites in an interactive way. Another study examined the use of BIM for localization of Unmanned Aerial Vehicle (UAV) in indoor environment taking advantage of April tags (Nahangi *et al.*, 2018). Siemiatkowska *et al.* (2013) studied the use of BIM-based map representation in which the robot could localize semantically using hierarchical path planning. Hamieh *et al.* (2017) developed a four step BIM-based path planning strategy which uses hierarchical refinement of the number of paths. Palacz *et al.* (2019) proposed graph-based approach for indoor navigation using BIM/IFC. Despite their great contributions, none of the aforementioned works studied the automatic translation of semantic data from BIM to the ROS. There also have been several research attempts in which the authors used GIS for robot navigation (Mirats-Tur, Zinggerling & Corominas-Murtra, 2009; Yang *et al.*, 2015; Yan, Zhao & Shen, 2013). However, the integration with BIM and the additional information that can be used for robot navigation is yet to be thoroughly studied.

3.4 Research Methodology

The current study proposes a novel approach which BIM and GIS data are used in robot navigation during/after construction phase. The research methodology is comprised of two steps: (1) developing Building Information Robotic System (BIRS) Ontology in order to bridge IFC and CityGML schemas to IEEE 1872-2015 and IEEE 1873-2015, and (2) enabling cross-domain interoperability through BIRS Data Exchange. Figure 3.1 illustrates the pipeline establishing the practical implementation of the robotic system using BIM and GIS for navigation.

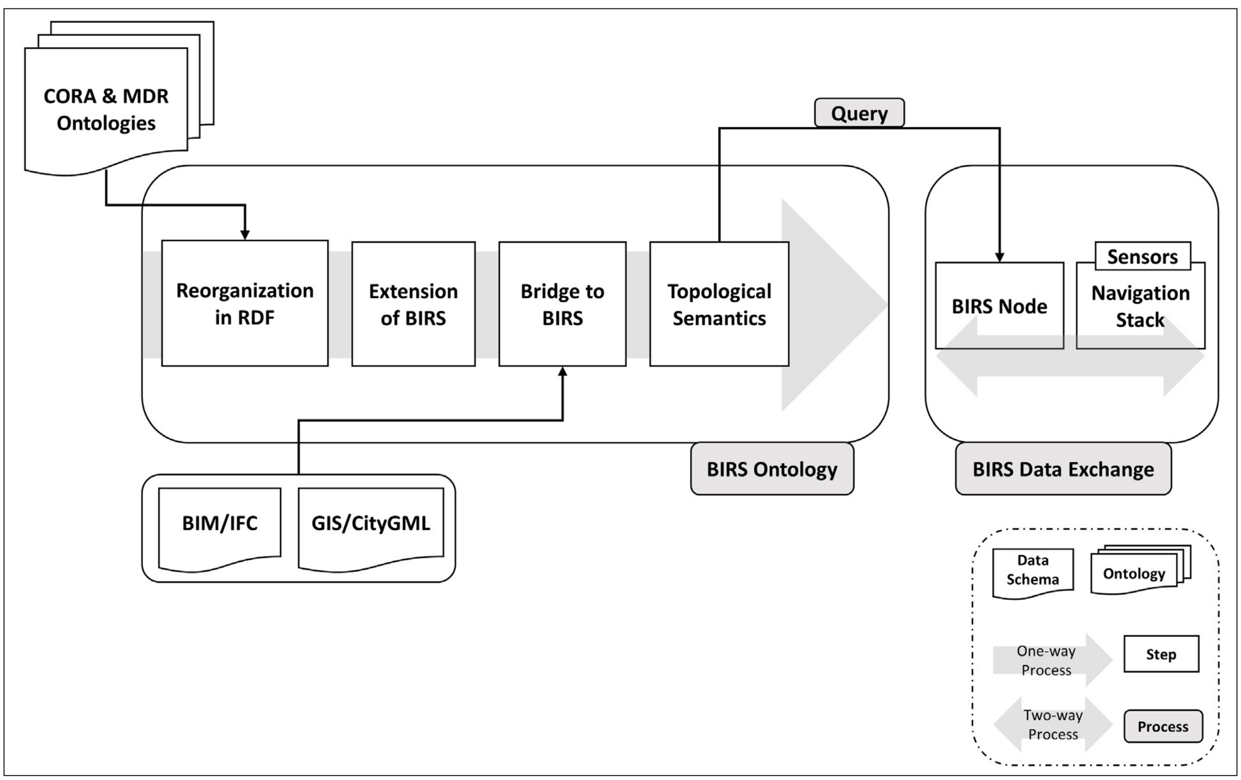


Figure 3.1 Proposed pipeline for implementing Building Information Robotic System (BIRS) supporting development of BIRS Ontology and BIRS Data Exchange

As illustrated in Figure 3.1, The first step (BIRS Ontology) creates an ontology bridging IFC and CityGML data to CORA and MDR. The second step (BIRS Data Exchange) reasons the BIRS ontology to create a BIRS node in ROS in order to translate the semantic data from the ontology to the robotic system. Both steps in the pipeline are explained in detail in the following sections.

3.4.1 Building Information Robotic System (BIRS) Ontology

The purpose of this section is to develop an ontology supporting BIM and GIS bridging to CORA and MDR. To achieve this, the existing IEEE standards need to be reorganized (the ontology classes and axioms remain intact) to facilitate the knowledge translation from engineering to application ontologies. Then, we express CORA and MDR in the RDF to be compatible with the development of median level classes. The combination of RDF and XML would enable users to interchange data among various applications (Karan & Irizarry, 2015). Since the resulting entities should comply with IEEE 1872-2015 and IEEE 1873-2015 standards, the intermediate level classes are developed to be integrated with the correspondent concepts from IFC and CityGML.

In order to extend CORA and MDR in our work, a short recall of the underlying concepts is required. CORA extends the Suggested Upper Merged Ontology (SUMO) which is a top-level ontology (Prestes, Carbonera, Fiorini, Jorge, Abel, Madhavan, Locoro, Goncalves, Barreto, Habib et al., 2013). SUMO supports definition of high-level knowledge concepts in the world. The highest SUMO class is *Entity* which has two further sub-classes; *Physical* and *Abstract*. The former describes the entities in 3D space and the latter represents the concepts which do not have spatial shape. In other words, *Abstract* contains anything which does not fall into *Physical* (Niles & Pease, 2001). *Physical* is a disjoint partition of *Object* and *Process*. *Object* describes existent objects in 3D space with no temporal effect on the space while *Process* follows a *"perdurantist"* approach that adds temporal effects and considers 4D orientation (Fiorini, Carbonera, Gonçalves, Jorge, Rey, Haidegger, Abel, Redfield, Balakirsky, Ragavan et al., 2015). *Abstract*, on the other hand, is defined not to be a subclass of *Object* and is categorized into the following sub-classes: *Quantity*, *Attribute*, *SetOrClass*, *Relation*, and *Proposition*. Figure 3.2 illustrates the SUMO taxonomies on which the CORA is developed.

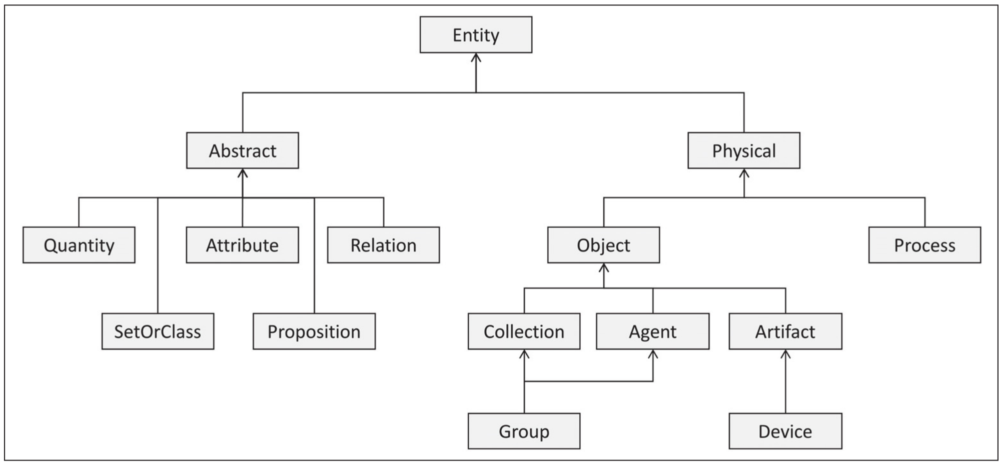


Figure 3.2 Basic SUMO taxonomies
Adapted from 708 (2015, p. 7)

IEEE 1872-2015 argues that *"Concepts and relations associated with design, interaction, and environment"* are too general to be incorporated in CORA and are not effectively covered by SUMO (708, 2015). To cover this gap, Fiorini *et al.* (2015) define a new class *Physical Environment* as a three dimensional environment which contains region and other artifacts existing in 3-D space dependent on the landmark. CORAX incorporates *PhysicalEnvironment* as the subclass of *Object* under *Physical* which is located in 3 dimensions and consist of one *Region* in minimum (708, 2015). IEEE 1872-2015 also defines *Design* as a subclass of *proposition* which has idealization relationship between design and artifact. In SUMO ontology, *content bearing physicals* represent propositions such as a descriptive sentence, a graph, etc. No restriction is applied for *ContentBearingPhysicals* to represent an idea. Therefore, we integrate the MDR as the subclass of *CORA:ContentBearingObject* since MDR aims to facilitate data interoperability between robots. IEEE 1873-2015 standard (730, 2015) subdivides maps into *Metric* and *Topological* in which *Metric* maps are the disjoint entity of the *Continuous Metric Maps* and *Discrete Metric Maps* representing physical layout of the environment and the objects within the robot physical environment. *Continuous* metric maps are comprised of the geometric elements while *Discrete* metric maps utilize bitmap illustration of the environment under which

OccupancyGridMaps are categorized. *OccupancyGridMaps* are the most widely used maps in Simultaneous Localization and Mapping (SLAM) and generally in robot navigation; are considered as *Discrete Metric Maps*. *Topological* maps are generally represented by sets of nodes and edges (Choi, Choi, Nam & Chung, 2011) which facilitates path planning task with running an algorithm on the created graph (730, 2015). Figure 3.3 illustrates the overall integral graph in which all the ontologies come together and shape an integral ontology taxonomy along with the proposed BIRS entities.

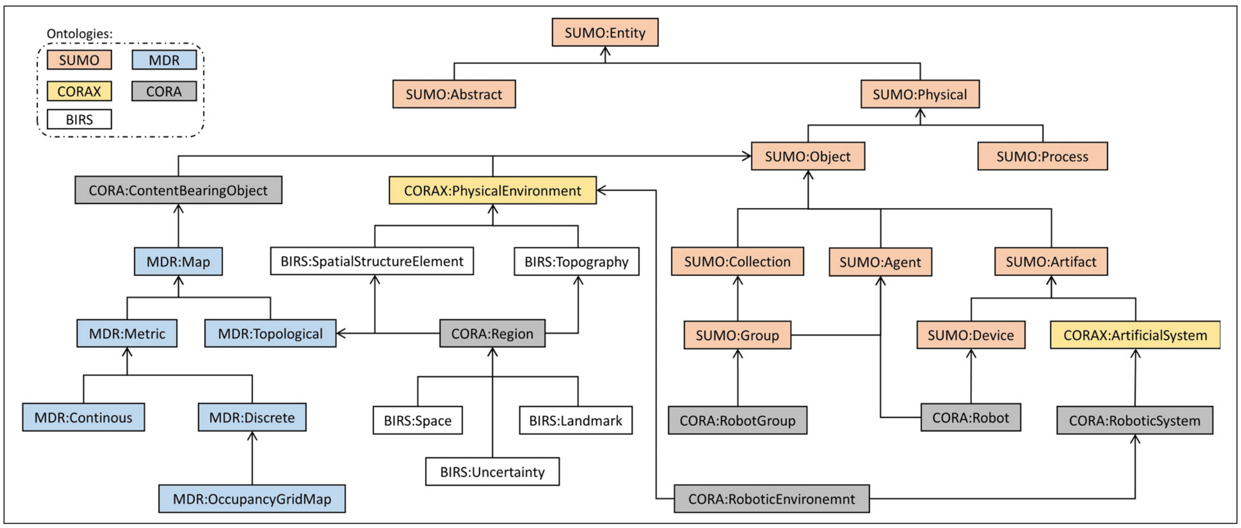


Figure 3.3 Integration of CORA and MDR ontologies with Building Information Robotic System (BIRS) Ontology indicating sub-class relationships (:SubClassOf)
Adapted from 708 (2015, p. 16) and 730 (2015, p. 3)

We extend an intermediate level between *CORAX:PhysicalEnvironment* and *CORA:Region* to differentiate between indoor and outdoor environments. This is required by the digital representation of the built environment that correlates with building components and their semantic attributes with the topographic and the existing condition information of the construction site (Karan & Irizarry, 2015). Therefore, *SpatialStructureElement* and *Topography* can be the median level which define *Region* more effectively. We follow the extension of CORA and MDR by including *Landmark*, *Space* and *Uncertainty* as the sub-classes of *Region* bridging construction physical environment comprised of BIM and GIS. TABLE 3.1 provides the definition of the new concepts provided in the BIRS.

Table 3.1 BIRS concepts definition

Concept	Definition	Reference
Landmark	*"A feature that is used for localization of a mobile robot. It is a feature whose pose in a coordinate system can possibly be measured (localized) by the robot's sensors with respect to a given map."*	(730, 2015)
Space	*"represents an area or volume bounded actually or theoretically. Spaces are areas or volumes that provide for certain functions within a building."*	buildingSMART
Uncertainty	Dynamics of the construction site which cannot be considered as the landmarks and have temporal effects on the construction job-site.	-

Landmarks are the physical building elements which the robot can use for localization. *IfcBuildingElement* is the entity which defines the properties of the building elements. Semantics of classes and properties are defined through axioms in the proposed BIRS ontology. The *SubClassOf* axiom is a demonstration of the defined relationship between the higher and the lower entity (Karan *et al.*, 2016). As an instance, since the *IfcWall* is a subclass of *IfcBuildingElement*, *IfcWall* inherits all the properties of *IfcBuildingElement*. It is also applicable to all IFC classes due to the fact that IFC is a hierarchical data schema. In BIRS, the building elements extracted as the sub-class of *IfcBuildingElement* are *IfcWall*, *IfcCurtainWall*, *IfcColumn*, *IfcDoor*, *IfcRailing*, and *IfcStair*. Figure 3.4 illustrates the relationships of BuildingElement with higher entity (landmark) and the properties associated with it in IFC schema. There are several quite essential properties in *IfcBuildingElement* for the translation of a building layout into a ROS compatible format. The shape and the location of the *landmark* can be derived through *ObjectPlacement* and *Material* properties. *IfcProduct* is the super-type of the *IfcBuildingElement* through which the local placement is defined. The coordinates of the geometric representation of BuildingElement is defined through LocalPlacement. Using the material properties of the *landmark* would be a contribution to robot navigation as well, but accessible through another pipeline than layout. Using the aforementioned IFC classes in the BIRS ontology, a BIM-based occupancy grid map is within reach. This map can be extracted in two ways. One is to use tools such as ifcConverter in order to export the map from IFC files to .svg, then to a ROS-compatible format such as .png, and the second method would use the BIM design authoring tools such as Autodesk Revit and Graphisoft ArchiCAD in order to export the map in .png format.

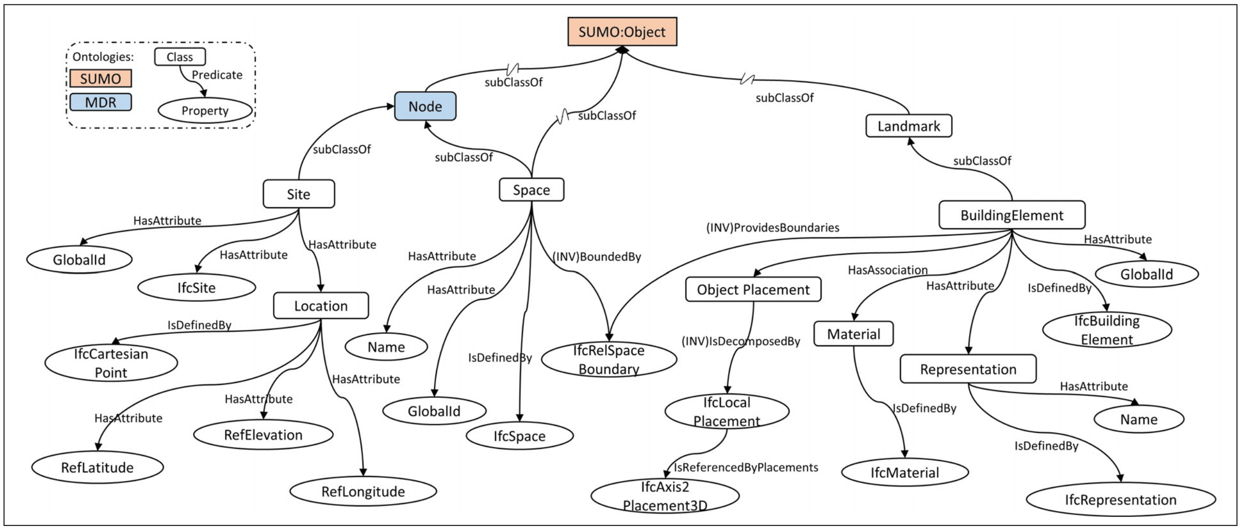


Figure 3.4 Partial indication of IFC classes relationships in BIRS ontology

From the extracted data, a topological map with each *space* considered as a node is expected as the output. Figure 3.3 illustrates the relationships between *space*, topological map and *CORA:Region*. In this respect, a space is a node that is bounded using the *IfcRelSpaceBoundary* relationship which itself provides boundaries for building elements. As illustrated in Figure 3.4, *IfcRelSpaceBoundary* provides relationships with *landmarks* and nodes used to generate the topological map containing the semantic information of the *spaces* and the *landmarks* for the purpose of robot navigation (implemented in Python). The use of IFC semantics for robot navigation is twofold. It contains the information of the *landmark* material in case the robot gets into a *space* for which the laser provides a point cloud unable to segment. In addition, the information of the nodes which are representing space names would enable semantic navigation. The application of the ontology for outdoor environments with knowledge of obstacles helps the robot to avoid collision. For the robot to gather information about surrounding of the building, existing and natural artifacts are integrated namely: existing buildings, water surfaces and vegetation are considered as obstacles. Figure 3.5 illustrates the relationships between CityGML and the BIRS ontology. The most important properties of outdoor artifacts are their location.

The geo-location properties of the landmarks are translated to BIM. Then, the integrated data are translated to the robot local position system to support obstacle avoidance. The procedure on how the GIS information is transferred to BIM is beyond the scope of the current study. More information in this regard can be found in (Karan, Sivakumar, Irizarry & Guhathakurta, 2014).

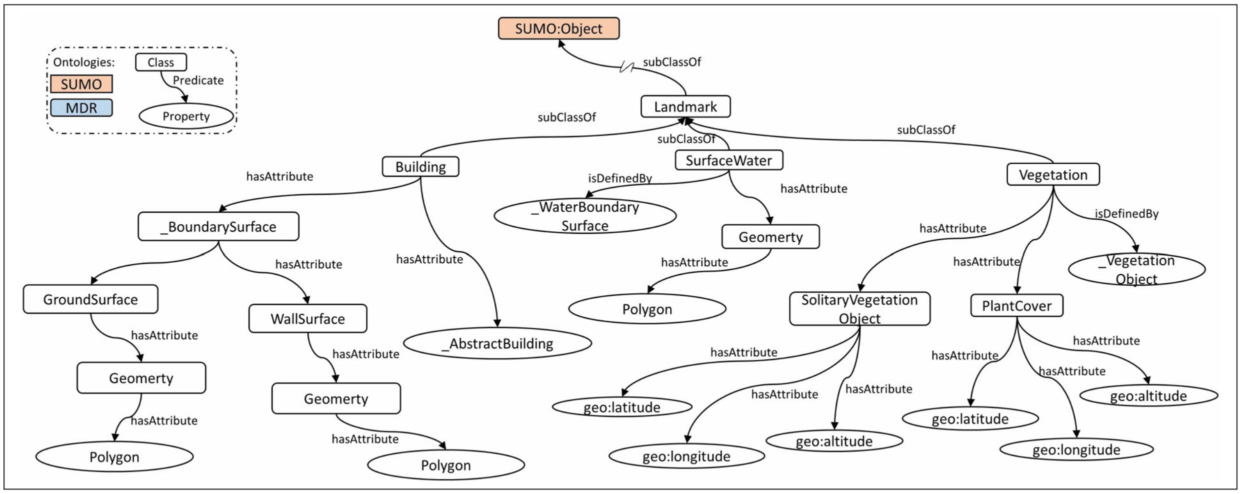


Figure 3.5 Partial indication of CityGML classes relationships in BIRS ontology

In the expected topological map, each pair of nodes are connected by an edge and since the edges are one-way relations, the resulting graph is directed. Extracted data from BIM, the edges are the transition between spaces (nodes), which is done through the doors (edges). *IfcDoor* is the *SubClassOf IfcBuildingElement* containing height and width which are defined through *IfcDoor* properties. Figure 3.6 illustrates the door relationships with regards to the landmark and to the edge. Furthermore, *IfcDoor* entity stores the information of door opening direction through y-axis of *ObjectPlacement*. BIRS uses *IfcDoor* information to create the edges. The center of the door in *IfcDoor* is defined by *IfcLocalPlacement* which inherits from its super-type *IfcProduct*. As it is illustrated in Figure 3.6, a door is also a *landmark* with which the robot can localize itself. If the spaces are not connected through a wall opening, the coordinates of wall opening are extracted through *IfcLocalPlacement* of *IfcOpeningElement*.

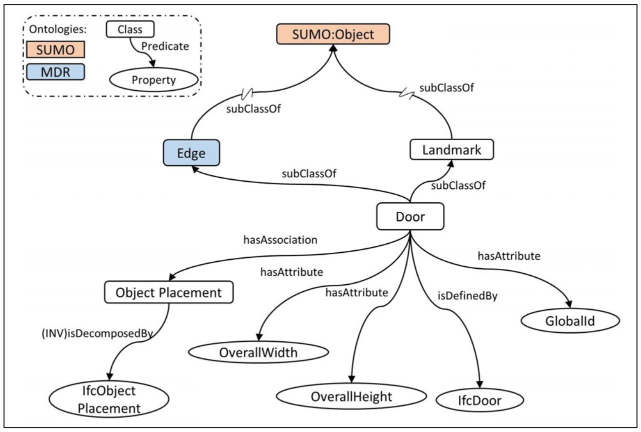


Figure 3.6 IfcDoor relationships in BIRS ontology

3.4.2 Building Information Robotic System (BIRS) Data Exchange

To achieve cross-domain data exchange using BIRS ontology, the IFC file is imported in Autodesk Revit 2020 and processed with a Dynamo script (visual programming tool for Autodesk Revit). The information for creating a semantic topological map is retrieved using the IFC parameters defined by the BIRS ontology. The correspondent information is then exported as an XML database containing semantic information for creating the topological map. We then created the semantic topological map with the nodes and edges in a Python script. Since the data need to be accessible to ROS, this Python query script (ROS node) parses the BIRS information in the XML database. The semantic information from BIRS is not directly understood by the robot since the information is represented as strings with meaning in the ontology. Hence, the node includes dictionaries translating the complex information to machine-friendly scales. Apart from the rooms' names, all the information in the graph's nodes and edges follow the same translation process. Any other node in the ROS environment can then subscribe to retrieve semantic information. As an example, when the robot enters a room with a curtain wall hard to detect by its sensors, the BIRS node provides the robot with enough information about the room so it can rely on the BIRS layout (occupancy grid). The BIRS node can quickly find the room where the robot stands from the rooms boundaries exported automatically using the low-level information of the navigation system. Due to the nature of the construction projects, there is a high number of activities and machinery which temporarily operate during the construction phase and are not fully represented in BIM. Hence, those entities that cannot be addressed with BIM, are categorized under *Uncertainty* in the BIRS and are dealt with the low-level navigation stack and real-time sensors. Detail on how the low-level navigation operates with the *Uncertainty* is beyond the scope of this paper.

3.5 Case Study

Many use cases can potentially benefit from BIM-GIS integration into robot navigation stack. The selected use cases aim to exemplify the application of using BIM and GIS to help the robot understand the spatial structure and the topographical environment in an autonomous navigation stack on construction sites. The context of the case is pavilion D ($2922.67m^2$) of École de technologie supérieure (ÉTS), which is covered with very light vegetation and surrounded by streets on two sides (Southwest and Southeast) and by buildings on the other sides. As illustrated in Figure 3.7, a topological graph database in created for the second floor of the ÉTS, pavilion D with BIM/IFC information using the BIRS ontology. Each node includes a set of information identified and extracted using the BIRS ontological approach. We then take BIRS information in order to create a second map supported by ROS, the *a priori* metric map (occupancy grid). The following four use cases are practical deployments tested with a Clearpath Jackal mobile robot.

3.5.1 Semantic Indoor Navigation

In this use case, the robot starts navigation and data collection from "CORRIDOR OUEST 2019" (west hallway) and is instructed to reach "W.C. HOMMES 2002" (men bathroom) in the building. The destination room, on the Eastern section of the building, needs to be scanned while the starting point of the robot is on the Western section. The coordinates of the desired room (center of the room) are provided by the topological map to the robot in order to reach the destination. The query script provides the destination coordinates in the BIRS node and the low-level navigation system subscribes to the node and fetches the required information. As illustrated in Figure 3.8, there is a long path to the destination with multiple rooms in between

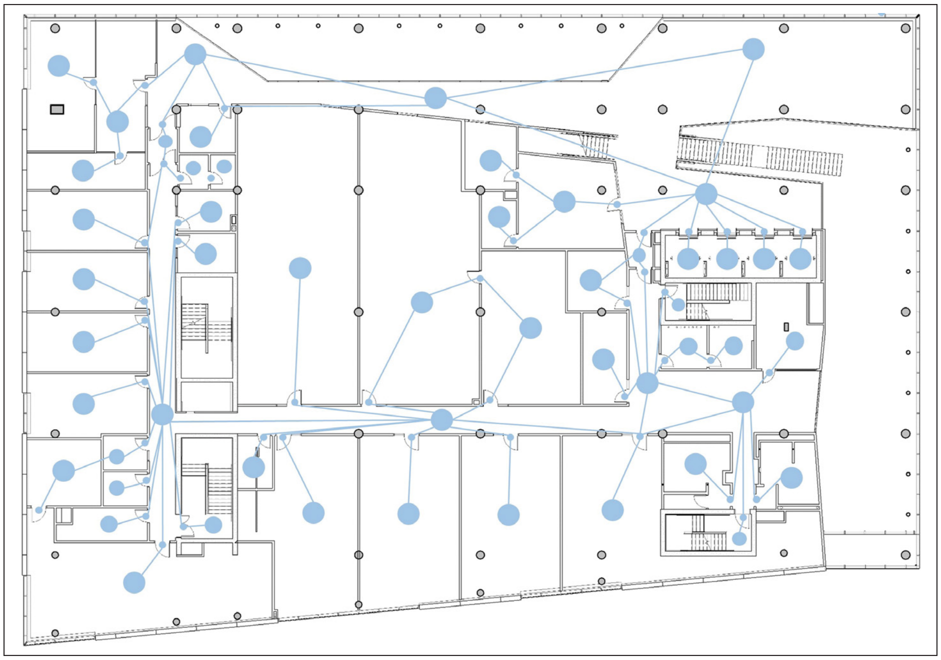


Figure 3.7 Topological Map representation of the ÉTS Pavillon-D

namely, "VESTIBULE 2043", "HALL 2044", "VESTIBULE 2042", "CORRIDOR EST 2007", and "ESPACE CLLABORATIF 2004". On its way to the destination node, the robot enters "HALL 2044" which has a large and high wall, made of glass, invisible to the robot's sensor. Figure 3.8 illustrates the map created by the SLAM algorithm which used laser scanner for navigation.

It is shown that the curtain wall is not detected in the navigation system (see left part of Figure 3.8 and Figure 3.9). Before entering the room, the navigation stack fetches information to BIRS node about the next room. The material of that wall is listed as invisible to the sensor, so the navigation can rely on the BIM original layout instead of the robot's sensor. Therefore, it prevents the robot to collide with the wall. Then, for passing through "VESTIBULE 2042", the robot's sensors are able to detect the door entrance. However, the information of both doors for "VESTIBULE 2042" node such as door width, door height, and the central point of the door is also provided to complement the real-time sensors data. The robot's task is to get into the room "W.C. HOMMES 2002" to scan the room to monitor if the equipment is installed. In the

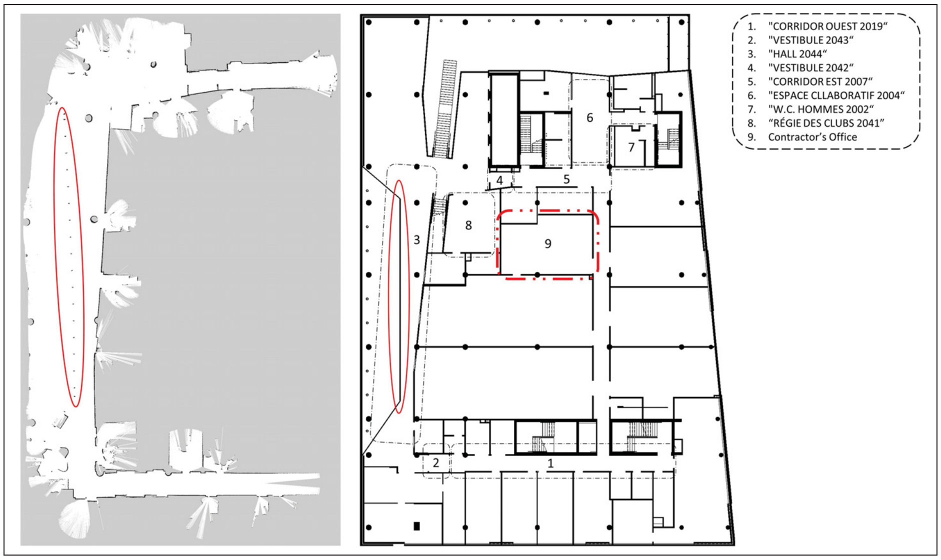


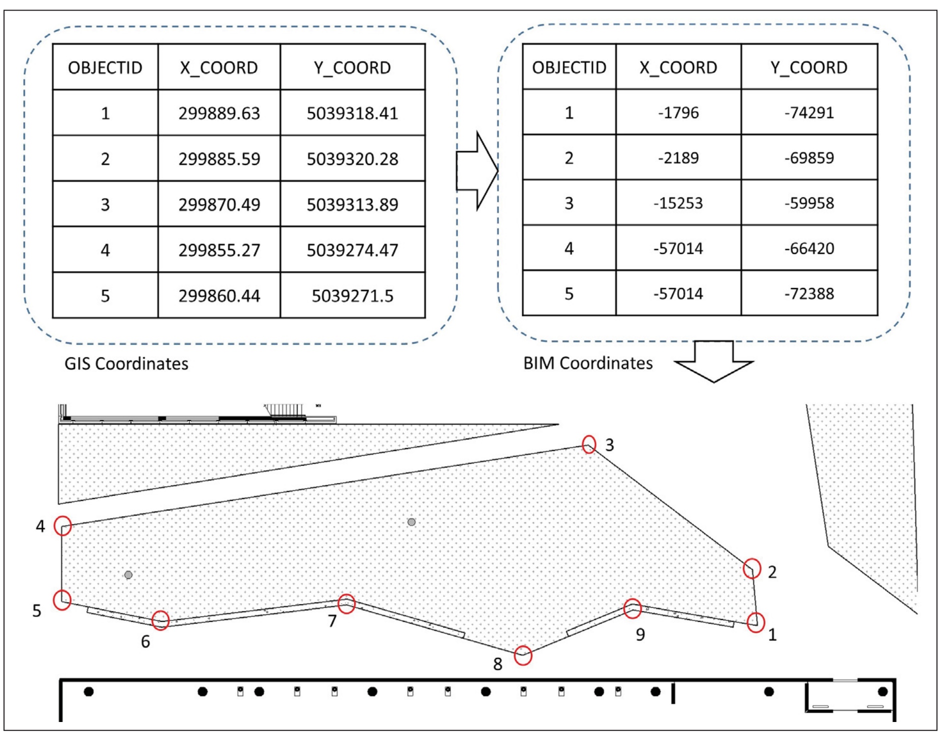
Figure 3.8 Map generated by SLAM algorithm (left) and map created from BIM (right)

Figure 3.9 The curtain wall in "HALL 2044" (left) and the outdoor environment (right)

destination node (room) the robot calls the database to query which equipment is to be installed so that the data collected can be compared with the as-planned model.

3.5.2 Semantic Outdoor Navigation

Another case study scenario relates to robot navigation in outdoor environments. In this use case, the robot navigates on the site around the building to collect data while there are several obstacles to be detected through BIM-GIS in order to contribute to obstacle avoidance. There is a landscape polygon covered with light vegetation, North of the building which is between the building of Pavilion-D and another building of the ÉTS facility. The polygon shape of the artifact contains 9 vertices. The coordinates of each vertex are retrieved from GIS and translated to the BIM environment. Similarly, the location of the vertices is provided by the BIRS node so that the polygon forms as an obstacle for the navigation system. Furthermore, outer boundary of the building is a wall, made of glass which the robot can hardly detect properly (see right part of Figure 3.9). As shown in Figure 3.10, all the information is encoded within an occupancy grid map compatible with ROS. The BIRS node provides the robot navigation system with all the required information, so it successfully complements the low-level information.



OBJECTID	X_COORD	Y_COORD
1	299889.63	5039318.41
2	299885.59	5039320.28
3	299870.49	5039313.89
4	299855.27	5039274.47
5	299860.44	5039271.5

OBJECTID	X_COORD	Y_COORD
1	-1796	-74291
2	-2189	-69859
3	-15253	-59958
4	-57014	-66420
5	-57014	-72388

Figure 3.10 Partial indication of coordinate transfer from GIS to BIM which creates an occupancy grid map

3.5.3 Progress Monitoring

In the third scenario, while the robot is navigating the construction site, it enters "CORRIDOR SUD 2010" (South hallway). As illustrated in Figure 3.11, the robot generates a map (see left part of 3.11) which is the as-built map (real state) of the section covered by the robot. In this case, the as-planned map (see right part of Figure 3.11) shows no planned wall at the time of data collection. This difference is not a sensors default; it shows that the project is ahead of schedule and the two walls on each side of the hallway were already installed. With the query script that was developed in the BIRS ontology, the robot has access to the BIM data and it fetches the information in this regard. There are two uninstalled walls defined as *landmarks* as *SubClassOf CORA:Region* (*SubClassOf SpatialStructureElement*) in the BIRS ontology and their correspondent information derived from IFC. As elaborated in the BIRS ontology, the wall on each side of "CORRIDOR SUD 2010" is a *landmark*; a building element defined by *IfcBuildingElement*. The correspondent information such as the GlobalID, location, material and room boundary relationships defined in the BIRS ontology is available through the BIRS node.

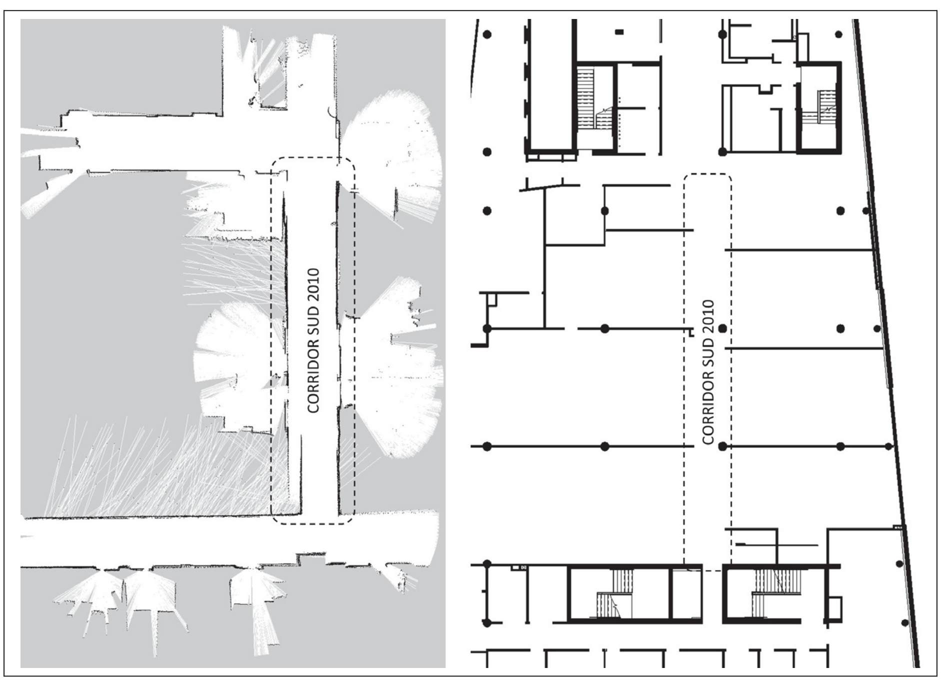


Figure 3.11 The As-built map created by the robot (left) and the As-planned map generated from BIM (right)

Based on the information retrieved from BIRS, the robotic system identifies which walls are installed ahead of schedule by having all the relevant details provided by the BIRS ontology. Similarly, this process can be followed for all the building elements which ultimately enables detailed and accurate comparison between as-planned and as-built.

3.5.4 Safety and Risk

The last use case scenario illustrates the potential for risk analysis on site. In this scenario, when the robot is collecting data, it detects anomaly which requires assistance. While the robot is on its way from “CORRIDOR OUEST 2019” to “W.C. HOMMES 2002” to collect data - right before entering “VESTIBULE 2042” - the robot detects a column as a *landmark* that is not planned in that location. Figure 3.12 illustrates the as-planned building layout (see right part of Figure 3.12) and the detected location of a column in the map generated by the robot (see left part of Figure 3.12). The BIRS ontology provides the information to the robot that no column is planned in that location. In this circumstance, an anomaly is detected on “NIVEAU 2” and the robotic system finds the closest contractor’s office to seek assistance. As illustrated in Figure 3.12, the BIRS ontology provides the robot with the location of contractor’s office. The room’s location is queried from the BIRS, so the robot can navigate itself to the office.

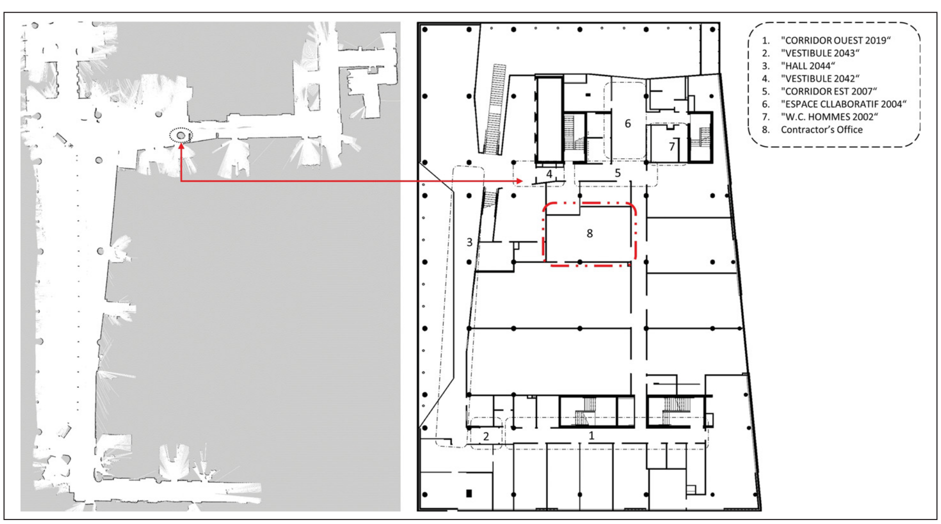


Figure 3.12 The detected anomaly on the map by the robot (left) and the as-planned map generated from BIM (right)

The robot changes its path towards the contractor's office using a common warning signal to indicate that an anomaly was detected. This does not necessarily mean that the column is installed in an incorrect place and that is why the robot seeks assistance. This may happen when there is an obstacle in the occupancy grid map (generated by the robot) which is not in the map created from BIM. In this use case scenario, the detected anomaly is reported to the contractor for further analysis. A remote warning could also be sent if an operation room exists to supervise the robot's activities.

3.6 Conclusion

Automating the data collection for progress monitoring of construction projects is challenging. UGVs are a good fit to fulfill this task but the first step is for the robot to be able to navigate on the site. There is a number of studies which address the problem of robot navigation with or without *a priori* map and utilize various navigation algorithms. The ontology provided by this paper, makes it possible for the semantic information of the building to contribute to the navigation. Information such as building elements' positions, textures, and their connections to one another, are extracted from IFC files and are fed to the navigation stack. Since the high-level information is added to the low-level navigation system, ontologies are used to reach this objective. First, established ontologies of the robotic domain are selected to be bridged with the construction data from IFC and CityGML to provide a topological database that can be queried. Then, the retrieved information is used to develop a ROS node that stores IFC and CityGML semantics to be published in the navigation stack and to be used in the low-level navigation system. The use cases show that the ontology provides semantic data that helps the robot to navigate and to understand what information is expected from its sensors. Besides, since there is no standard data format for data exchange between the BIM authoring tool and ROS, this paper uses the flexible XML data format, for data exchange between the robot and BIRS. A second type of data format leveraged the occupancy grids common to the robotic domain. The IfcBuildingElement and its sub-types are used to create that occupancy grid, thus contributing to the robot navigation. The topological database also provides the robot with information for the equipment in the spaces where data are acquired to be compared with the data previously collected on the site. This can be used for progress monitoring as well as for safety information for the robot itself.

The applications of the BIRS ontology are not limited to the ones explained in this paper and many other data exchange problems could be approached by extending the explained ontology in this paper (such as including Mechanical, Electrical, and Plumbing (MEP) equipment in the ontology in order to provide a database for facilitating automated comparison between as-planned vs. as-built). The empirical application of the robot navigation on construction sites can also be extended to positive impacts on the productivity, risk and safety analysis, circulation map on the site and sustainability of projects.

As for limitations of the system, semantic web technologies are evolving rapidly, and so are the tools used for adopting them. For this reason, there is no standard method or strategy for semantic data exchange between domains, thereby making it somewhat challenging to seek the best pipeline to implement semantic web technologies. In this paper, we used a set of established standards and data schemas to enable semantic navigation of mobile robots on construction sites. The adopted ontologies come with some limitations, so as a result, their limitations are also applicable to this study. The objective of this study is to bridge the knowledge representation between the AEC and the robotic domains without adding additional complexity. Hence, we selected the well-established and broadly used robotic ontologies to be bridged with IFC and CityGML. In addition, robotic and construction domains utilize a number of different software tools, platforms and data formats which are incompatible with one another. This is one of the reasons why we adopted ontological approach for semantic data translation between domains. However, the query script we developed does not follow a standard and just extracts the information defined in the BIRS ontology. The current study complements the state-of-the-art in navigation systems by including semantic information and yet, the practical robot navigation remains highly dependent on the low-level information received from the sensors as well the strategies to implement low-level navigation. This work now needs to be extended with the information of MEP to help avoid potential obstacles and for other applications such progress monitoring and quality control. The topological database is also currently being leveraged for high-level path planning in upcoming works.

3.7 Acknowledgement

The authors are grateful to Natural Sciences and Engineering Research Council of Canada for the financial support through its CRD program 543867-2019 as well as the industrial partners of the ETS Industrial Chair on the Integration of Digital Technology in Construction.

CHAPTER 4

SEMANTIC OPTIMAL ROBOT PATH PLANNING USING BUILDING INFORMATION GRAPHS ON CONSTRUCTION SITES

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Article submitted to *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, February 2021.

4.1 Abstract

With the growth in automated data collection of construction projects, the need for semantic navigation of mobile robots is increasing. In this paper, we propose an infrastructure to leverage building-related information for smarter, safer and more precise robot navigation during construction phase. Our use of Building Information Models (BIM) in robot navigation is twofold: (1) the intuitive semantic information enables non-experts to deploy robots and (2) the semantic data exposed to the navigation system allows optimal path planning (not necessarily the shortest one). Our Building Information Robotic System (BIRS) uses Industry Foundation Classes (IFC) as the interoperable data format between BIM and the Robotic Operating System (ROS). BIRS generates topological and metric maps from BIM for ROS usage. An optimal path planner, integrating critical components for construction assessment is proposed using a cascade strategy (global versus local). The results are validated through series of experiments in construction sites.

4.2 Introduction

Building Information Modeling (BIM) has brought many advantages by storing building elements' semantics and geometries (Karan & Irizarry, 2015). Conventional methods of data collection for the purpose of progress monitoring rely on periodic observations, manual data collection (which is mostly textual data and a limited number of photos), and personal interpretation of the project progress (Álvares & Costa, 2019). These aforementioned conventions are error-prone, time-consuming and cost-ineffective since they are subjective processes (Teizer, 2015). Manual data acquisition by individuals would result in decentralized data; coming from different sources in different formats, thereby making it somewhat challenging to manage and analyze them. According to de Soto *et al.* (2018), automation of monotonous and repetitive construction processes would significantly enhance construction efficiency. Hence, there is a growing need in the construction industry to automate data collection task. In addition, the applications of data collection using an Unmanned Ground Vehicle (UGV) can provide new kinds of information and applications such as equipment tracking and 3D reconstruction which would ultimately have positive impacts on quality control, safety and sustainability of the construction projects.

With tremendous progress in mobile robots capabilities, the interest in adopting mobile robots for data collection on construction sites is increasing. Rugged platforms with high manoeuvrability are commercialized for this usage (Pomerleau, 2021) and several works are enhancing their autonomy for navigating these challenging environments (Kim *et al.*, 2018; Asadi, Chen, Han, Wu & Lobaton, 2019). A handful of fundamental steps still need to be addressed for the deployment of robots on construction sites, such as their usage by non-experts (untrained) operators and the automatic integration of the diverse requirements related to construction management in their mission planing. Our solution leverages BIM semantics extracted in an interoperable data schema, IFC, and translated for robot indoor navigation. This semantic information, intertwined with the robot navigation and mission, help the operator manage the robotic system as they share conceptual knowledge of their environment (Kostavelis & Gasteratos, 2017).

This paper proposes a novel method for semantic robot navigation with an optimal path planning algorithm using building knowledge on construction sites. The optimal path is extracted from user inputs using BIM/IFC which provide digital representation of the construction project (Karimi & Iordanova, 2021). The resulting path (which is not necessarily the shortest path) can be altered with the weights of several criteria such as robot and workers safety, BIM new information requirement and sensors sensitivity to environmental features. In this step, the building semantics play an essential role on defining the start, the end and the transitional coordinates with which the robotic system plans the path. Furthermore, all along the mission, the local paths are computed based on the relevant complementary information for the low-level navigation extracted from IFC. This is essential to cope with limitations of the robot. For instance, a path planner should avoid trajectory near glass walls: they are hard to detect by many sensors. Luckily, information about wall materials can be retrieved from BIM. Among the conventional methods on path planning (Crespo *et al.*, 2020), we use topological map representation in order to store the building semantics in nodes and graphs. The current paper contributions are as follows:

- An optimal high-level path planner integrated with the low-level navigation (cascade navigation stack);
- Semantic teleoperation and navigation for autonomous UGV during the construction process;
- Practical implementation of the proposed system deployed on an autonomous mobile robot navigating a construction site.

The next section will summarize the inspirational works to our approach. Then, section 4.4 describes the generation of topological maps (hypergraphs) from IFC information. Section 4.5 explains the IFC-based path planning algorithm in details. The setup of our field experiment to validate the proposed system is described in section 4.7. The results of our experimental validation are discussed in section 4.8. Finally, section 4.9 summarize the contributions and the next steps of our work.

4.3 Related Work

Conventional methods of indoor path planning often refer to optimal path as the shortest path calculated by various algorithms such as A* and Dijkstra's (Palacz *et al.*, 2019). To enhance the performance of these planners, many studies suggested ways to leverage BIM/IFC for indoor path planning. Wang et al. (Wang, Zuo, Guo, Li, Mei & Qiao, 2020) develop a framework for converting the BIM digital environment to a cell-based infrastructure to support indoor path planning. In this work, they emphasize on the *"BIM voxelization"* process rather than the path planning problem. In another study, a BIM-based path planning strategy is used for equipment travel on construction sites (Song & Marks, 2019). The authors extract the start and end points from BIM and then generate the shortest sequence of rooms for the operator, but does not support robot path planning. Ibrahim *et al.* (2017) propose a path planning strategy based on BIM for an Unmanned Aerial Vehicle (UAV) on construction sites which uses a camera for data capturing. They use BIM geometries to define a path for outdoor environments but do not address indoor semantic robot path planning. In this direction, Follini, Terzer, Marcher, Giusti & Matt (2020) utilize BIM geometries for path planning of an UGV supporting construction logistics application. Their proposed system uses a human-assisted approach in a controlled environment and is yet to thoroughly leverage BIM/IFC semantics in a construction site. Ibrahim & Golparvar-Fard (2019) proposed an optimal route for a data collection mission using an UAV. They utilize 4D BIM to identify which building spaces are expected to change during the construction phase (implemented in a simulated environment) so that the flight path navigate through those areas and collect data.

Delbrügger *et al.* (2017) developed a framework supporting humans and autonomous robots navigation which mostly uses building geometries in a simulated environment. Nahangi *et al.* (2018) assessed indoor localization of an UAV using AptilTags with their known location in a BIM-generated map. They present this work as a proof-of-concept for the use of AprilTags in indoor environment. However, due to inaccuracy of localization in their work, they improve their previous work by using Extended Kalman Filter (EKF) in their localization framework (Kayhani *et al.*, 2019). Another study examined the use of BIM in robot localization in which the proposed system uses a hierarchical reasoning for path planning (Siemiatkowska *et al.*, 2013). BIM was also demonstrated to be powerful for the identification of different paths from which a hierarchical refinement process can find the shortest path (Hamieh, Makhlouf, Louhichi & Deneux, 2020). That work provides only high-level path (rooms sequence) with respect to BIM geometries and the integration with ROS is not studied. An approach using hypergraphs generated from IFC files was also developed in which a modified A* algorithm is able to detect the optimal path among nodes in the graph (Palacz *et al.*, 2019).

In these inspiring works three aspects of the BIM potential for indoor robot path planning are yet to be thoroughly studied: (1) considering the full potential of the BIM/IFC semantic rather than only the geometry (2) integrating the high-level (rooms sequence) with the low-level sensor-based information in a full navigation stack (3) the field validation of strategy using BIM/IFC for both global and local path planning. In this paper, we cover these gaps by integrating Building Information Robotic System (BIRS) into a navigation system in ROS in order to determine the optimal path and then navigate autonomously.

4.4 topological building maps created from BIM/IFC

IFC data schema provides construction stakeholders with semantic information of buildings containing attributes and relationships between different entities (Ismail, Strug & Ślusarczyk, 2018). This information can be extracted in graph database (Strug & Ślusarczyk, 2017). However, the use of that information for reasoning is complex since the IFC files encompass large amounts of data. In order to cope with this, we first identify the required data for robot navigation on construction sites, then, we extract and store the data in an XML database. The conceptual semantic relation between BIM/IFC and robot navigation is covered in a previous paper on BIRS (Karimi, Iordanova & St-Onge). We extend the hypergraphs of Palacz *et al.* (2019) with the semantic and geometric information of IFC files. All the semantic information required to the global and local planners retrieved from IFC is in the form of a topological map.

As IEEE 1873-2015 730 (2015) defines, nodes and edges are the components of topological maps and we fill them with the following information:

- Nodes contain the rooms information namely: room's name, room's unique ID, room center, room area, walls' unique IDs, wall material, last scan date, construction activity (hazard for the robot).
- Edges contain the doors information namely: door's unique ID, door's location, doors opening direction.

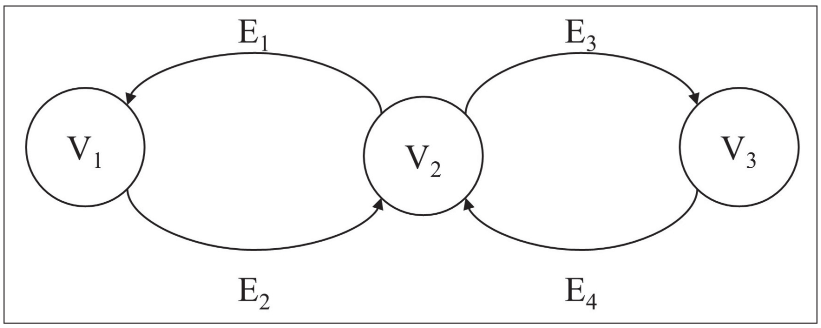

Figure 4.1 A directed hypergraph of $S = (V, E)$ where $V = \{V_1, V_2, ..., V_n\}$ is a set of nodes and $E = \{E_1, E_2, .., E_m\}$ is a set of hyperedges. Each node (V_i) is an *IfcSpace* containing its relationships and each hyperedge (E_j) is an *IfcDoor* with its attributes extracted by BIRS (Karimi *et al.*)

In the hypergraph, one node is created per *IfcSpace* and for each *IfcSpace*, the bounding *IfcWall* and *IfcCurtainWall* elements are identified. With the above-mentioned information, a graph is generated as illustrated in Figure 4.1. Then, the edges need to be attributed with the cost (weight) of passing over each (from a room to another). In this direction, $W = (W_V, W_E)$ is a pair of weights where W_V and W_E are the node and hyperedge weights respectively. W_{V_i} is the i node total weight obtained from:

$$W_V = w_m + w_a + w_s + w_h \tag{4.1}$$

where w_m depends on the walls material, w_a, on the room area, w_s, on the room scan-age, and w_h, on the room hazards. W_{E_j} is the j hyperedge weight obtained from:

$$W_E = w_d \tag{4.2}$$

where w_d depends on the door opening direction. For passing from one node to the other, there might be several paths the robot can use. The overall weight of a path (from start to end node) is as follows:

$$W = \sum_{i=1}^{n} W_{V_i} + \sum_{j=1}^{m} W_{E_j} \tag{4.3}$$

One challenge for the robot is to be able to detect obstacles. To help the robot predict and avoid potential failures, the material properties of the walls are extracted through *IfcMaterial* and its super-type *IfcProduct*. The weight of each curtain wall, i.e. walls that are *invisible* by design, in each node is $w_m = 12$, while all others are $w_m = 4$ since they can be easily detected. The time required to go through a transition node is also taken into account, i.e. bigger rooms take more time for the robot to cross. Accordingly, the weight for the rooms less than $50m^2$, between $50m^2$ to $100m^2$ and more than $100m^2$ are $w_a = 2$, $w_a = 8$ and $w_a = 12$ respectively. Since one of the core purpose of deploying robots on construction sites is to collect data, the scanning age of all rooms is incorporated. The progress monitoring needs up-to-date data and when the robot is collecting data it can optimise its path to visit more rooms and collect more data. The scanning periods are selected according to industry needs, therefore, we assign $w_s = 10$, $w_s = 6$, $w_s = 0$ for the scanning period of less than 1 week, between 1 week and 2 weeks, and more than 2 weeks respectively. Since the construction projects evolve constantly, the safety aspects of robot navigation are essential. In this direction, the data collection for the spaces with ongoing construction activities should be postponed to a safer moment for the robot to navigate those rooms. If the hazardous space is one of the transition nodes, an alternative route needs to be automatically planned so we assign $w_h = 500$ for the weight of passing through such spaces. In this case, another path will be selected by the algorithm if there is any. If there is not an alternative safe path for the robot, the algorithms provides a warning for high-weight paths so that the supervisor of the robotic deployment is warned. The hypergraph representing building topological map enables the robotic system to find the optimal path by running an algorithm. In this paper, we use directed hypergraph (with directed hyperedges) allowing us to assign cost for door opening directions. *IfcDoor* as a sub-class of *IfcBuildingElement* provides the center coordinates of the doors creating hyperedges (with their coordinates) in the hypergraph. *IfcDoor* also stores the opening direction through y-axis of *ObjectPlacement* parameter. For pushing and pulling the door, we assign $w_d = 2$ and $w_d = 6$ to the hyperedge's weight respectively. This is due to difficulty for pushing and pulling the doors respectively. Ultimately, the total weight of passing one to the other is the sum of nodes weights and edges.

4.5 Finding The Optimal Indoor Path

As Gallo, Longo, Pallottino & Nguyen (1993) define, directed hypergraphs are divided into two categories according to their hyperedges namely: forward hypergraph (F-hypergraph) and backward hypergraph (B-hypergraph). The former is a directed hypergraph in which one node diverges to several nodes and the latter is the one in which several nodes converge to one node. As an example of applications, F-hypergraphs are employed for time analysis on transportation networks Prakash & Srinivasan (2017). Also, B-hypergraphs are used to perform deductive analysis to find the optimal path in a hypergraph. The combination of B-hypergraph and F-hypergraph is a BF-hypergraph having both divergent and convergent nodes (Gallo *et al.*, 1993). In topological building layouts, we deal with BF-hypergraphs since we have spaces which connect several spaces to other spaces (an example of such nodes is corridors). In addition, we intend to find the optimal path (a *"deductive database analysis"* from several possible paths) based on several criteria which are represented as weights in the hypergraph, therefore, we use the *"Shortest Sum B-Tree"* algorithm which finds a hypertree (subhypergraph) of the nodes as explained in Gallo *et al.* (1993). We also use *additive weighting function* to calculate the cumulative weight of each possible route and then we choose the lighter route which is the optimal path for the robot.

In order to create the hypergraph, we first retrieve all the relevant IFC information. The process is done with a Dynamo script (a visual programming tool) to extract the IFC parameters in order to

```
Inputs:
  layout_graph : hypergraph
  tail_room, head_room : node
  door : hyperedge
  path_weight : hyperedge_total_weight
Outputs:
  semantic_path : list<node, hyperedge>
  x_y_path : list<nodes_coordinates,
  hyperedges_coordinates>
  hyperedge_total_weight : number
```

Figure 4.2 Data structure for IFC-based semantic optimal path planner algorithm

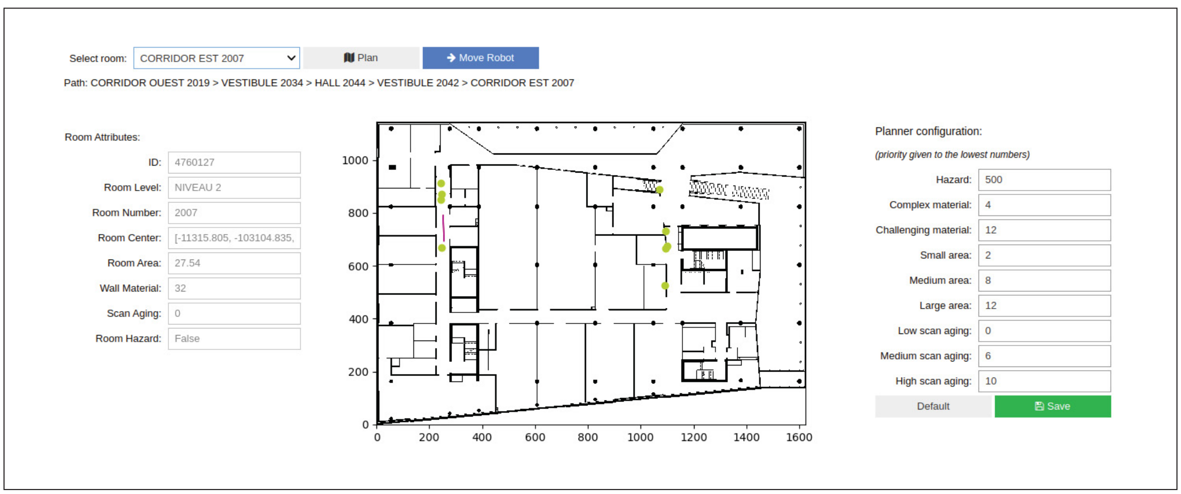

Figure 4.3 Semantic Graphical User Interface for the intuitive operation of the robot navigation on construction sites. The controls in the header allow selecting a destination and generating the path. The panel to the left shows the attributes of the selected room. The center contains a map of the environment, with the robot's pose in real time being represented by the purple arrow. The center points of the rooms and doors in the path are represented in the map by the yellow circles. The right panel allows the user to reconfigure the different weights that are applied to the path generation

export the IFC information in a XML database. A Python script is developed to parse the XML data in order to translate meaningful data to ROS (for example, the rooms center coordinates are retrieved as strings so they need to be parsed to be integrated with the robotic system). With an hypergraph of the whole building, the user defines the start and end nodes (rooms), and let the algorithm find the optimal path. Since we are implementing BF-hypergraph, each pair of nodes is connected with two directed hyperedges together, thereby making a comprehensive B-hypergraph within the BF-hypergraph. This practice allows considering forward and backward direction in a path so that the door opening direction is considered. *"Shortest Sum B-Tree"* algorithm provides the possible hyperedges from a start node to other nodes Gallo *et al.* (1993). Then, the retrieved information is used to create a sub-hypergraph from the start node to all other nodes representing all the possible paths. By giving the destination node to the sub-hypergraph, the possible paths from start to end node are identified and finally the lowest cumulative weight of the paths is retrieved. Having a set of nodes and hyperedges from the optimal path, the building information is extracted to enable semantic navigation. Each node is represented by the name of the corresponding space and the center coordinates of that room. As illustrated in Figure 4.2, the optimal path outputs a set room names, their coordinates and a set of door coordinates in the sequence of node location and hyperedge (door) location. The room names enable semantic navigation and the 2-D coordinates provide destinations one after the other.

4.6 Semantic Graphical User Interface

A Graphical User Interface (GUI) was developed based on BIM semantics to allow users to intuitively operate the robot and configure the path planner. The GUI connects to the ROS running in the robot and presents semantic information of the building and data from the robot in real time. The integrated high-level and low-level navigation system moves the robot to the desired destination. The GUI allows the non-expert users to work with their domain knowledge, thereby making robot deployment more intuitive and simpler. Figure 4.3 illustrates the interface window. The GUI is developed in Python notebooks, allowing for easy integration of visualization widgets and customization.

The GUI provides the building's rooms in a drop-down list, from which the user selects a destination and then launch the path planner to find the optimal path. The center area of the GUI shows a map of the building, with the robot's pose being updated in real time, along with the paths objectives. The left panel shows the selected room's (end node) attributes. The right panel allows the user to alter the weights of each parameters of the path planner. After changing and saving the new weights, the user can generate the path again and see the results on the map. Finally, the user can click on the *Move Robot* button to trigger the robot to start moving.

4.7 Field deployment

Our approach was validated from simulation to the field with an experimental case study. The goal was to drive a mobile robot through the corridors of one of the buildings at the École de technologie supérieure, for which a complete BIM model was available, and collect data. The semantic path planner was used to generate a set of waypoints from the user inputs, then a low level A* path planner aided by a collision detection stack navigates the robot.

Our robotic platform, shown in Figure 4.4, is built from a four-wheeled unmanned ground vehicle (Clearpath Jackal) equipped with wheel encoders, an internal IMU and an onboard NVidia Xavier computer. The Jackal is delivered with ROS nodes for control, odometry estimation (from encoders and IMU) as well as diagnostics tools provided by ROS.

The sensing system, which was envisioned for point cloud collection in construction sites, contains two LiDARs, five depth cameras and one tracking camera. The sensors are positioned in different directions to cover as much as possible of the robot's surroundings. While all sensors collect and record data of the environment, most of them are also used by the navigation stack for localization and collision avoidance. Below we present a detailed description of each sensor or group of sensors:

- **Front facing cameras:** One Intel Realsense D435i depth camera and one Intel Realsense T265 tracking camera are mounted in front of the robot. The T265 software estimates the camera's pose and integrates data from the base odometry (wheel encoders and IMU), providing accurate odometry that is fed to the localization algorithm. The D435i provides depth images that are used to detect obstacles immediately in front of the robot, triggering an emergency stop;

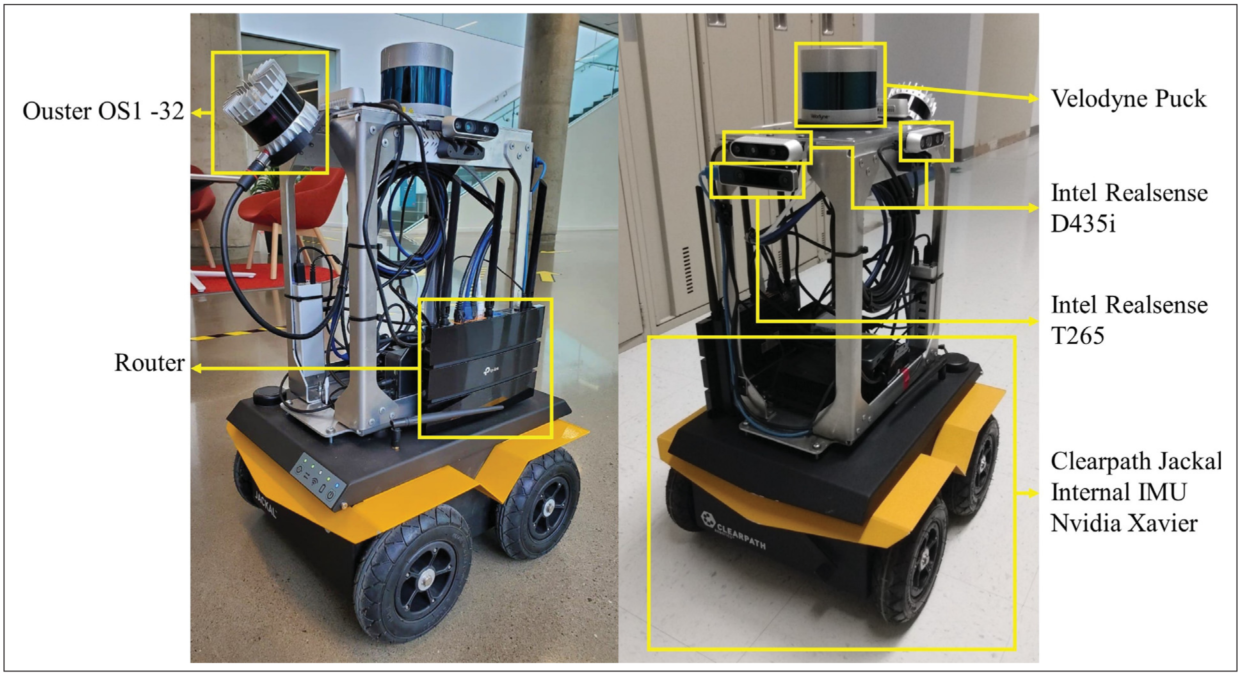

Figure 4.4 Mobile robot platform equipped with various sensors

- **Velodyne Puck 32MR LiDAR:** Mounted horizontally on top of the robot, it captures laser scan data from all around the robot. This information is used by the localization algorithm to estimate the robot's global position on the building map;
- **Depth cameras:** Three Intel Realsense D435i depth cameras are mounted pointing to the top and left and right sides of the robot. Their purpose is to collect RGB images and depth images from the walls around the robot and from the ceiling;
- **Ouster OS1 LiDAR:** The last sensor, an Ouster OS1 LiDAR is mounted in the back of the robot, inclined by an angle of 45 degrees in order to capture point clouds of the ceiling. Since this sensor has a large 90° field of view, it is also able to cover the walls and part of the back of the robot.

Figure 4.5 gives an overview of the system. The robot pose in the map is obtained through the use of a ROS implementation of the Adaptive Monte Carlo localization algorithm (ROS wiki, 2020; Thrun, 2002). Before deploying the robot, wall geometry information is extracted from BIM to generate an occupancy grid of the building. During the robot navigation, this map, the odometry, and the laser scan data from the horizontally mounted Velodyne LiDAR are fed to the localization algorithm, which then estimates the robot's current pose in that map. When a destination room is selected, the semantic path planner outputs the preferred path to that room as a list of waypoints, containing the center points of each room, door and corridor in the path. An A* path plannerHart, Nilsson & Raphael (1968) then calculates the shortest path from the robot's current position to the next waypoint in the list. Velocity commands are generated from the A* path and sent to the robot's internal controller to drive it though that path.

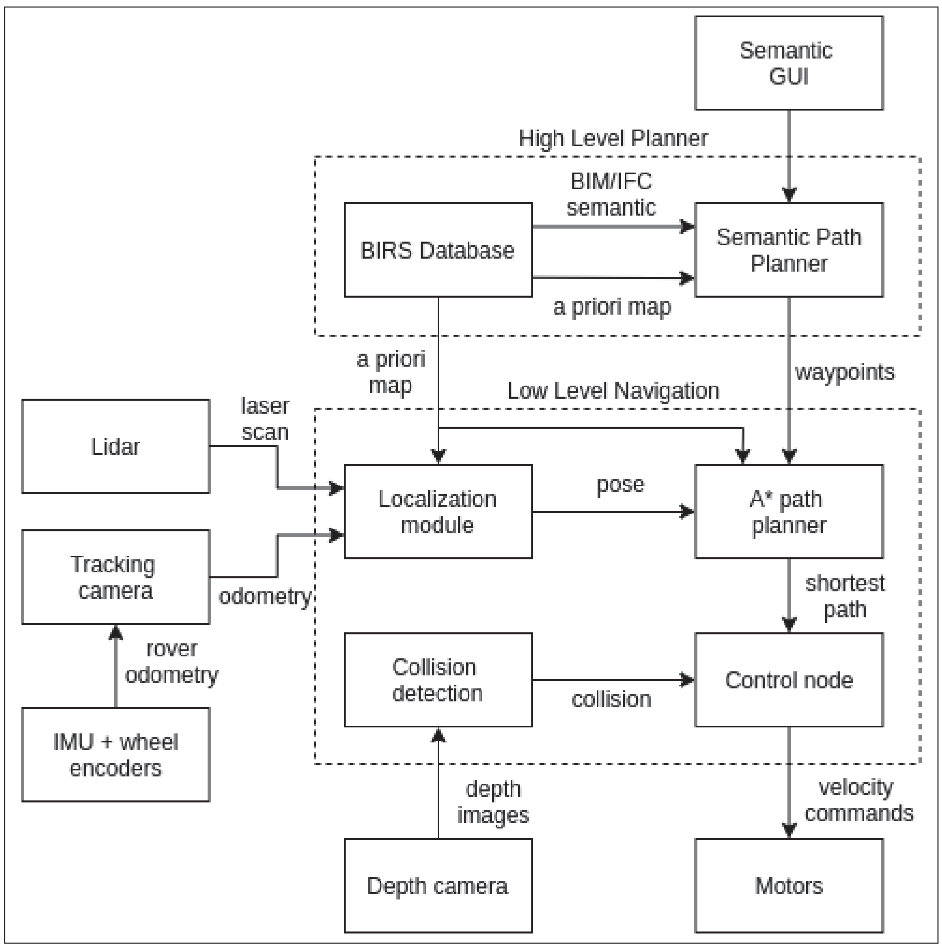

Figure 4.5 System Overview: A high level planner that process BIM/IFC information and user inputs is integrated to a low level navigation stack in a cascade design. The low-level module takes care of the localization, local path planning and collision avoidance tasks, while the high-level planner generates paths based on BIM/IFC semantics

The simulation was performed using the Gazebo Simulator. The building information is exported to create a 3D model, a digital twin. Clearpath, Gazebo and the ROS community provide all the required software packages required to generate an accurate simulation of our robotic platform. Figure 4.6 shows the simulated robot and its environment with different wall textures and transparency.

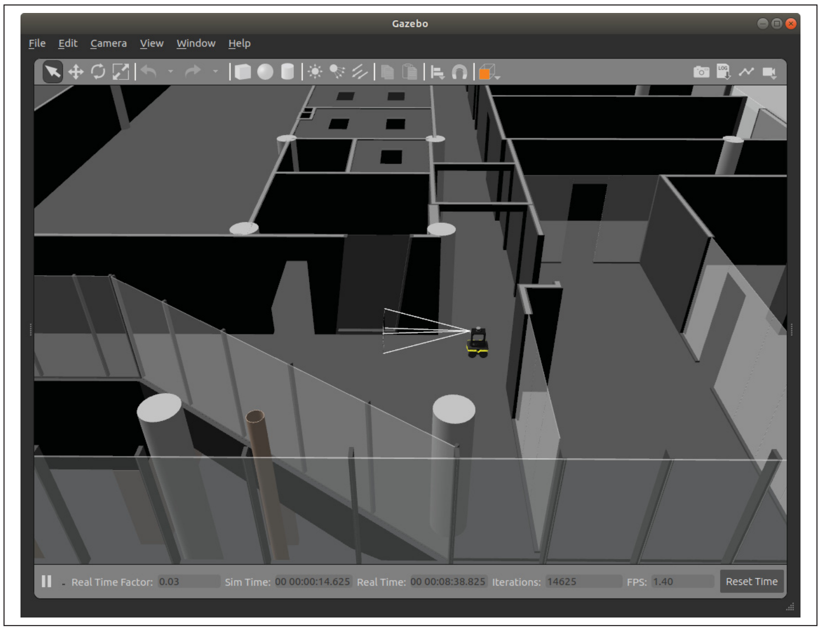

Figure 4.6 View of the simulated environment used to test the BIM/IFC optimal path planning approach. The building 3D model was built with geometry information extracted from the BIM. The robot model simulates the sensors and possesses the same characteristics as the real robot

4.8 Results

The experiment had two main objectives:

1. Test the effectiveness of the semantic path planner in generating the optimal path to reach the destination, given the building information obtained from BIM/IFC.
2. Test how changes in the building information affect the final path that is generated.

In our case study, the robot starts in a corridor (CORRIDOR OUEST) on the west side of the building and must reach an open area (CORRIDIR EST) on the eastern part of the building. Figure 4.7 shows the building map, and the path in red line generated by applying the A* algorithm from start to end. This is the shortest possible path between the two points, taking into consideration only the building geometry and a small safety collision radius around the robot. When the Semantic Path Planner is applied to the same scenario, a similar result is obtained as expected, represented by the blue path in Figure 4.7. Since there are no doors, undesirable materials or hazards in the path, the algorithm outputs a list of rooms that must be visited by the robot that represent the shortest distance from start to end. The semantic path planner provided the order of rooms' names from the start to the end as it is show in the GUI in Figure 4.3. Therefore, the user operating the robot can intuitively track the path from the data collected. In this direction, the as-built data can be directly compared to the as-planned since the path is recorded semantically. Also, the waypoints of rooms' center coordinates and doors' center coordinates are provided by the semantic path planner. If there is a door made of materials invisible to sensors (such as glass), the complementary door coordinates helps for safer, smarter, precise data collection. Following this, the A* algorithm finds the shortest path between the waypoints.

In a second run, the building information was altered to include a construction operation carried out in the area highlighted with a dashed box in Figure 4.7 (not visible in the GUI). Since the construction activity represents a hazard with a high cost for the Semantic Path Planner, a different path passing through another corridor is automatically selected, as illustrated by the orange path. Nevertheless, the high cost of the shortest path triggered a warning in the system indicating a hazard to the user through the semantic GUI. Therefore, the user can understand the risks associated with navigation through an active construction area and decide whether to scan the environment or postpone it to a safer time. The orange path was automatically generated, although it is not the shortest path, as the optimal path from the default parameters mentioned in section 4.5. This path passes along a large curtain wall invisible to the robot's sensors. The additional semantic information provided by the BIRS is given to the robot as well as the BIM occupancy grid so it contributes to collision avoidance with the wall. The GUI provides the user with the scan aging of the rooms so the user can decide which rooms to select as the destination for data collection. This allows the users to run multiple data collection mission with the robot which increases the efficiency of robot deployment on construction sites. As illustrated in Figure 4.7, the integrated BIM-ROS information provides a cascade navigation system on construction sites enabling autonomous and accurate data collection of the spaces scanned.

Figure 4.7 High-level and low-level paths: A* generates the shortest path possible between start and end, not taking advantage of the BIM/IFC semantics. Path 1 has the lowest total weight among other alternatives. Path 2 is automatically generated when there is a hazard to the robot in path 1

4.9 Conclusion

This paper presented a semantic path planner that uses building information from IFC data schema to generate optimal paths for safe and efficient navigation of autonomous robots on job sites during the construction phase. We used the BIRS for extracting building information from IFC represented in a hypergraph structure. Path planning algorithms can then be used to calculate optimal paths in this graph given the building information. Weights are designated to each connection in the path to represent how different conditions can affect the robot's navigation and to prioritize paths with more desired characteristics. The optimal semantic path is then integrated with low-level navigation system and A* algorithm is used to calculate the shortest path within the optimal path. The effectiveness of the path planning to generate different paths given different conditions was shown in a simulated and real life case study.

This algorithm can be extended in the future to take into consideration Mechanical, Electrical and Plumbing (MEP) semantics for data collection. Different locations can be added based on the kind of information needed at a specific time of construction through the GUI in order to provide the robot more destinations to collect data. Therefore, the high-level path planning algorithm would provide a more efficient route for data collection as well as semantic navigation. Also, this paper provided semantic navigation of mobile robot on construction sites, therefore, a user study will be conducted in order to assess the usability of the semantic navigation approach.

4.10 Acknowledgment

The authors are grateful to the Natural Sciences and Engineering Research Council of Canada for the financial support through its CRD program 543867-2019, to Mitacs for the support of this field study as well as Pomerleau - the industrial partner of the ÉTS Industrial Chair on the Integration of Digital Technology in Construction.

CHAPTER 5

DISCUSSION

The current thesis develops and implements a system that leverages BIM-GIS information for a a quicker, smarter and more efficient robot navigation on construction sites. This is the final output which accomplishes the research objective. The thesis adopts a design science research, which aims at developing an artifact as the final output to reach the research objective. The adopted methodology leverages a design cycle in which an artifact is designed, developed and evaluated in each chapter to provide a robust result to be used in the next steps of the research. In this direction, three research questions are articulated and each of them leverages DSR to develop an artifact to find the answer. The artifact of one paper is then used in the next paper to develop another. All developed artifacts of the papers are then aggregated to develop the final output of this research. The artifact of each paper is as follows:

- The SLR (chapter 2) develops an artifact which is the construction-related information that can be leveraged for autonomous robot navigation.
- The BIRS ontology uses the artifact developed in chapter 2 to develop another artifact in chapter 3 to extracts the relevant information and transfer the semantic building-related data to the robot navigation system.
- The developed artifact in chapter 3 is used to develop another artifact in chapter 4 which is a high-level path planner providing complementary building information to plan the optimal path considering building semantics, geometry and safety measures.

As illustrated in Figure 5.1, the developed artifact of one paper is leveraged in the design cycle of the next paper. In other words, each paper uses the previous paper's findings to develop and build on. Ultimately, all the artifacts come together to reach the research objective. Within this process, the research questions are answered, thus contributing to the AEC industry and the body of knowledge.

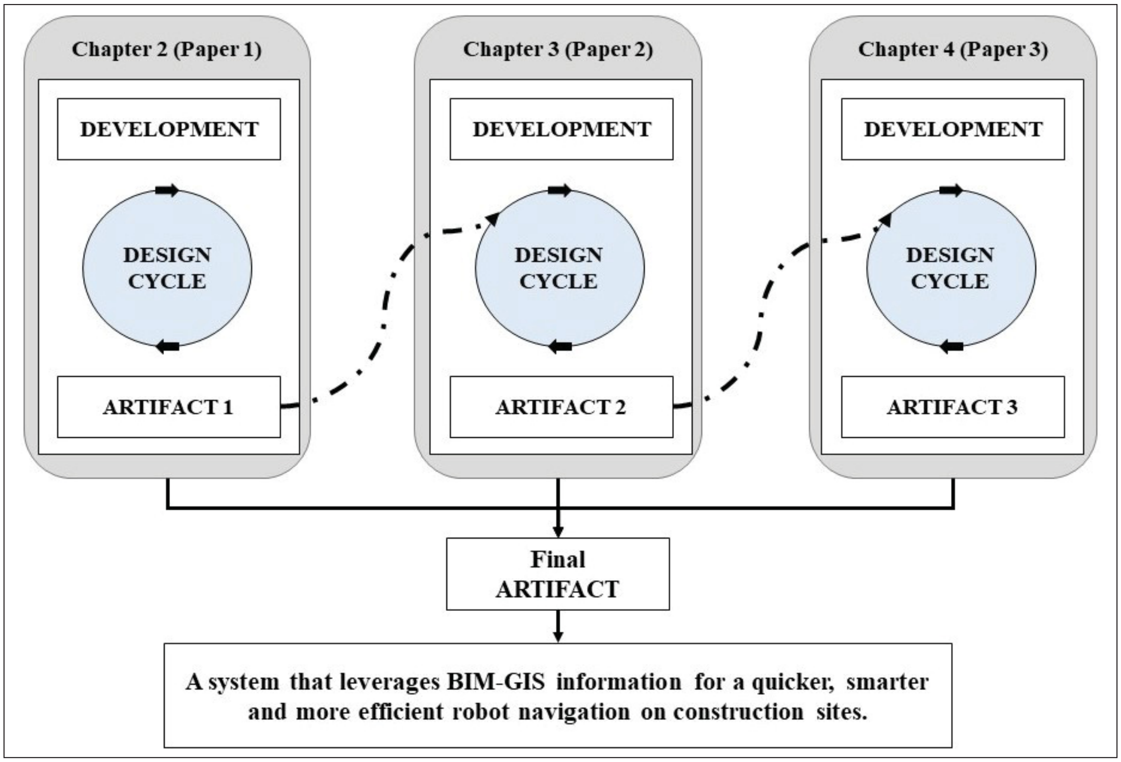

Figure 5.1 Connection of the three papers regarding the artifact development

5.1 Papers' Contributions

Each paper aims at contributing to the body of knowledge by answering to the thesis research questions which are as follows:

- **Paper 1 (Chapter2):**
  - Mapping Trends, challenges, potentials, and deficiencies in BIM-GIS integration for robot navigation.
  - Visualizing and analyzing the citation patterns of journal articles along with the analysis of studies
  - Defining the requirements for robot positioning using BIM-GIS integration
- **Paper 2 (Chapter 3):**
  - An ontology bridging BIM-GIS data to IEEE 1872-2015 and IEEE 1873-2015 standards.
  - Cross-domain data structure enabling exchanges between construction and robotic domains.

  - A practical implementation of the proposed ontology and data structure to deploy it on an autonomous mobile robot navigating a construction site.
- **Paper 3 (Chapter 4):**
- An optimal high-level path planner integrated with the low-level navigation (cascade navigation stack);
- Semantic teleoperation and navigation for autonomous UGV during the construction process;
- Practical implementation of the proposed system deployed on an autonomous mobile robot navigating a construction site.

CONCLUSION

Autonomous UGVs can be used to provide accurate and reliable data from construction sites. Efficient autonomous data collection requires data integration between the construction and robotic domains to increase adaptability and efficiency of mobile robots. Based on the systematic literature review (chapter 2), we identified the opportunities to integrate digital data from the built environment with the robot navigation system. These data can be extract from BIM and GIS to provide holistic information of the spatial structure and topography of construction projects respectively. In the scope of this thesis, we focused on enhancing the efficiency of data collection by leveraging BIM-GIS data in autonomous robot navigation. To achieve this, we developed the BIRS ontology to (1) extract the relevant information from the digital built environment and (2) to enable cross-domain semantic data translation. The results of chapter 3 show the application of this ontology that can be used for progress monitoring of construction projects. In addition, the relevant complementary information for the low-level navigation is extracted from IFC files. In order to address robot's limitation, we developed a path planner which calculates the 'shortest' path to a given target. It will, for example, avoid a trajectory near glass curtain walls (chapter 4) since they are invisible to the robot's sensors and can lead to difficulties in the navigation.

Findings

The current thesis aims to enhance the efficiency of data collection on construction sites, as stated in the research objective mentioned in section 1.1.3.1. The first research question was *"What are the requirements of using BIM and GIS integration to be utilized in robot navigation and how a full stack navigation system can be implemented?"*. The systematic literature review (chapter 2) finds the answer to this question by articulating what construction-related information can be leveraged for autonomous robot navigation. This is done through investigating a great number of scholarly papers; thus, identifying the BIM-related and GIS-related contributions to robot navigation. Furthermore, BIM-GIS integration has its challenges, therefore, data formats to cope with interoperability issues are also investigated and identifies. The second question which was *"How the construction and robotic knowledge can come together to semantically transfer the building information to the robotic system?"* is answered through development of an ontology supporting semantic data translation (chapter 3). The BIRS ontology, first extracts the relevant information that has been identified in chapter 2 and then provides a pipeline to transfer the semantic building-related data to the robot navigation system. The third research question was *"How BIM-GIS data can be integrated with the robot navigation system for practical implementation of semantic navigation?"*. This question is answered through development of a high-level path planner that provides complementary building information to plan the optimal path considering building semantics, geometry and safety measures. Chapter 4 describes the answer to the third question.

Limitations and future work

The current thesis focuses on a portion of a bigger research project (automated progress monitoring of a construction project), specifically on the autonomous data collection using BIM and GIS. The BIRS ontology leverages semantic web technologies to enable semantic data translation from the construction to the robotic domain. This was necessary because of the lack of a standard data format to connect BIM and ROS in both directions. Semantic web technologies have attracted researchers' attention in recent years and are evolving rapidly. The tools of implementing them are also progressing, thereby making it somewhat challenging to find the best methodology in this regard. We utilized IEEE 1872-2015 and IEEE 1873-2015 standards to develop the BIRS ontology. These standards come with their limitations which are applicable to the ontology developed by us. Nevertheless, the BIRS ontology can be further extended to incorporate MEP information for potential obstacle avoidance, or to provide additional waypoints for robot navigation.

As for the BIM-based path planner, the algorithm considers walls, columns, doors, and room information for path planning. Other building elements, especially MEP data, can be included in the path planner algorithm to provide a set of locations for the robot to go to and collect data. The BIM-based optimal path planner enables semantic navigation through a GUI for which a user-experience study needs to be carried out in future.

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