Generative Excavation Path Planning using BIM: A Simulation-based Approach with Pure Pursuit and Differential Drive Robots

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DEDICATION

To

my mother, father, brother, and sister.

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ABSTRACT

Earthmoving is ubiquitous in construction. However, persistently low availability of skilled labour and conventional techniques, especially in excavation works, has resulted in a consistent decline in construction productivity. Excavation is not new to automation; however, the focus has been on the automation of digging operations. On the contrary, excavation requires that a machine cover the whole area under consideration for successful operation instead of point-to-point movement. This research, therefore, implements generative excavation coverage path planning strategies using BIM. The generative parameters used for creating paths are the area, the size of the excavator/robot, and the number of excavators/robots. The path assessment criteria are completeness of coverage and time. The coverage path planning algorithm devised in Revit Dynamo is exported into MATLAB via Microsoft Excel to simulate differential drive robots using the pure pursuit algorithm to provide a proof-of-concept for the idea. Simulations showed that the coverage of excavation was complete with an overlap of 20-30% for the area of slope stability. The sweep pattern requires 3-5% less time than the spiral pattern. The variation is due to the different sizes of the excavators. For multiple agents, this may also vary depending on the number of agents. This approach affords greater flexibility to the planners by devising excavation strategies beforehand. Moreover, it would also help improve excavators' on-site manoeuvrability and productivity that, for years, have relied on operators' judgement and experience. Furthermore, these paths can be transmitted directly to robots to perform excavation leading to the automation of the whole process.

Keywords: Excavation, Multi-robot, Complete Coverage Path Planning, BIM.

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LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

ALS	Autonomous Loading System
AR	Augmented Reality
ABCS	Automated Building Construction System
AHP	Analytical Hierarchy Process
BIM	Building Information Modelling
BCD	Boustrophedon Cellular Decomposition
CBSE	Component-Based Software Engineering
CCPP	Complete Coverage Path Planning
CMU	Concrete Masonry Unit
CPP	Chinese Postman Problem
CRC	Collective robotic construction
CSP	Covering Salesman Problem
DCR	Distributed Coverage of Rectilinear Environments
DARP	Divide Area based on the Robots' initial Position
GPS	Global Positioning System
ICT	Information and Communication Technology
IES	Intelligent Earthwork System
IoT	Internet of Things
LADAR	Laser Detection and Ranging
LiDAR	Light Detection and Ranging
LUCIE	Lancaster University Computerized Intelligent Excavator
PMV	Predicted Mean Vote
POCSAC	Planning and Operations Control Software for Automated Construction

PPIs	Project Performance Indicators
PTP	Point-to-point
R&D	Research and Development
REX	Robotic Excavator
RFID	Radio Frequency Identification
ROS	Robot Operating System
STC	Spanning Tree Covering
STCR	Single-Task Construction Robot
THOR	Terraforming Heavy Outdoor Robot
TSP	Travelling Salesman Problem
UAV	Unmanned Autonomous Vehicle
U.S.	United States
UWB	Ultra-Wideband
Wi-Fi	Wireless Fidelity

CHAPTER 1 : INTRODUCTION

This chapter presents the rationale for the study. Starting from the background of declining productivity in the construction sector as a significant problem and emerging technologies being the most suitable solution to address this issue, it moves forward to the problem statement, which is enunciated based on the gap identified in the literature regarding emerging technologies, especially about robotic application on construction sites and their integration with BIM. The objectives are then delineated, followed by a brief section outlining the structure of the written dissertation.

1.1 Automation in Construction

It is a well-established fact that the construction industry is the most important sector of any country's economy (Bock, 2015; Hampson et al., 2014), which, according to (Arditi & Mochtar, 2000), contributes around 3 to 8 percent of the Gross Domestic Product of most nations. Ironically, it is one sector whose productivity has declined for decades (Allen, 1985; Bock, 2015). This phenomenon is further aggravated by the fact that the construction industry has lagged behind other sectors due to its slow adoption of newer technologies (Bogue, 2018; Davila Delgado et al., 2019). Therefore, it is in ever greater need of technological advancement (Melenbrink et al., 2020). The Pakistani construction industry is no different (Farooqui et al., 2008). Hence, there is an urgent need for automation in the construction industry.

Robotics is not new to construction, with robots working on construction sites since the 1980s (Castro-lacouture, 2009). However, the restriction of robots to single tasks, their lack of manoeuvrability in often unstructured construction sites, unlike factory settings, and the low quantity and quality of data available for robots to effectively perform tasks limited the rate of their adoption in the industry (Saidi et al., 2016; Vähä et al., 2013).

Advancements in BIM and sensing technology in recent years have provided solutions to these problems, spurring research in construction robotics (Davila Delgado et al., 2019; Oesterreich & Teuteberg, 2016; Vähä et al., 2013). In this regard, BIM has become the standard tool for digitalising construction data (Pan & Zhang, 2021). However, it has mostly been adopted in the preconstruction stage, with limited implementation in the construction and facility management stages (Bilal et al., 2016; Eadie et al., 2013). Furthermore, the voluminous data generated through BIM is not fully utilised during most construction projects, leading to the wastage of valuable information that otherwise could have been extracted from such data (Bilal et al., 2016; Ding et al., 2020). Integrating BIM with robotic hardware may provide an effective means of:

1. Providing the robot with high-quality information regarding the site and the structure under construction.

2. Minimizing the wastage of large amounts of data by applying BIM in the construction phase.

In this regard, (Lee et al., 2015) linked a Building Information Model (BIM) with a Single-Task Construction Robot (STCR) for building deconstruction. (Davtalab et al., 2018) developed a software platform, Planning and Operations Control Software for Automated Construction (POCSAC), by integrating BIM with a robotic platform for additive manufacturing. (Ding et al., 2020) proposed a robot system that assembled bricks in three simple configurations designed in BIM and then integrated with the robot. (S. Kim et al., 2021) integrated BIM with a Robot Operating System (ROS) to perform simulations of a robot performing painting operations only. A more recent study by (Chen et al., 2022) used BIM to export information to a physics engine for global path planning of robots on construction sites using the A* algorithm.

1.2 Excavation Automation

Almost all construction operations require excavation. Excavators are often employed where trenching, cutting, and soil removal are necessary (Hemami, 2008; Quang Ha et al., 2002; Turner, 2008). Furthermore, they are also used for lifting heavy objects and sometimes even demolition. This versatility makes excavators standard equipment on all construction projects (Eraliev et al., 2022; Sol et al., 2022).

Given the frequent use of excavators during construction, their implementation on-site in recent times has created some concerns. The process still involves significant manual labour, even though it is highly mechanised (J. Kim et al., 2020). Subsequently, working in dangerous and dusty environments during excavation poses a severe risk to the workers' safety and health (Schmidt & Berns, 2015). Furthermore, relying on conventional means of excavation operations has significantly decreased productivity (Eraliev et al., 2022; Melenbrink et al., 2020). Automation and robotics in excavation works can provide several benefits, including increased safety for both the public and the workers, uniform quality and higher accuracy than labour, increased productivity and efficiency with lower costs, and an improved work environment by eliminating noise and dust-related tasks (Ha et al., 2019; Melenbrink et al., 2020).

Excavation operations have been considered for automation for quite some time, with perhaps the first robotic excavator, REX, pioneered by (Whittaker & Motazed, 1986b) at Carnegie Mellon University. However, the research was focused only on the digging aspect of the excavation operation. This approach models the excavator boom-bucket assembly as an industrial arm to evaluate the soil and excavator mechanics. Subsequent studies by (Bradley & Seward, 1998; Halbach & Halme, 2013; Jud et al., 2019; Moon & Seo, 2017;

Pluzhnikov & Schmidt, 2012; Schmidt et al., 2010; Stentz et al., 1999) also focused primarily on this facet of excavation.

However, excavation is not just the digging and dumping process; an excavator must also traverse the area under consideration to accomplish the task. This aspect falls within the domain of mobile path planning, which further divides into point-to-point and coverage path planning (Cao et al., 1988; S. K. Kim et al., 2012). Point-to-point (PTP) path planning involves an excavator moving from a starting point to an endpoint while avoiding obstacles (Klančar et al., 2017). (S.-K. Kim et al., 2003; Schmidt & Berns, 2015) have addressed this element of excavator operations.

But point-to-point movement only partially treats excavator path planning. An excavator must move throughout the area under consideration to execute excavation. Complete coverage path planning (CCPP) addresses this problem. It is a variant of the Travelling Salesman Problem (TSP), also known as the Covering Salesman Problem (CSP) (Arkin & Hassin, 1994). A region is defined and subdivided into cells or neighbourhoods, and an agent must visit each specific cell to ensure completeness of coverage (Galceran & Carreras, 2013). An excavator's coverage path planning problem has been studied by (J. Kim et al., 2020; S. K. Kim et al., 2012) to develop an Intelligent Earthwork System (IES).

1.3 Problem Statement

From the literature, one can observe that significant research in excavator path planning has concentrated on excavator-soil interaction, which, while necessary for on-site navigation, offers little assistance to planners when developing and comparing offline path plans for autonomous robotic excavators. Furthermore, the use of Building Information Modelling (BIM) has also been limited, resulting in the wastage of a considerable amount of data that could otherwise help in coverage path planning.

1.4 Research Approach

The primary focus of this thesis is to devise a strategy to generate coverage path plans using BIM for multiple excavators. It is a well-established fact that the labour productivity of the construction sector is significantly lower than that of the manufacturing sector. Conventional techniques and a lack of automation are the main factors in this concerning fact. The case is especially true for excavation operations. Hence, this study addresses the productivity issue in the excavation process by introducing BIM and robotics.

The aim of this study is not to automate the whole excavation operation. Excavation is a collection of repetitive activities executed one after the other. These activities include moving the excavator to the excavation site, relocating the excavator to cover the area, digging, and dumping. Moreover, the dumping task requires the excavator's collaboration with the dump truck. Researchers have done considerable work to automate excavator digging-dumping operations and move excavators to the site using point-to-point path planning. Though these studies have been instrumental in automating excavation, they have limited the excavator to a static configuration. However, actual excavation operations necessitate an excavator to cover the whole site. Therefore, this research only treats the excavator relocation problem to cover the excavation area. Given that point-to-point path planning is essentially a subset of the coverage problem, this study indirectly and concurrently addresses the former aspect.

Furthermore, the offline approach, where an excavation site plan is already available, is used for coverage path planning. The source of information for generating paths is a BIM model that allows planners to provide input in producing coverage patterns based on their requirements. This approach keeps humans in the loop as planners, with autonomous robots working on-site. Simulations of the coverage path plans using multiple robot scenarios in MATLAB provide the basis for evaluating the efficacy of each pattern. Hence, the objectives of the study are as follows:

1. Identify robotic attributes which can address labour productivity issues in the construction industry.

2. Develop a coordination and communication algorithm for multi-excavator path planning using information from BIM.

3. Validate the algorithm through simulation.

In brief, the analysis of different coverage patterns on multiple robot scenarios using BIM can provide a strong base for evaluating excavator efficiency and subsequently improving the productivity of the whole process.

1.5 Thesis Structure

Chapter 1: Introduction

This chapter describes the research background, the motivation leading to the research, the problem statement, and the research objectives.

Chapter 2: Literature Review

Chapter 2 provides a detailed literature review of the study from conventional methods to improve productivity to the emergence of BIM and robotics in construction.

Chapter 3: Methodology

Methodology chapter outlines the processes through which this research was conducted. It also describes in detail the development of the complete coverage algorithm for multiple robots and its simulation workflow.

Chapter 4: Results and Discussion

In this chapter, the simulation results are discussed based on a sample site plan modelled on BIM. Distance-time graphs for each pattern are analysed and coverage analysis is performed.

The main aim of the study is outlined in this chapter. A background is provided related to declining productivity in the construction sector, especially excavation, and how automation of the process can alleviate the problem. Problem statement is enunciated followed by listing of the objective, and lastly thesis structure is briefly described.

CHAPTER 2 : LITERATURE REVIEW

A comprehensive literature review is presented in this chapter. The discussion starts with a review of the decreasing productivity trend in the construction industry. A discourse on the conventional methods the researchers have proposed to improve this declining trend follows. The Industrie 4.0 and the emerging technologies paradigm are then discussed, especially in the context of BIM and robotic applications in construction. The chapter then moves on to the studies specifically related to the thesis and concludes with the gap analysis that provides the course this study would take to address the identified gap.

2.1 Productivity trend in the construction industry

Productivity in the construction sector has become a perennial issue. Although it is one of the most influential segments of the economy, accounting for as much as 3 to 8 per cent of the GDP of most nations (Arditi & Mochtar, 2000), its productivity has been in a constant state of decline, with only some brief improvements due to periods of economic boom (Teicholz, 2013). Perhaps the last time the construction sector experienced growth in productivity in the U.S. was in the 1960s when it reached its peak (Stokes, 1981). Since then, it has shown no improvement and has deteriorated (Allen, 1985; Barbosa et al., 2017; Teicholz, P., Goodrum & Haas, 2001).

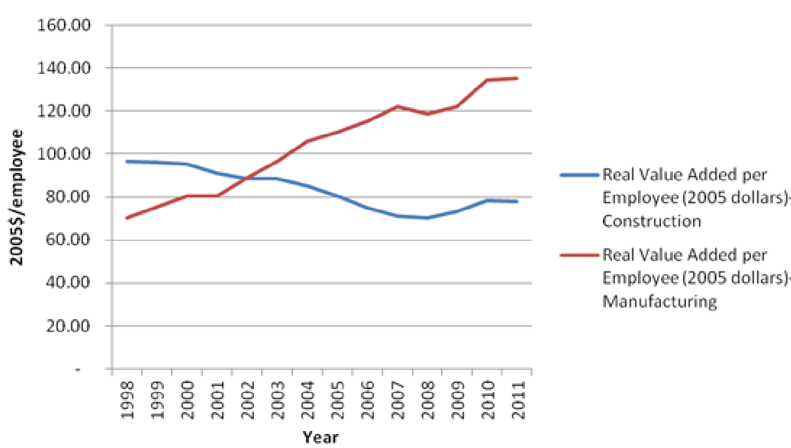

Figure 2.1: Productivities of the construction and manufacturing sectors'. (Source: (Teicholz, 2013))

Figure 2.1 compares the productivity of the construction and manufacturing industries in the U.S. (Teicholz, 2013). It is apparent from the figure that the manufacturing sector has performed far better than the construction sector in terms of productivity growth. A study by (Abdel-Wahab & Vogl, 2011) to measure construction productivity trends in the U.S., Europe, and Japan also indicated that productivity decline in the construction industry was not an endemic issue but was persistent throughout the globe. The same was highlighted by (Bock, 2015; Handbook, 2012) separately, which showed declining productivity in the Japanese construction industry, as shown in Figure 2.2. Hence, it is evident that the construction industry needs methods and techniques to address the pressing issue of constant productivity decline.

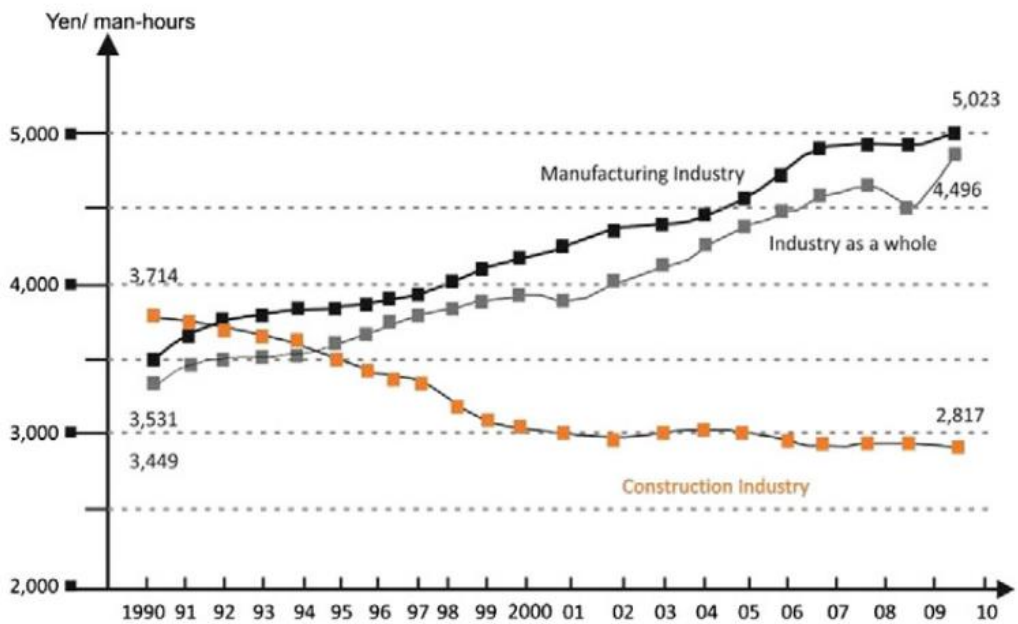

Figure 2.2: Comparison of the Japanese construction industry with the manufacturing and whole industries. (Source: (Handbook, 2012))

2.2 Conventional methods to improve productivity

2.2.1 Site Management Techniques

Concerning construction site management (Thomas et al., 1989) studied the effects of material management on construction projects, where they identified that organising storage areas, expediting material delivery, housekeeping, predicting material availability, and efficient material handling were the key factors to improve productivity on site. With the help of these factors, the authors developed an integrated material management program for construction sites. (Halligan et al., 1994) evaluated the effects of external and environmental factors on labour productivity. They provided an Action-response Model through which the management could identify the primary causes of loss of productivity and take measures to counter them. (Christian & Hachey, 1995) and (Christian & Hachey, 1996) developed a system, Personal Consultant Plus, which calculated production rate estimates for contractors. It was a computer-assisted model which would estimate production rates for delaying factors which the contractor identified as might vary the productivity of tasks. (Thomas & Napolitan, 1995) provided a quantitative analysis of changes in the scope of construction to labour productivity by collecting data on 522 workdays on three projects. The results showed that there was a cumulative loss of 30% of labour productivity due to changes and the resulting disruptions due to them. They concluded that efficient management of change can reduce productivity loss during projects. (Thomas et al., 1999) in their research showed that labour productivity was most affected when there were disruptions between the material delivered and assembly by investigating three different projects. The study was followed by (Thomas et al., 2002), where the authors investigated the concept of lean delivery to reduce the variability in workflow to improve construction labour productivity. In this regard, (Koskela, 1992) had already provided general lean construction principles. (Hanna et al., 2004) proposed a method to quantify the impacts of changes on labour productivity by considering six factors. The study also performed a sensitivity analysis to evaluate the significance of all the factors over one another. (Mohamed & Srinavin, 2005) devised a model which could predict changes in labour productivity due to temperature variations in the environment based on the Predicted Mean Vote (PMV) index that incorporated a combination of three items:

1. Thermal environment.
2. The task being performed.
3. Clothing of the crew.

The model simulates the conditions that would bring the worker comfort into the optimal range to increase productivity. (Doloi, 2008) provided an Analytical Hierarchy

Process (AHP) based model that would help managers to identify the most significant issues causing productivity loss. Addressing any one of these issues would significantly improve labour productivity.

2.2.2 Conventional methods reaching their technological limit

Recent research, however, has indicated that conventional technologies have hit their technological ceiling, meaning they can no longer be improved beyond their current

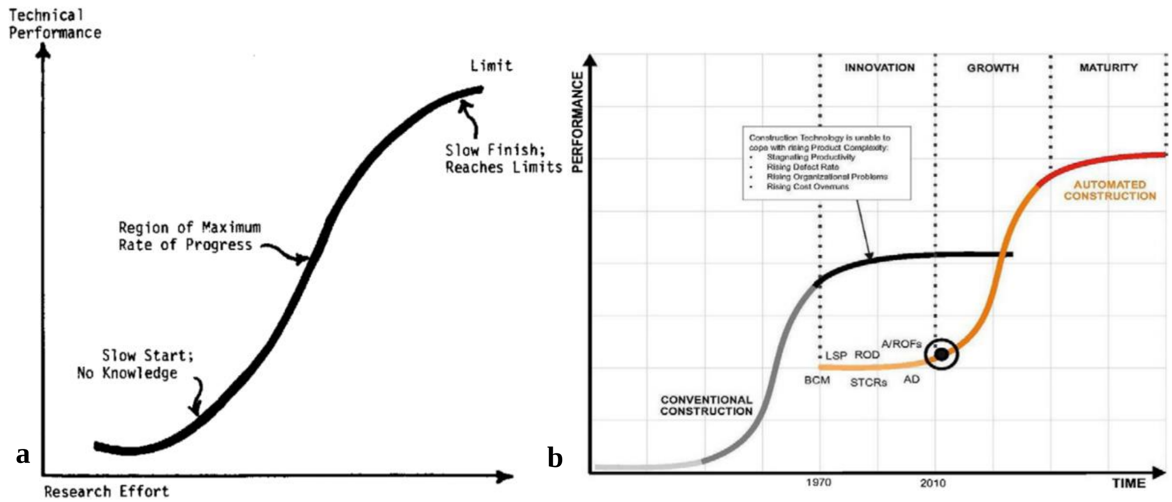

Figure 2.3: (a) Technological transition S-curve (Foster, 1985) , (b) Technological transition curve applied to construction (Bock, 2015).

state. This technological stagnation of traditional methods is succinctly described by (Foster, 1985) using an S-curve in Figure 2.3 (a), which demonstrates that further technological advances become increasingly challenging to achieve after a certain point. (Bock, 2015) further applies this concept to the construction industry in Figure 2.3 (b), highlighting that the industry has experienced a consistent decline in productivity and growth due to the limitations of conventional technologies.

Emerging technologies such as robotics and BIM have the potential to improve productivity and efficiency significantly. By automating tasks previously done by humans, robotics can help reduce the time and cost associated with construction projects while improving safety and quality. Furthermore, digitalising building information provides an efficient means to speed up processes that, hitherto, had been highly tedious and time-consuming. These new technologies provide a promising pathway for the future of construction, offering the potential to overcome the challenges posed by the limitations of traditional methods.

2.2.3 The Onset of Automation in the Construction Industry

Conventional use of automation to improve productivity has relied on monitoring and control methods that depend on data collected from construction sites through sensing devices to measure project performance indicators (PPIs), for example, cost, schedules, material use, etc. (Navon, 2007). These technologies include Radio Frequency Identification (RFID), Global Positioning Systems (GPS), Wireless Fidelity (Wi-Fi), and Ultra-Wideband (UWB), which are forms of positioning and visual sensing technologies. In addition to these video and audio technologies, Laser Detection and Ranging (LADAR) and Light Detection and Ranging (LiDAR) are also used for positioning and location purposes (Castro-lacouture, 2009; Navon, 2007). (Navon, 2007) investigated the use of these sensing technologies to monitor material and labour. The study's conclusion highlighted that tracking and controlling material movement through these devices is significantly more manageable than locating labourers on construction sites. RFIDs were also used by (Jaselskis & El-Misalami, 2003; Wang, 2008) to track material supply for efficient procurement and inspection of material quality. Both had the objective of increasing productivity on-site. (Caldas et al., 2006) applied GPS for locating materials on construction sites, thereby improving worker productivity by reducing idle time and work disruptions due to delayed availability of materials. (Zhai et al., 2009) quantified the effects of integrating automation and information technology on construction sites on labour productivity by investigating the implementation of 4 trades (concreting, structural steel, electrical, and piping). The results showed a strong positive correlation between automation and labour productivity. These sensing technologies have also been integrated with heavy machinery to improve productivity. The Caterpillar AccuGrade is a prime example of heavy machinery that uses GPS technology and automatic blade positioning to enhance the precision of site work operations (Castro-lacouture, 2009).

Building Information Modelling (BIM) is also an automation platform which provides complete information relating to the properties of building elements. In addition, it shows the visual model along with the sequence of arrangement of these elements (C. Eastman, P. Teicholz, R. Sacks, 2008). Its implementation is discussed in detail in 2.5.

2.3 Industrie 4.0 and emerging technologies in construction

The revolutionary Industry 4.0 paradigm, known by its different variations such as Smart Manufacturing or Smart Production, has been vigorously supported by various private enterprises and the governments of the developed world to mark a move towards increased use of ICT in the industrial sector (Oesterreich & Teuteberg, 2016). This paradigm shift relates to the digitization and automation of industrial processes (Oesterreich & Teuteberg, 2016), which allows for the creation of flexible and autonomous networked systems which, working in real-time, collaborate to construct products faster with increased efficiency and precision while minimizing wastage simultaneously (Bock, 2015).

The increase in the automation processes in the manufacturing industries worldwide, spurred by the Industrie 4.0 paradigm, has thrown into sharp relief the lack of state-of-the-art technologies in the construction sector (Bock, 2015; Oesterreich & Teuteberg, 2016). This backwardness is understandable as the construction process, unlike other industries, is multi-variegated, complex, involves multiple stakeholders, requires diverse materials and the product is always unique (Bock, 2015). Add to that minimal R&D investment and the reluctance of the sector to adopt newer methods. All this has led to technological stagnation in the construction sector.

Given this, efforts are underway to address the backward tendency of the construction industry. The work has been mostly related to the automation of information handling via computers, focusing on the use of Building Information Modelling (BIM). However, employment of BIM has been restricted to pre-construction or the design stage, although application in other phases of the building lifecycle is also underway (Bilal et al., 2016; Melenbrink et al., 2020; Vähä et al., 2013). In addition to this, additive manufacturing techniques such as 3D printing projecting a new dimension of prefabrication are witnessing an increase in interest concerning construction activities (Craveiro et al., 2019), and on-site sensing for geometric quality assurance is also being evolved for construction needs (M. K. Kim et al., 2019).

In robotics, the construction industry lags far behind (Melenbrink et al., 2020). Although research in construction robotics and automation started as far back as the 1980s (Ardiny et al., 2015; Castro-lacouture, 2009), progress has been slow due to the project-specific nature of the industry and the short-sighted focus of construction companies, which focus more on temporary gains than long-term payoffs (Castro-lacouture, 2009). Hence, it is essential to raise awareness among industry professionals about the viability of robots as a solution to the issues prevalent in the construction sector. The subsequent sub-section will delve into the application of robots in the construction industry.

2.4 Robotic application in construction

Robotic applications in the field of construction fall into three distinct phases:

1. Site Preparation.
2. Substructure anchoring.
3. Construction of superstructure elements (Melenbrink et al., 2020).

The following subsections explain each phase in detail, with potential for research highlighted in each of them.

2.4.1 Site Preparation

Site preparation clears land of debris, rubbish, or demolition material before construction starts and includes earthmoving activities for excavation purposes (Melenbrink et al., 2020). Conventional heavy equipment has become the solution for site preparation, and retrofitting them with robotic applications is usually the norm (Melenbrink et al., 2020). In this regard, the focus has been mainly on teleoperated robots, which require manipulation by an operator from a distance, as shown in Figure 2.4. These robots have proven beneficial in dangerous environments, especially where there are safety concerns for direct human intervention, such as disaster sites (Kitahara et al., 2019; Nagatani, 2014). Companies such as Volvo, Caterpillar, and Komatsu have developed their respective models of heavy equipment with some degree of autonomy. For example, Volvo's Electric Site project uses autonomous haul units with human-operated wheel loaders on sites (Volvo Information Press, n.d.). THOR (Terraforming Heavy Outdoor Robot), also a project of Volvo, is an excavator that manipulates the bucket without the assistance of an operator (Schmidt & Berns, 2015). The study demonstrated that THOR could work with autonomous haulers and wheel loaders in the Volvo Electric Site project (Volvo Information Press, n.d.). However, the excavator and loader can only work on pre-planned paths without autonomous coordination with the dumpers (Melenbrink et al., 2020).

There has also been the development of novel technologies to address site preparation automation from the basic principles rather than just installing robotic applications on conventional machinery.

Figure 2.4: A teleoperated heavy equipment with a jackhammer attached developed by BROKK (Melenbrink et al., 2020).

REX was perhaps the first excavator to have a substantial degree of autonomy. The machine employed a supersonic jet cutter to dislodge material and avoid direct contact with it. This technique ensured minimal damage to the equipment (Whittaker & Motazed, 1986a).

In addition to this, much work has focused on site preparation for extra-terrestrial environments such as the Moon and Mars (Boles et al., 1993). The NASA Chariot mission, a space probe launched to explore the moon's surface, was installed with lightweight dozer blades to ascertain the feasibility of digging into the lunar surface (Mueller et al., 2009). Another study by (Halbach et al., 2013) involves simulating robotic regolith mining for the initial construction phase of the Mars Homestead Project, which includes excavating the sloped area for masonry structures and storing the regolith for future resource utilization. (Thangavelautham et al., 2017; Thangavelautham & Xu, 2021) have developed an energy model for base construction and ground preparation. The proposed model considers site preparation operations such as terrain clearance, excavation, and levelling, which are crucial for constructing an infrastructure to support the base using a multi-robot system. Various other studies have also concentrated on lunar or Martian site exploration and preparation, and it may be likely that further development in robotics for this particular phase of construction would come from this research (Melenbrink et al., 2020).

2.4.2 Substructure Anchoring

The construction activity that follows site preparation is the sub-structure or anchoring work. Generally, the process followed in shallow anchoring is formwork, rebar placement, and concreting (Melenbrink et al., 2020). The other methods are piling or post-driving. These methods, not as complicated as shallow anchoring, are more suitable for unsupervised autonomous construction, such as placing fences or other temporary structures (Melenbrink et al., 2020).

In the shallow anchoring process the research has been mostly related to automating the concrete pumping operation such as the Ergonic system, developed by the company Putzmeister, or its counterpart Smartronic created by Zoomlion, which are teleoperated concrete pumps having semi-autonomous boom control, see Figure 2.5, which allows for more accurate placement of concrete, and also decreases boom vibrations, hence extending life (Melenbrink et al., 2020).

In the piling method, a few examples of automation are present (Melenbrink et al., 2020). (Hovila, 2012) provided results for the autonomous impact pile driving operation by introducing automation in the positioning system, measuring resistance offered by the pile-ground interaction in real-time, and cutting these piles after forcing them into the ground. Heavy equipment, such as pile drivers and front loaders, perform post-driving operations at the level of fencing, or the activity is manually performed (Melenbrink et al., 2020). There is evidence in the literature that there is much room for unsupervised automation in this field, specifically in the anchoring phase of construction (Melenbrink et al., 2020).

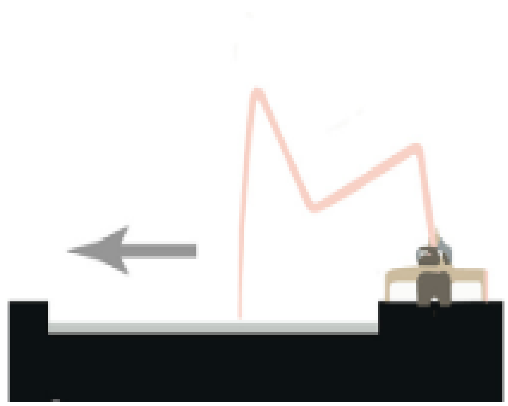

Figure 2.5: Concrete pump with a semi-autonomous boom which allows to fix the vertical height while the boom is moved horizontally (Melenbrink et al., 2020).

2.4.3 Superstructure Construction

Construction of the superstructure is perhaps the most expensive and time-consuming stage, and it is this stage where the stakeholders witness the final constructed product. Due to this fact, researchers have focused more on automating this aspect of construction than any other (Melenbrink et al., 2020). Gantry systems, adopted from the manufacturing sector, have been considered a possible choice for autonomous construction (Melenbrink et al., 2020). One such system, the Automated Building Construction System (ABCS), implemented by Japanese constructors Obayashi Corporation, could assemble all building components (Ikeda & Harada, 2006). Similarly, another Japanese contractor, Shimizu, see Figure 2.6, developed their own version of a gantry system known as SMART (Castro-lacouture, 2009). These systems, however, first require on-site assembly, which is impossible without human supervision. Hence, gantry systems not only increase the cost of construction (Castro-lacouture, 2009) but also have limited degrees of freedom (Melenbrink et al., 2020).

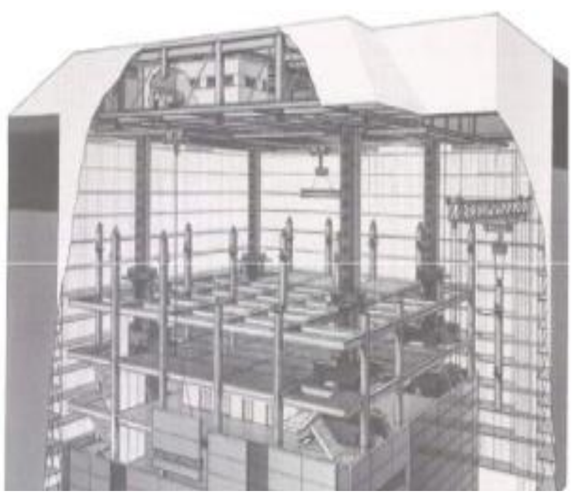

Figure 2.6: SMART robot gantry system developed by Shimizu (Melenbrink et al., 2020).

On the other hand, mobile robots have more manoeuvrability than gantry systems, need no assembly on-site, and can build much larger structures than themselves (Melenbrink et al., 2020). In this regard, Concrete Masonry Unit (CMU) construction has been the focus of researchers through mobile robots. Single-task construction Robots (STCRs) such as BRONCO (Pritschow et al., 1996) have been developed for tasks such as bricklaying and an Australian company, Fastbrick Robotics, has created a robot, Hadrian X, which conveys and places CMUs according to a pre-defined path with minimal human intervention as illustrated in Figure 2.7 below (Melenbrink et al., 2020).

Figure 2.7: Hadrian X conveying concrete masonry units on a wall using its long telescopic boom (Melenbrink et al., 2020).

The other category of mobile robots used alternatively to STCRs is the terrestrial type (ground-based rovers). These types of robots are more versatile with respect to emulating human-performed tasks and offer more precision with efficient power utilization (Melenbrink et al., 2020). One such type of end effector robot was designed by (Doerstelmann et al., 2015) to construct a fibre composite shell over a pneumatic mould. The Mesh Mould project also utilized an end effector robot which is capable of bending, cutting, and welding rebars in a project codenamed Dfab House, during the execution of which it built load-bearing walls (Dörfler et al., 2019). However, the concrete was placed and cured through human intervention.

2.4.4 Collective Robotic Construction (CRC)

Collective robotic construction (CRC) inspired by biological elements and deriving insights from nature's builders has also recently gained (Petersen et al., 2019). The TERMES robots developed by (Werfel et al., 2014) make use of this very concept to construct structures larger than themselves. The robots combine infrared and sonar sensors, using the structure as a reference to localize and guide subsequent construction activities. This idea has been demonstrated in lab settings using customized foam blocks (Werfel et al., 2014). This approach is still in its formative stages and has much potential for research (Ardiny et al., 2015; Melenbrink et al., 2020; Petersen et al., 2019).

Figure 2.8: UAVs being used to assemble a simple fibre structure using custom-made lightweight material (Wood et al., 2019).

Researchers have also developed Unmanned Autonomous Vehicles (UAVs) to perform on-site construction, but most of the research in this regard has been demonstrated as a proof-of-concept only (Erlandsen, 2017; Melenbrink et al., 2020). Quadrotor UAVs have been used to assemble lightweight material simulating construction material to form structures (Lindsey et al., 2012; Wood et al., 2019), as shown in Figure 2.8. However, these robots are not power-efficient and are still incapable of lifting heavy loads, not to mention the complications of their aerodynamic capabilities (Ardiny et al., 2015; Melenbrink et al., 2020). Moreover, studies are also present in the literature that show robots performing additive manufacturing to automate construction. (Jokic et al., 2014) used terrestrial robots in the Mini-builders project for additive manufacturing, as shown in Figure 2.9. The project used three robots to manufacture a ceramic structure using the 3-D printing technique. However, the robots required human supervision and could not coordinate among themselves.

2.5 Building Information Modelling (BIM)

2.5.1 Data visualization using BIM

BIM (Building Information Modelling) is an exciting advancement in the architecture, engineering, and construction (AEC) industry that creates one or more precise digital representations of a building. These digital models of the building give efficient tools to designers throughout the design process, delivering better analytical capabilities and control over manual techniques. When finished, these computer-generated models contain the precise geometry and data required to assist many parts of the building's construction, manufacturing, and procurement processes. Furthermore, due to the availability of all architectural, structural, mechanical, and electrical information available in the model as activities, it is possible to show clashes in the designs, virtually leading to better planning of the building facility (C. Eastman, P. Teicholz, R. Sacks, 2008).

Figure 2.9: The Mini-builders project using 3 distinct but collaborating task-specific robots to construct a ceramic structure (Jokic et al., 2014).

The pre-construction phase of the construction process has benefited the most from BIM. However, construction and facility management stages of the building lifecycle are now being incorporated with BIM to effectively monitor the building processes (Bilal et al., 2016). (Goedert & Meadati, 2008) used BIM for documenting the construction process to relate the as-built information to the building model. (Chiang et al., 2015) incorporated the power utilization data of building residents into BIM to supply the occupants with their energy usage patterns and compare them to baseline Ecotect so that they might be able to save power. (Isikdag et al., 2007) combined Geographic Information System (GIS) with BIM to develop an effective fire response mechanism. (Yeh et al., 2012) used a wearable device for augmented reality information sharing with on-site staff through BIM. (Genty, 2015) demonstrated the concept of virtual reality through BIM. In the project, Callisto-Sari, an immersive room was built that afforded a 3D visualization of the as-built structure before the start of construction activities. Furthermore, the viewers could interact with the model, getting a realistic overview of the facility. (Meža et al., 2014) also worked on a similar concept; however, their study implemented the idea of using augmented reality (AR). They used component-based software engineering (CBSE) to process BIM data to visualize at any point on the site with high precision using a mobile device.

(Kai et al., 2018) employed BIM with the Internet of Things (IoT) to refine all the lifecycle activities in a steel bridge construction project. The authors presented a framework to show that by using BIM and IoT together, real-time construction data is shared among all the stakeholders, allowing timely responses to situations and dynamic decision-making. This framework was named Smart Steel Bridge Construction.

2.5.2 Integration of BIM with Robots

Combining BIM with robotic algorithms is still in its nascent stage. This fusion of BIM and robots taps into the immense information-generating potential of BIM and the robot's hardware capabilities to handle large amounts of data. Integrating BIM with robotic hardware may provide an effective means of:

1. Supplying the robot with precise site and building data.
2. Reducing waste of vast volumes of data created via BIM by utilising this data throughout the building lifecycle phase.

In this connection, (Lee et al., 2015) linked a Single-Task Construction Robot (STCR) for building deconstruction with (BIM). Planning and Operations Control Software for Automated Construction (POCSAC), a software platform created by (Davtalab et al., 2018), combines BIM with a robotic platform for additive manufacturing. An autonomous system that constructed bricks in three straightforward configurations created in BIM and then connected with the robot was also proposed by (Ding et al., 2020). (S. Kim et al., 2021) combined BIM with a Robot Operating System (ROS) to simulate a robot that could only execute painting tasks. However, there is still significant room for research in this field, especially about BIM and its integration with multiple robots.

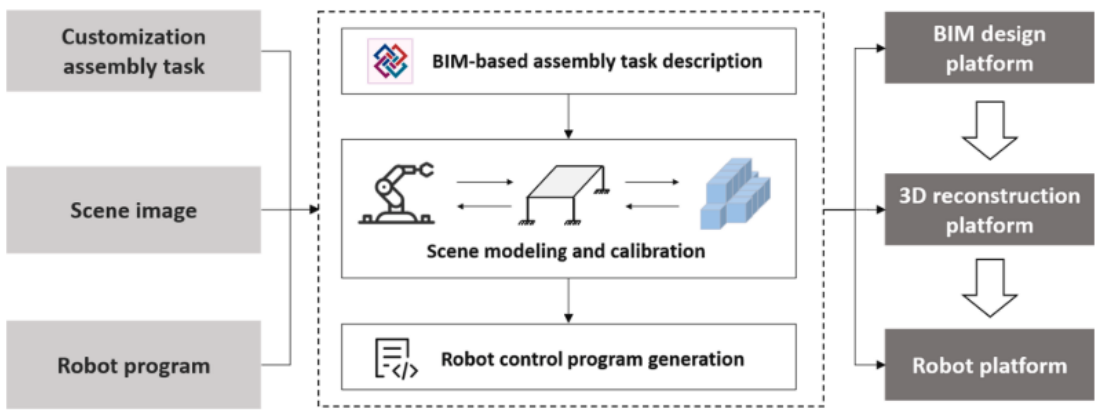

Figure 2.10: BIM-robot task planning methodology (Ding et al., 2020).

2.6 Related Works

The primary focus of this thesis is to devise a strategy to generate coverage path plans using BIM for multiple excavators to address the productivity issue in the excavation process by linking BIM and robotics. Therefore, the forthcoming subsections will examine the works in the literature closely related to this topic.

2.6.1 Automated Earthmoving

The Carnegie Mellon Robotics Institute developed the REX, possibly the first robotic excavator, after extensive research in automating excavation to dig ground while avoiding any underneath utilities to make the process less hazardous (Whittaker & Motazed, 1986b). After that, (Bradley & Seward, 1998) created the Lancaster University

Computerized Intelligent Excavator (LUCIE), which automated bucket movement for different soil types. The Autonomous Loading System (ALS), developed by (Stentz et al., 1999), combined the digging and dumping process to automate the excavator bucket motion as performed during excavation. (Pluzhnikov & Schmidt, 2012; Schmidt et al., 2010) devised a behaviour-based strategy to automate the excavation process for various site conditions by considering the motion of the excavator bucket with different soil types. As part of Volvo's autonomous excavator project, Terraforming Heavy Outdoor Robot (THOR), this study was further developed by (Schmidt & Berns, 2015) using simulations and an updated version of the A* Algorithm for safe point-to-point movement and position transition of an excavator. (Halbach, 2019; Halbach & Halme, 2013) created an algorithm for surface earthmoving and used the Avant 635 wheel loader as a real-world model to test it. The algorithm uses path planning and scooping operation scripts that simulate complete coverage. However, the loader returns to its default position before scanning its front for additional snow removal, resulting in longer paths. (Moon & Seo, 2017) used BIM in the same way to develop plans for digging tasks.

It is apparent from the literature that the predominant emphasis has been on developing a bucket-excavator interface similar to a robotic industrial arm or on motion planning for surface activities. The mobile path planning aspect has not received much attention. (S.-K. Kim et al., 2003) have worked on global path planning for earthmoving equipment on construction sites by developing an improved SensBug algorithm that generates a collision-free path for the equipment to trace to the excavation area. Working on the Intelligent Earthwork System (IES), (J. Kim et al., 2020; S. K. Kim et al., 2012) developed complete coverage path planning (CCPP) algorithms for an autonomous excavator. (J. Kim et al., 2020) have developed an offline Complete Coverage Path Planning algorithm based on Boustrophedon Cellular Decomposition and the A* Algorithm to avoid excavator isolation. While making a path, the Wavefront Path Transform Algorithm created by (Zelinsky et al., 1993) was used to account for the availability of a dump truck. A revised A* Algorithm comparable to the BA* Algorithm proposed by (Viet et al., 2013) alleviated the isolation or deadlocks that limited the excavator's mobility. The authors simulated five case study scenarios to compare the path-planning strategies eight professional excavator operators would adopt during excavation.

2.6.2 Multi-robot Coverage Path Planning

A complete coverage path ensures that a machine covers all regions of a given area. This type of navigation has a variety of applications, including floor cleaning, maritime exploration, field harvesting and ploughing, grass mowing, structural examination, and mine removal (Choset, 2000). The Coverage Path Planning (CPP) problem is a version of the traditional Travelling Salesman Problem (TSP), also known as the Covering Salesman Problem, in which each of the salesman's "n" clients is willing to meet in a "neighbourhood" (Arkin & Hassin, 1994). To achieve complete coverage, the agent must visit every point in the free space (Choset, 2001; Galceran & Carreras, 2013).

The coverage algorithms can be classified according to the completeness of the free space coverage, as heuristic or complete, or according to the knowledge provided to the agents beforehand (Choset, 2001; Galceran & Carreras, 2013). The second type is further subdivided into offline when the information presented to the agent is *"a priori"* and unchangeable, and online, where the agent has little or no prior knowledge of the environment (Choset, 2001). Furthermore, deploying several agents for these activities can not only improve the system's coverage efficiency but also increase its robustness, meaning that the system can keep performing even after the failure of any agent (Karapetyan et al., 2017).

(Kurabayashi et al., 1996) proposed an offline multi-robot coverage strategy based on a Voronoi diagram-like and boustrophedon approach. To evaluate efficiency, they created a cost function based on the path lengths of each robot. (I. M. Rekleitis et al., 1997) used a visibility graph-like decomposition space to enable coverage with numerous robots.

The goal is to remove odometry mistakes by utilising the robots as beacons for one another. (Butler et al., 2000) proposed a collaborative sensor-based coverage system DCR (Distributed Coverage of Rectilinear Environments). DCR runs independently on all the robots in a team, with each robot having a rectilinear shape (square or rectangle). These robots cover a shared and connected world with rectilinear barriers and detect them purely by touch sensing. The algorithmic separation of collaboration and coverage is the central concept of DCR. This distinction allows a coverage strategy to be applied to a single robot in a cooperative situation, making it considerably easier to establish coverage. Using multiple robots, (Easton & Burdick, 2005) put forth a method that covered the boundaries of a 3D structure. The inspection of separated blade surfaces inside a turbine is represented graphically, with each robot's inspection pathways pre-planned using a heuristic search. The planned routes share the inspection work equally among the robots while providing comprehensive border coverage. (I. Rekleitis et al., 2008) extended the Boustrophedon Cell Decomposition approach (Choset, 2000; Choset & Pignon, 1998) from single robots to multi-robot systems. Depending on the restrictions of robot interaction, the authors presented two types of algorithms: distributed coverage and collaborative coverage. Both methods employ sensor-based methodologies and assume an unknown environment. In this technique, an auction mechanism to calculate the shortest path avoids repeated coverage and increases robot team cooperation. (Janchiv et al., 2013) in their study used flow networks (directed graphs) to address the CCPP problem. Exact cellular decomposition divides the environment map into cells, and each cell broken at an obstacle intersection and rejoined again at its end acts as a node for the robots to visit. Navigation within the cell is possible through pre-created templates. (Fazli et al., 2013) employ the Art Gallery Problem to attain visual coverage. Because the 'static guards' are dispersed around the area, stationing a robot at each guard station would offer complete 'visual' coverage to the entire space.

(Karapetyan et al., 2017), in their research, implemented the Chinese Postman Problem (CPP), a modified variant of the Travelling Salesman Problem (TSP). This method characterized optimality as a MinMax problem, in which offline job allocation minimized the longest path across a set of robots to maintain coverage completeness. The authors offered two heuristic approaches. The first, Coverage with Route Clustering, uses exact cellular decomposition to compute an Eulerian path within the graph to solve the CPP. The algorithm then divides this path among a set of robots for coverage. Coverage using Area Clustering, the second option, uses a greedy algorithm to partition cells equally among the robots for covering the cell area and then arrange according to the proximity of the robots to a specific cell. Divide Area based on the Robots' initial Position (DARPs), proposed by (Kapoutsis et al., 2017), aims to optimize the multi-robot coverage problem by separating areas into clusters depending on the number of robots and their beginning positions. The area clusters were discretized into cells using the approximate cellular decomposition technique. The Spanning Tree Covering (STC) Algorithm developed by (Gabriely & Rimon, 2003) was utilized in the second phase to attain completeness and efficiency in coverage. (Azpúrua et al., 2018) modified the approximate cell decomposition method by dividing the free space into hexagonal cells rather than square-shaped ones. The process involves splitting the environment into hexagonal cells, which are then grouped and allocated to various Unmanned Aerial Vehicle (UAV) teams for geographical surveys. After that, a path-planning algorithm generates effective coverage paths within each cell, allocating varied heights to the UAVs to avoid collisions. The technique has been evaluated using both simulated and actual experiments. In their study, (Lin & Huang, 2021) explored the application of multi-robot systems to achieve complete online coverage across three different map designs: simple geometric layouts, home environments, and large open spaces. Their objective was to reduce repeated visits to the same regions to decrease the overall computation time required for comprehensive coverage. For this, the authors introduced a novel cost function that assesses local coverage improvements for global optimization. Their experiments conducted in diverse environments contributed to the development of a collaborative CCPP (Complete Coverage Path Planning) technique for multi-robot systems through incremental exploration minimization.

2.6.3 BIM-based Robotic Path Planning

BIM has been instrumental in streamlining the workflows for construction projects, affording greater flexibility in data manipulation (C. Eastman, P. Teicholz, R. Sacks, 2008). However, the vast potential of BIM remains untapped (Ding et al., 2020). Using BIM models to provide the correct pathways for robots is one such application. (S. Kim et al., 2021) created task plans for a painting robot using BIM and simulated them using ROS (Robot Operating System). (Tan et al., 2021) collected photographs of a building on the Shenzhen University campus for structural examination using an Unmanned Aerial Vehicle (UAV). They adopted a model-based (offline CCPP) technique where they used the BIM model to produce navigation perspectives for complete coverage of the building façade. (Chen et al., 2022) did a more recent study on this, employing BIM to export information to a physics engine for global path planning of robots on building sites using the A* Algorithm.

2.7 Gap Analysis

Given the above literature, this study performed a gap analysis to identify a niche in the recent research on BIM, robotics, and construction activities as shown in Table 2.1. The characteristics that were selected for this purpose were:

1. Excavation is the target construction activity to automate since it mainly includes repetitive tasks, which are ideal for automation.
2. Complete coverage path planning as a mode of robotic application for the activity since excavation requires coverage of the whole area under consideration.
3. BIM as the path planner.
4. Multiple robots for optimization.

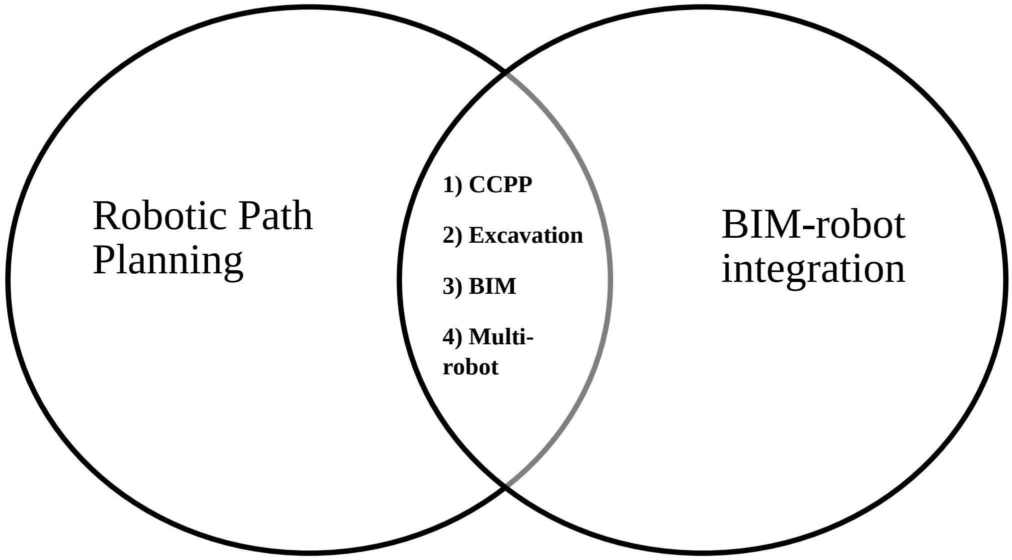

Figure 2.11: Research gap Venn diagram.

Table 2.1: Gap Analysis.

Author	Sr. #	Article name	Characteristics			
			Excavation	**Complete Coverage Path Planning (CCPP)**	**Multi-agent system**	**BIM**
S. K. Kim et al., 2012	1	Intelligent navigation strategies for an automated earthwork system.	YES	YES	NO	NO
Moon & Seo, 2017	2	Virtual graphic representation of construction equipment for developing a 3D earthwork BIM.	YES	NO	NO	YES
Halbach, 2019	3	Autonomous Area Clearing with a Robotic Wheel Loader.	YES	YES	NO	NO
J. Kim et al., 2020	4	Task planning strategy and path similarity analysis for an autonomous excavator.	YES	YES	NO	NO
Tan et al., 2021	5	Automatic inspection data collection of building surface based on BIM and UAV.	NO	YES	NO	YES
Azpúrua et al., 2018	6	Multi-robot coverage path planning using hexagonal segmentation for geophysical surveys.	NO	YES	YES	NO
Lin & Huang, 2021	7	Collaborative complete coverage and path planning for multi-robot exploration.	NO	YES	YES	NO
This Research	8	**Generative Excavation Path Planning using BIM**	YES	YES	YES	YES

From this, it was found that studies were conducted on excavation and its integration with BIM and robots. Similarly, coverage path planning has been implemented using multiple robots, but not for excavation. Figure 2.11 illustrates this gap with the help of a Venn diagram. So, this research will focus on developing a generative coverage path planning strategy using multiple robots for excavation purposes.

The chapter presented the literature review that has been conducted for this dissertation. The declining productivity trend in construction and the traditional construction techniques employed to rectify the falling productivity are discussed. Furthermore, emerging technologies, specifically robotics and BIM, are reviewed that can effectively increase construction productivity. Finally, previous studies and gap analysis are put forward that provide the basis for this research.

CHAPTER 3 : RESEARCH METHODOLOGY

This chapter describes the detailed methodology devised to carry out this research. An overview of the research design provides the steps undertaken to conduct the research, starting from the preliminary phase, where the topic was selected till the validation of the algorithm using simulations on MATLAB. Factors affecting labour productivity and the benefits of robots in the construction sector are discussed. Then, details of the coverage path planning algorithm on BIM are provided, along with its generative parameters. Finally, the process to run simulations in MATLAB is described in detail.

3.1 Research Design

Excavation is a tedious and time-consuming process that automation can make more efficient and productive. To achieve this, a new and innovative methodology is proposed in this research, which involves creating coverage paths for multiple excavators using BIM technology. These paths are created using Sweep and Spiral Pattern templates, which are divided based on the number of agents inputted by the user to generate new routes for each excavator. The system evaluates the time required to cover each path by running robotic simulations on MATLAB, allowing for accurate estimates of the time needed for each excavation operation. By automating the excavation process, this methodology provides a more efficient and cost-effective solution to site excavation.

Figure 3.1 provides a comprehensive overview of the approach followed in conducting the research. The process included four distinct phases, each with its objectives and tasks. The initial phase involved preliminary work to establish the study's groundwork. The second phase was focused on identifying and selecting the most suitable path-planning strategy for the research. In the third phase, an optimization mechanism was chosen to enhance the efficiency of the process. Finally, in the fourth phase, Building Information Modelling (BIM) was integrated to perform a simulation-based case study using MATLAB.

3.1.1 Preliminary phase

The preliminary phase in this study involved the literature review, which was the basis for the gap analysis that identified the problem. The problem identified had two aspects: the general aspect highlighted the declining productivity in the construction sector, and the conventional techniques used to treat this problem are no longer effective. The second aspect was identifying the construction process that can be targeted to increase productivity. The excavation process was selected since it is performed in almost all construction works and is executed using hydraulic excavators that, though they are powerful and versatile, have undergone limited automation. Emerging technologies provide a solution to these problems. BIM was used as the planner to create paths for excavator(s) to traverse that can be implemented on both excavators and robots, automating the operation. This procedure finally culminated in selecting the field of the study, "Excavation path planning using BIM".

3.1.2 Selecting a Path Planning Strategy

Once "Excavation Path Planning using BIM" was decided as the field of research, the next step was to investigate the different path planning strategies that were prevalent. The literature identified two fundamental path-planning strategies.

1. Point-to-point (PTP) Path Planning
2. Complete Coverage Path Planning (CCPP)

Point-to-point (PTP) path planning is a technique that involves searching for an optimal path for an agent to move from a starting point to an endpoint while avoiding obstacles in the environment (Klančar et al., 2017). This technique is commonly used in robotics and autonomous systems to ensure safe and efficient navigation. Complete coverage path planning, on the other hand, first divides a region into cells and requires an agent to visit each cell to ensure that the entire area has been covered (Galceran & Carreras, 2013). Therefore, the movement of the excavator was automated using complete coverage path planning since excavation requires complete traversal of the area to be excavated rather than moving from one location to another.

3.1.3 Model Optimization

Following the selection of the path planning strategy that would be the focus of this study, one further step was to optimise it. Complete coverage path planning divides the area under consideration into cells, with each cell forming a waypoint for the excavator or robot to follow. Since optimisation requires each waypoint to be visited once without repetitive visits, this takes the form of a generalised Travelling Salesman Problem called the Covering Salesman Problem. Therefore, to solve the problem, Sweep and Spiral templates were used to allocate waypoint clusters to the excavator(s) or robot(s). These templates provided a way around the issue of repetitive visits. Next, to increase the efficiency of the process, it is necessary to decrease the time. For this, multiple excavators or robots were employed, each having its pre-allotted waypoint cluster following the Sweep or Spiral template.

3.1.4 Integration with BIM Case Study

The final step in the methodology was to implement the Sweep and Spiral templates on a BIM site plan as a case study. A building site plan was created in Revit, which is a BIM platform. The site plan was divided into grids which were then given Sweep and Spiral orientations to assess the efficiency of each pattern. Furthermore, the patterns were split into waypoint clusters based on the number of excavators/robots so that each agent would have its own distinct set of waypoints to avoid collision. Simulations on MATLAB were performed to check the efficiency of each pattern, where the parameters for assessing the efficiency were:

1. Coverage.
2. Time.

The waypoints generated in Revit Dynamo were exported to MATLAB via Microsoft Excel due to the flexibility Excel offered in synchronising with Revit Dynamo and MATLAB.

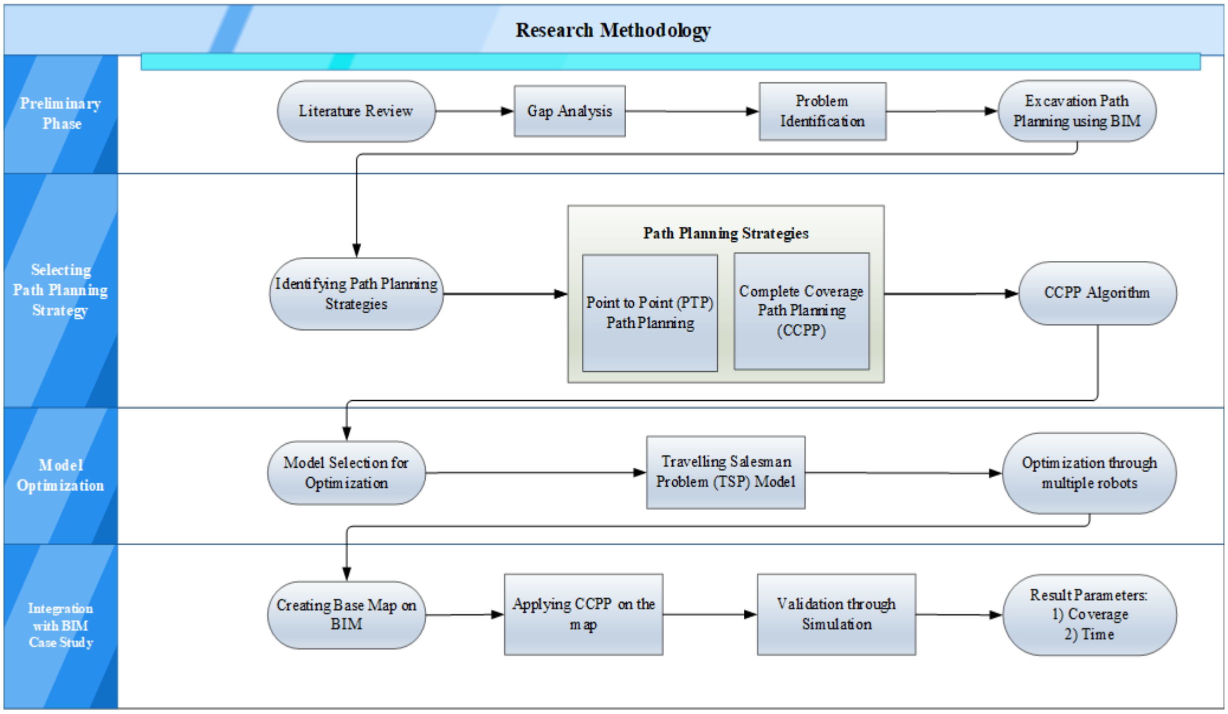

Figure 3.1: Detailed research methodology.

3.2 Factors affecting Labour Productivity

It has already been argued that labour productivity is declining in the construction industry. Determining the primary reasons behind this decrease in labour productivity was essential to initiating the research. For this, a content analysis of the 25 papers was performed. This analysis revealed that the key factors affecting labour productivity on construction sites are:

1. Labour Motivation
2. Labour Skill and Experience
3. Labour Attitude

The detailed bar chart is depicted in Figure 3.2 Therefore, the focus must be on these three key factors to ameliorate this declining trend in the construction sector.

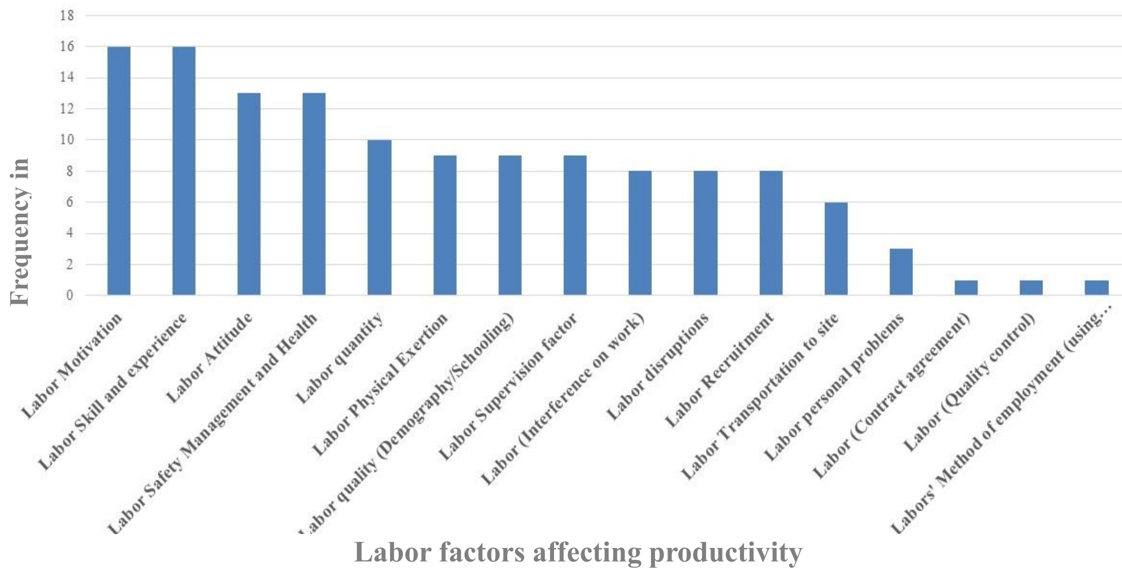

Figure 3.2: Factors affecting labour productivity.

3.3 Benefits of robotic application on construction sites

In addition to determining the factors affecting labour productivity on construction sites, it was also necessary to ascertain the benefits of robotic applications. Similar to finding factors affecting labour productivity through content analysis, the same approach was used to see the benefits of robots in construction. Figure 3.3 shows the results of the analysis done using 25 research articles. The top three benefits of applying robotics to construction sites were:

1. Speed
2. Quality of finish
3. General site safety

Hence, it was ascertained that these three factors contributed the most to increasing construction productivity.

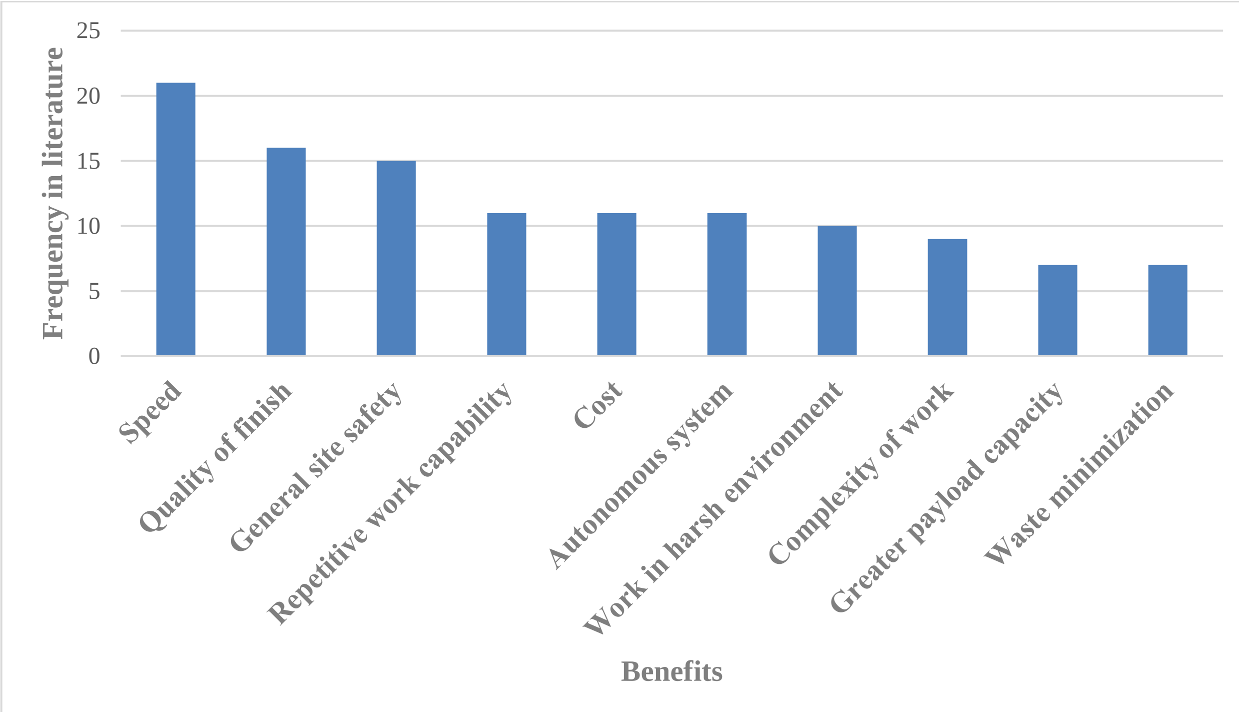

Figure 3.3: Benefits of robotic application on construction sites.

3.4 Coverage path planning algorithm on the BIM platform Revit

As discussed in the preceding section, excavation requires an excavator to cover the whole site to dig the soil and prepare it for subsequent construction. Therefore, a site plan for the region must be present to model this geometrically. The following subsections elaborate on the method adopted to create sweep and spiral patterns and divide them according to the number of excavators or robots needed to complete the coverage of a site. The BIM platform Autodesk Revit is used to create a building model. From this, the site plan is extracted into its API (application programming interface), Revit Dynamo, to break the area into a grid of waypoints, generate paths from them, and split them to accommodate multiple agents. Figure 3.4 describes the process in detail.

3.4.1 Creating a grid of waypoints

The primary purpose of this study is to use BIM-based models to perform excavation path planning. A building model already created in the BIM platform Revit can be utilised to achieve this. The first step would be to extract the site plan from this model. The site plan removes all structural components and shows only the area where the building will be constructed. The next step is to export this site plan from the Revit GUI to its Dynamo API. This process requires surface geometry extraction of the site plan from Revit to Dynamo. Once the surface geometry is extracted into Dynamo, it is converted into a polygon mesh where each vertex of the site plan highlights the geometry of the site. Figure 3.5 (a-c) illustrates this process.

After creating the mesh, the vertices of the corner-most points of the site geometry are isolated, see Figure 3.4 (a). From these vertices, the diagonal vertices are separated as shown in Figure 3.4 (b). Since the shape is rectilinear in most site plans, the diagonal provides the longest distance between two points in the area. Using this approach ensures complete coverage. Therefore, spacing this length for the maximum excavator turning radius provides waypoints for the excavator to move from one corner to the other, see Figure 3.4 (c). The process of spacing diagonal waypoints based on the maximum excavator radius is mathematically represented in equation 3.1 below. However, the waypoints must be constructed to cover the whole region instead of providing a path through the diagonal. Hence, a cross product is taken from each x-point of the diagonal to each y-point using the "lacing" option in Dynamo. This technique breaks the whole area into a grid of waypoints, as shown in Figure 3.6 (d) and equation 3.2. It must be noted that not all sites are perfectly rectilinear in shape. Therefore, the approximate cellular decomposition technique is used, which approximates the area as a rectilinear region to create waypoints.

$$\boldsymbol{DS = Length\ of\ Diagonal\ \div Maximum\ Excavator\ Turning\ Radius} \quad \textbf{(3.1)}$$

Where, DS = Diagonal spacing and,

Maximum excavator turning radius = 7 -12m as given by (S. K. Kim et al., 2012).

$$\boldsymbol{Grid\ points = i_{1\to n}\ \times j_{1\to m}} \quad \textbf{(3.2)}$$

Where, *i = x-coordinate going from 1 to n^{th} number,*

j = y-coordinate, going from 1 to m^{th} number.

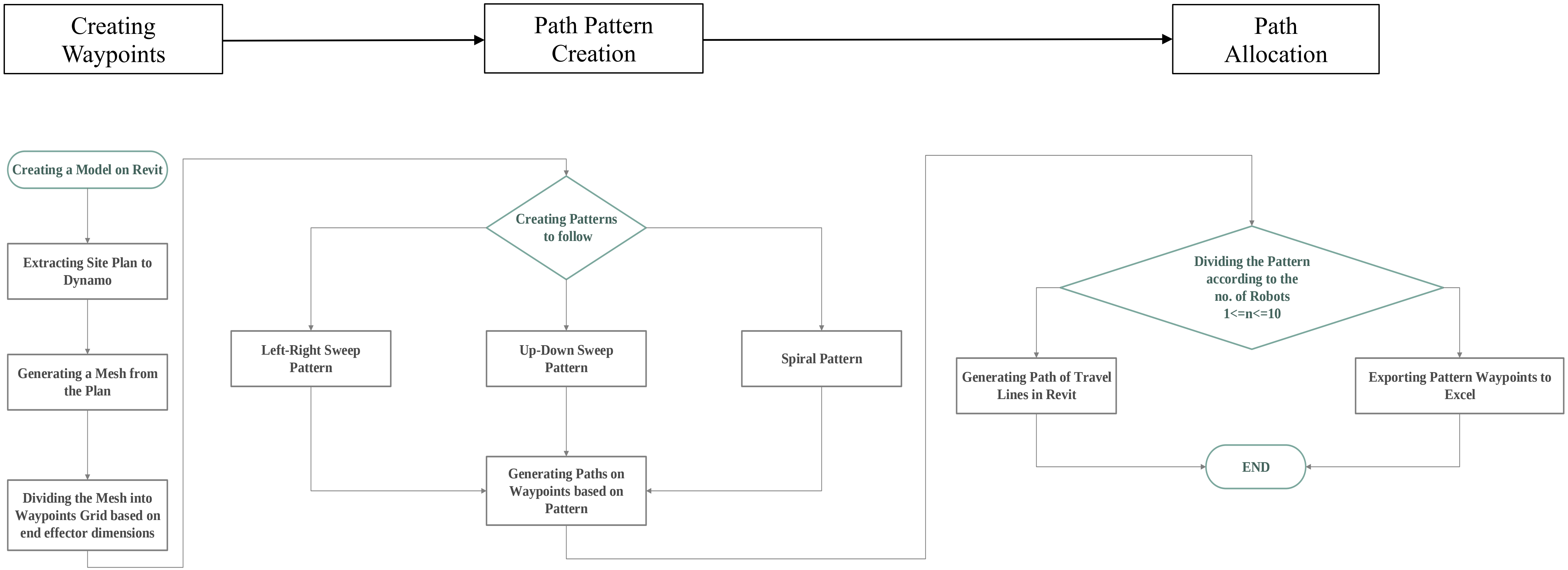

Figure 3.4: Coverage Path Planning Algorithm on BIM.

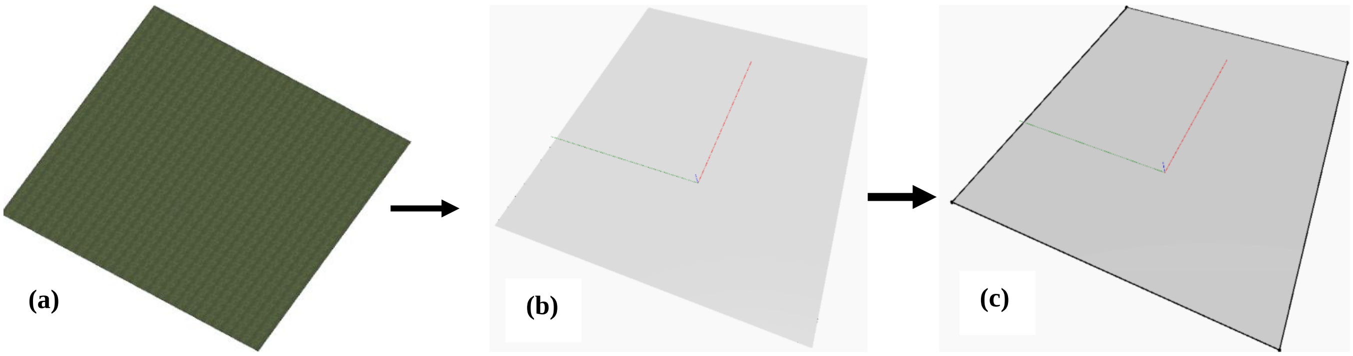

Figure 3.5: (a) Site plan of the model on BIM, (b) Surface geometry extraction, (c) Polygon of the mesh with its vertices.

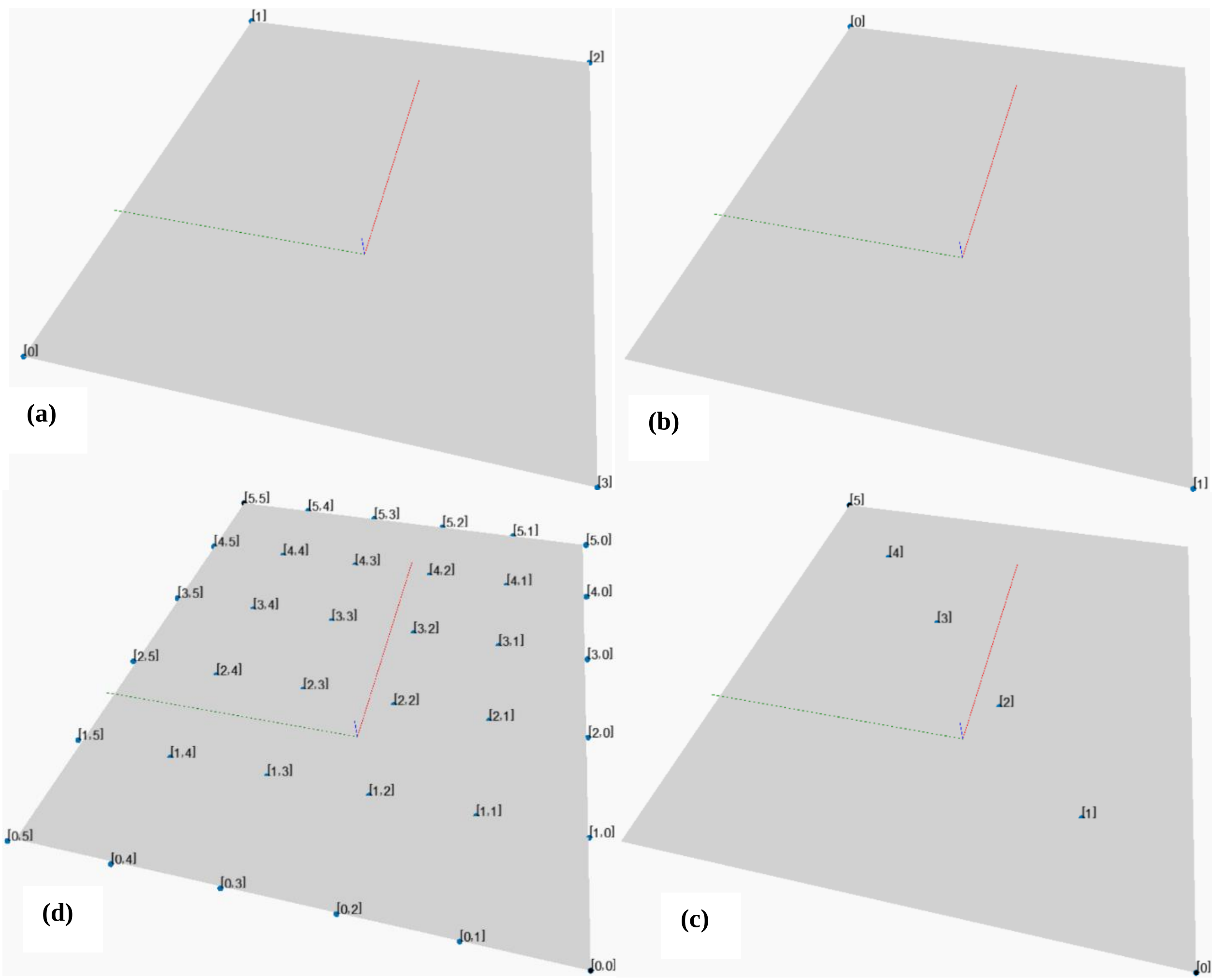

Figure 3.6: (a) Finding vertices points, (b) Diagonal vertices, (c) Spacing based on diagonal for coverage, (d) Creating waypoints.

3.4.2 Path pattern creation

Following the division of the site area into a grid of waypoints, these waypoints have to be connected in such a sequence that allows the excavators or robots to cover the whole grid with minimal overlaps. Therefore, the waypoints were connected in pre-defined templates or patterns to achieve this. Two patterns turned up most often in the literature that provided coverage with minimal overlap:

1. Sweep pattern (up-down) and (left-right)
2. Spiral pattern

It can be argued that an optimisation algorithm might have been used to create efficient paths of complete coverage, especially nature-inspired algorithms that solve the problem by finding the global minima based on a random analysis of the problem and adapting at each iteration to reach the global minimum. However, since the paths are pre-planned, using sweep and spiral pattern templates, specifically in this study, affords the planners greater flexibility and freedom to choose whichever pattern they deem feasible based on various site and equipment restrictions they encounter during the excavation operations. Furthermore, using such algorithms only adds another layer of computational complexity that can easily be avoided using pre-planned templates that offer similar results. The path patterns once created resemble those in Figure 3.7 (a-c). The start and end points can be adjusted based on the planners' needs, and the waypoints can also be adjusted to account for the presence of obstacles.

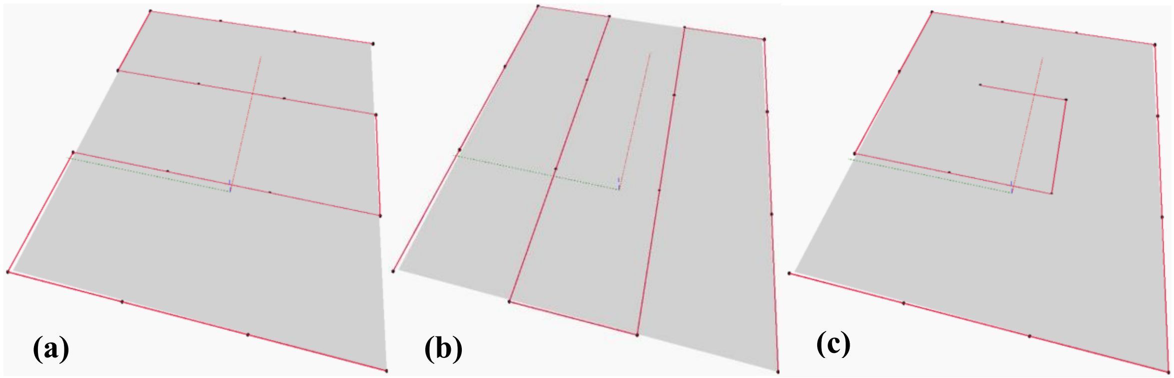

Figure 3.7: (a) Sweep Pattern (up-down), (b) Sweep Pattern (right-left), (c) Spiral Pattern.

3.4.3 Path allocation

The final step in the method is to divide the waypoints among multiple excavators or robots. This division is relatively straightforward. The list of waypoints has been created with the relevant sequencing for the sweep and spiral patterns in the preceding subsection. That list is now split into multiple clusters of waypoints, which can be assigned to different excavators or robots. Figure 3.8 (a-c) illustrates the division of waypoints into specific clusters for each excavator or robot. Here, too, the planners gain the flexibility to choose the number of agents they require to finish the operations. These clusters are then used to generate the "path of travel lines" in the Revit GUI. They are simultaneously exported into Excel for their subsequent transfer to MATLAB for simulation-based analysis.

3.5 Generative Parameters for Excavation using BIM

It is apparent from the method mentioned above that the planners can apply different path-planning options based on different parameters to assess the viability of the solution they get. Hence, the three primary parameters that define the generative capability of the path-planning algorithm in Revit Dynamo are:

1. The size of the excavator or robots.

2. The number of excavators or robots.

3. Pattern to be selected (spiral or sweep).

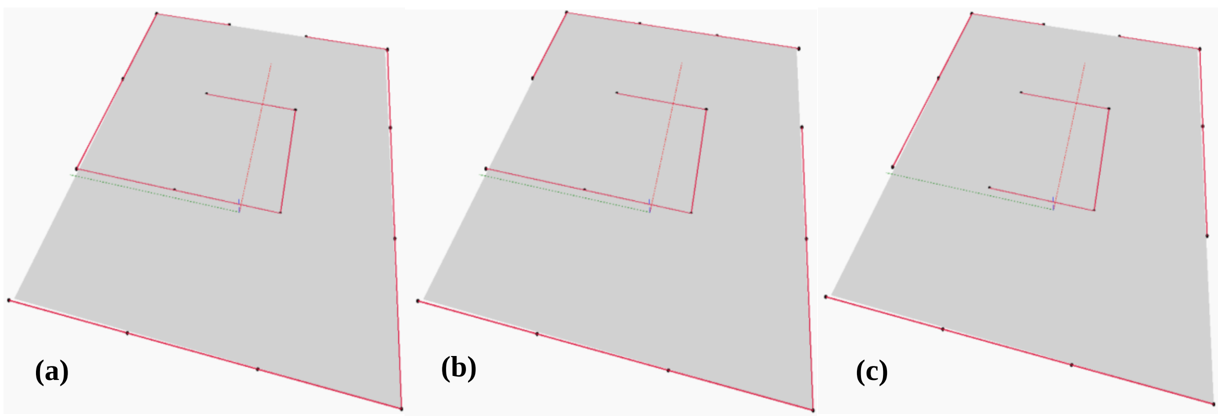

Figure 3.8: (a) 2 robots path allocation, (b) 3 robots path allocation, (c) 4 robots path allocation.

The excavator's or robot's size determines the number of waypoints generated to create the grid. The number of excavators or robots divides the paths among each agent to avoid overlaps and collisions. As for the pattern selection, the planners can choose from sweep patterns (up-down) and (right-left), and spiral patterns. The waypoints are sequenced so that these specific patterns are created. These factors can be assessed through simulations, which, for this study, have been done in MATLAB.

3.6 Parameters for results analysis

The previous section outlines the parameters that constitute the generative capability of the algorithm. This section defines the parameters that provide the means to assess the completeness and efficiency of the combinations of the generative parameters.

Parameters to measure the effectiveness of the paths allow for objective decision-making by planners to evaluate each combination and derive meaningful conclusions using the simulation results. The two parameters to assess the effectiveness of the paths are:

1. Coverage.
2. Time.

Coverage means that the excavator or robot has covered every waypoint generated. Subsequently, it also means that the area under consideration has been excavated with minimal overlap. Equation (3.3) mathematically describes this definition. Equation (3.4) provides an evaluation of overlapping areas.

$$\boldsymbol{Coverage}\ (\%) = \frac{\boldsymbol{Sum\ of\ Excavator\ Robot\ Areas}}{\boldsymbol{Total\ Area\ to\ be\ excavated}} \times \mathbf{100} \quad \textbf{(3.3)}$$

If coverage percentage < 100, then incomplete coverage.

If coverage percentage = 100, then complete coverage.

If coverage percentage > 100, then complete coverage with overlap and offset area.

$$\boldsymbol{Overlap}\ (\%) = \frac{\boldsymbol{Sum\ of\ Excavator\ Robot\ Areas - Total\ Area\ to\ be\ excavated}}{\boldsymbol{Total\ Area\ to\ be\ excavated}} \quad \textbf{(3.4)}$$

Time, on the other hand, signifies the efficiency of the path, that is, how much time the excavator(s) or robot(s) are taking to travel the total distance while covering the area. This can be measured through simulation by plotting a distance-time graph to visualise the time taken to cover the total distance for different combinations of the generative parameters.

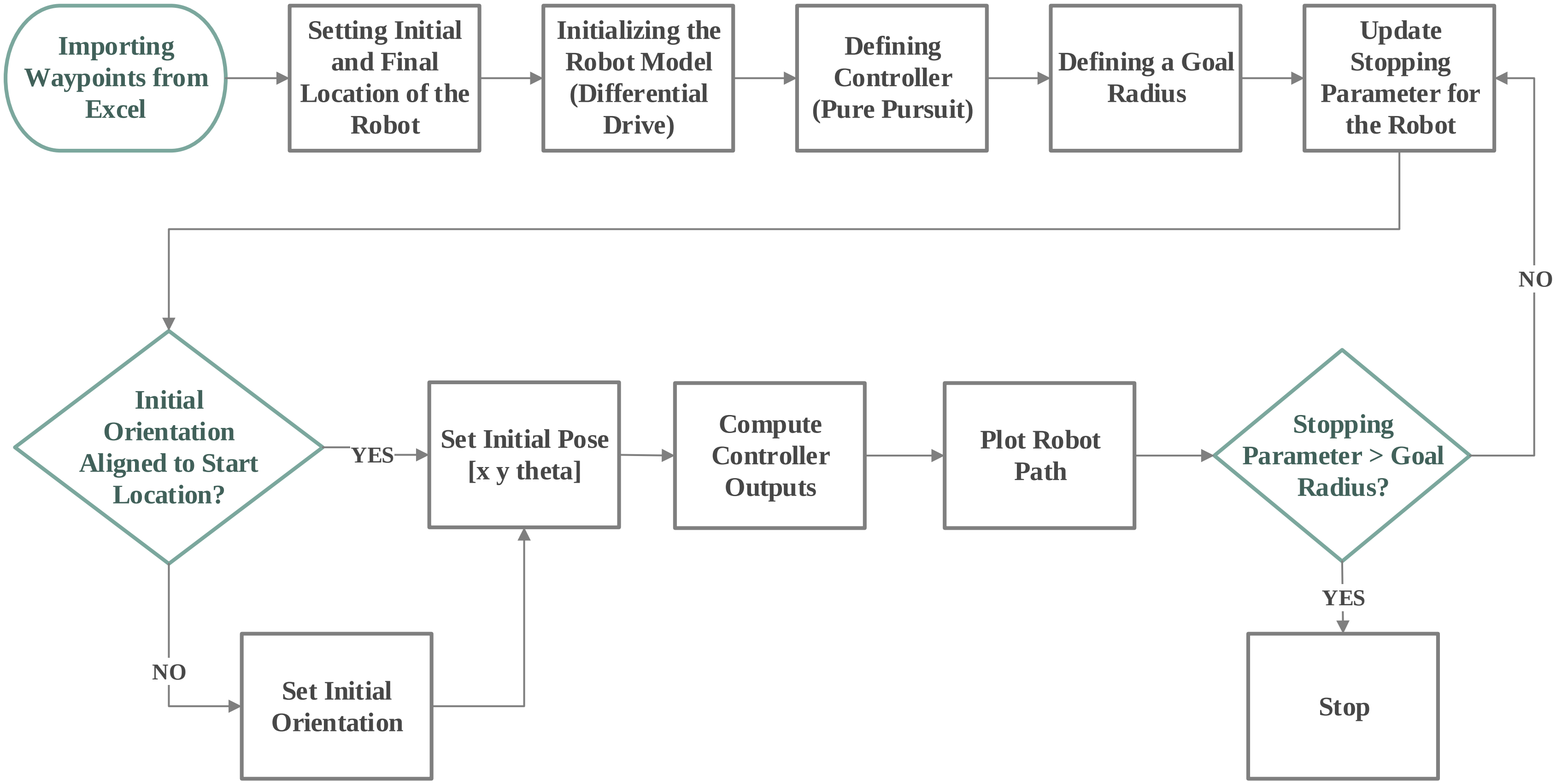

Figure 3.9: MATLAB coverage path planning simulation flowchart for multiple robots/excavators.

3.7 MATLAB Coverage Simulation Flowchart

Several steps are involved in importing waypoints from MS Excel and modelling robot movement in MATLAB, as shown in Figure 3.9. The process is initialised by importing the waypoints from Microsoft Excel to define the excavators' or robots' paths. Once the waypoints have been imported, the robot's initial and final locations must be established. After defining the starting and ending points, the Differential Drive Model needs to be initialised. This model represents the robot's movement and ensures that it moves realistically since a real excavator closely resembles the mechanics of a differential drive robot. The Pure Pursuit path tracking algorithm is used to control the robot's movement along the path, which requires the Desired Linear Velocity as a defining parameter. Pure Pursuit is chosen as the path planning controller algorithm since other algorithms such as Dijkstra, the A* algorithm, and the D* algorithm calculate the shortest path between two points based on some heuristic function. In this study, however, this is not required. What is required is that given a set of waypoints, the controller algorithm would trace a path through them. Hence, a path-tracking algorithm best suits this requirement. The Pure Pursuit algorithm perfectly fits this description, whereby it calculates the trajectory of motion based on the "Look ahead distance" from one waypoint to another, meaning that the algorithm seeks a waypoint at every location within a specific radius, allowing the agent to trace a path through the waypoints.

A goal radius must also be defined to ensure the robot knows when it has reached its destination. This radius represents the distance between the robot's current position and destination. Before beginning the simulation, the robot's initial orientation must be checked to ensure it is aligned with the starting waypoint of the path planned in Revit Dynamo. Once this is done, the initial pose of the robot model can be set, which is a vector containing the x and y coordinates (the initial location) and the initial orientation in radians.

Lastly, a plot of the waypoints imported from Dynamo via Excel can be created to represent the robot's movement visually. The simulation can then be performed, and the changing coordinates can be documented at a specific time interval. The robot(s) will continue to move until the distance to the goal radius is less than a defined parameter.

The methodology chapter explained the techniques and tools devised to conduct this study. After an exposition of the research design, the factors affecting labour productivity and the benefits of robots in the construction industry are described. This is followed by a detailed illustration of the coverage path planning algorithm developed in BIM, its generative parameters, and how to assess it. Lastly, an account is given of the validation of the algorithm using MATLAB simulation.

CHAPTER 4 : RESULTS AND DISCUSSION

This chapter discusses the simulation-based validation of the complete coverage algorithm. It evaluates the time efficiency of the algorithm for each of the three patterns by analysing the distance-time graphs of one, two, three, and four robots. Finally, coverage analysis is used to find out the excavated area and overlap percentage.

4.1 Algorithm validation through simulation in MATLAB

The complete coverage algorithm derived in Revit Dynamo created waypoints and path patterns based on the generative parameters discussed in the previous chapter. However, it is also necessary to check its functionality. This functionality check does not mean the algorithm's efficacy would be evaluated. Only the efficiency of the paths that have been generated would be tested. Since trying the paths on actual excavators or robots was not feasible due to financial constraints, the next best option was to assess them using simulations. Therefore, simulations were performed on MATLAB to check the efficiency of the paths based on the total time taken to traverse the entire distance of each path.

A site plan was created on Revit, as shown in Figure 4.1. The site plan was exported to Revit Dynamo, and the coverage algorithm was used to create the paths on the site plan. The paths were then sent to MATLAB via MS Excel, where the simulations on different combinations of these paths and robots were run with the desired linear velocity of the controller set to 10 m/s for each case, and the results were plotted on distance time graphs. Figure 4.2 depicts a sample of the simulation.

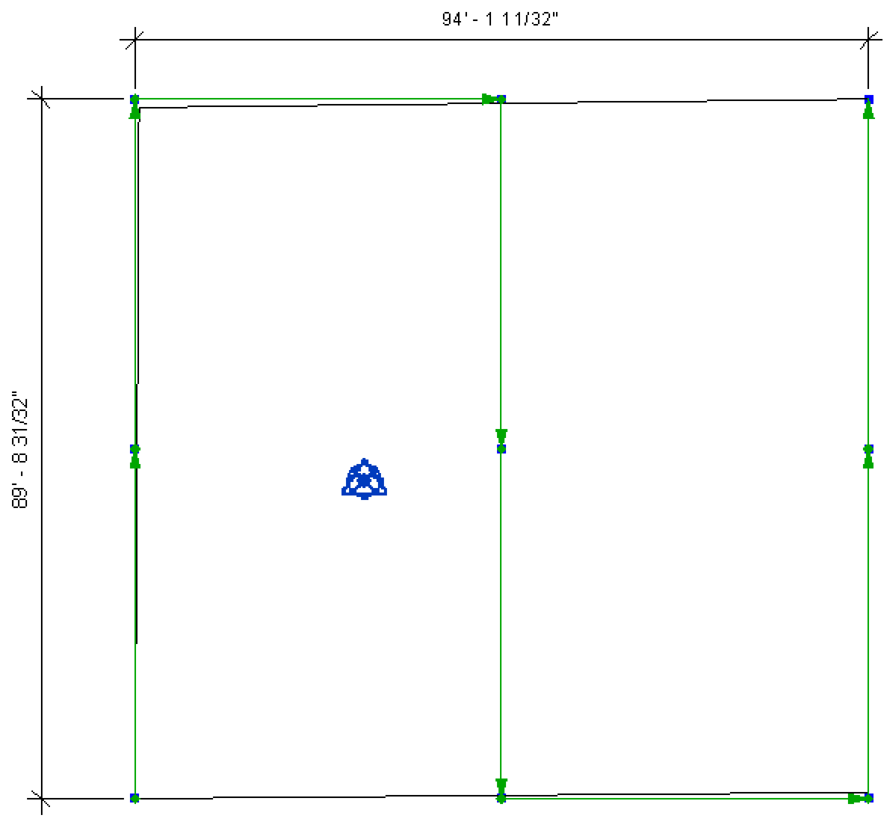

Figure 4.1: Site plan on Revit with sweep path.

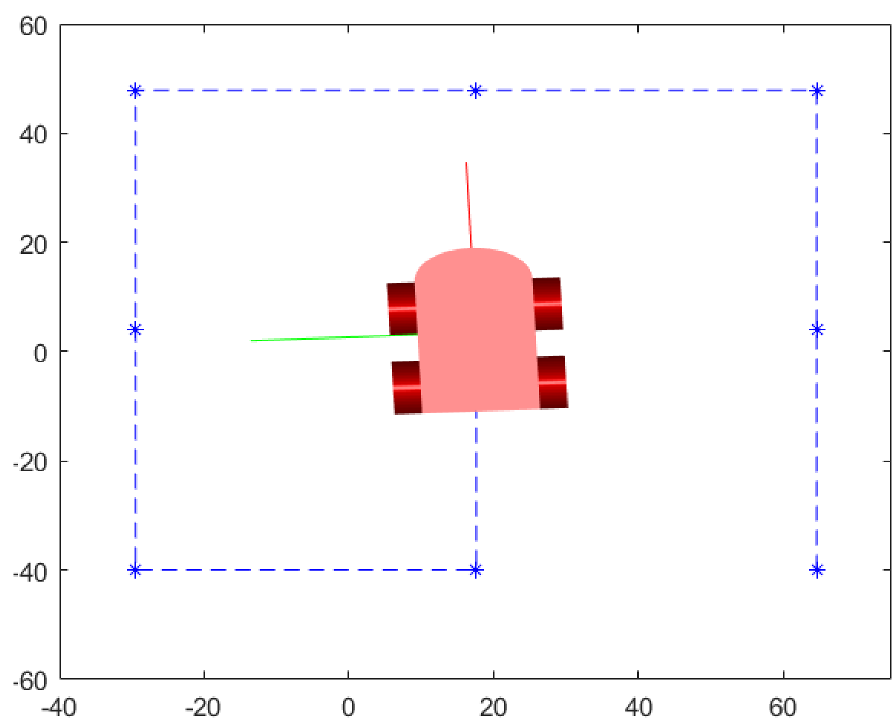

Figure 4.2: Simulation showing the differential drive robot following a path in MATLAB.

4.2 Single Robot Distance-Time Comparison

Table 4.1: Pattern comparison for single robot.

Patterns	Single Robot Cumulative Distance Covered (cm)	Time (s)
Spiral	269.087	99.0
Sweep up-down	286.585	101.8
Sweep left-right	278.165	98.7

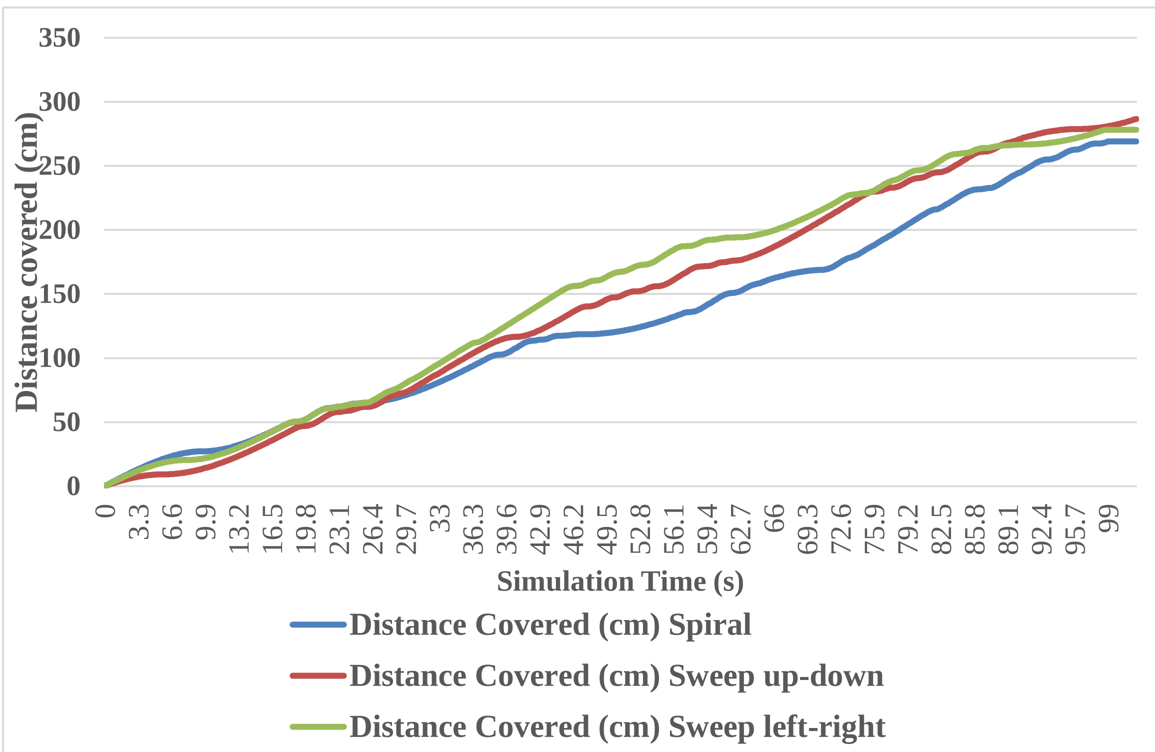

Figure 4.3: Single robot distance-time graph.

The time taken to complete the total distance for a single robot was compared between the three patterns: sweep up-down, sweep left-right, and spiral. The results showed that the sweep up-down pattern took 3.14% more time to complete the distance than the sweep left-right pattern and 2.75% more time than the spiral pattern. While the spiral pattern only took 0.303% more time to travel the distance than the sweep left-right path.

4.3 Two Robots Distance-Time Comparison

Table 4.2: Pattern comparison for two robots.

Patterns	Single Robot Cumulative Distance Covered (cm)	Time (s)
Spiral	261.165	90.2
Sweep up-down	267.978	92.8
Sweep left-right	266.196	89.6

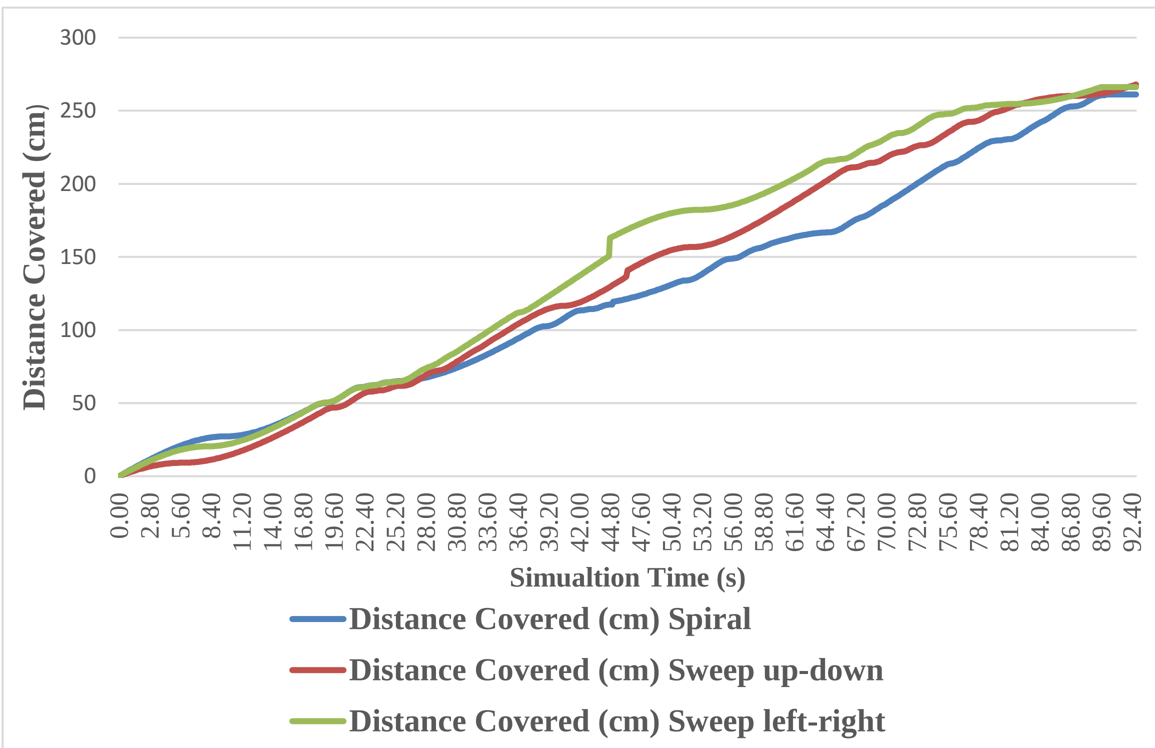

Figure 4.4: Two robots' distance-time graph.

The time taken to complete the total distance for two robots was compared between the three patterns: sweep up-down, sweep left-right, and spiral. The sweep up-down path took 2.88% more time than the spiral pattern and 3.57% more time than the left-right sweep pattern to complete the distance. While the spiral pattern only took 0.665% more time to travel the space than the sweep left-right path.

4.4 Three Robots Distance-Time Comparison

Table 4.3: Pattern comparison for three robots.

Patterns	Single Robot Cumulative Distance Covered (cm)	Time (s)
Spiral	240.61	76
Sweep up-down	272.167	77.8
Sweep left-right	256.635	76

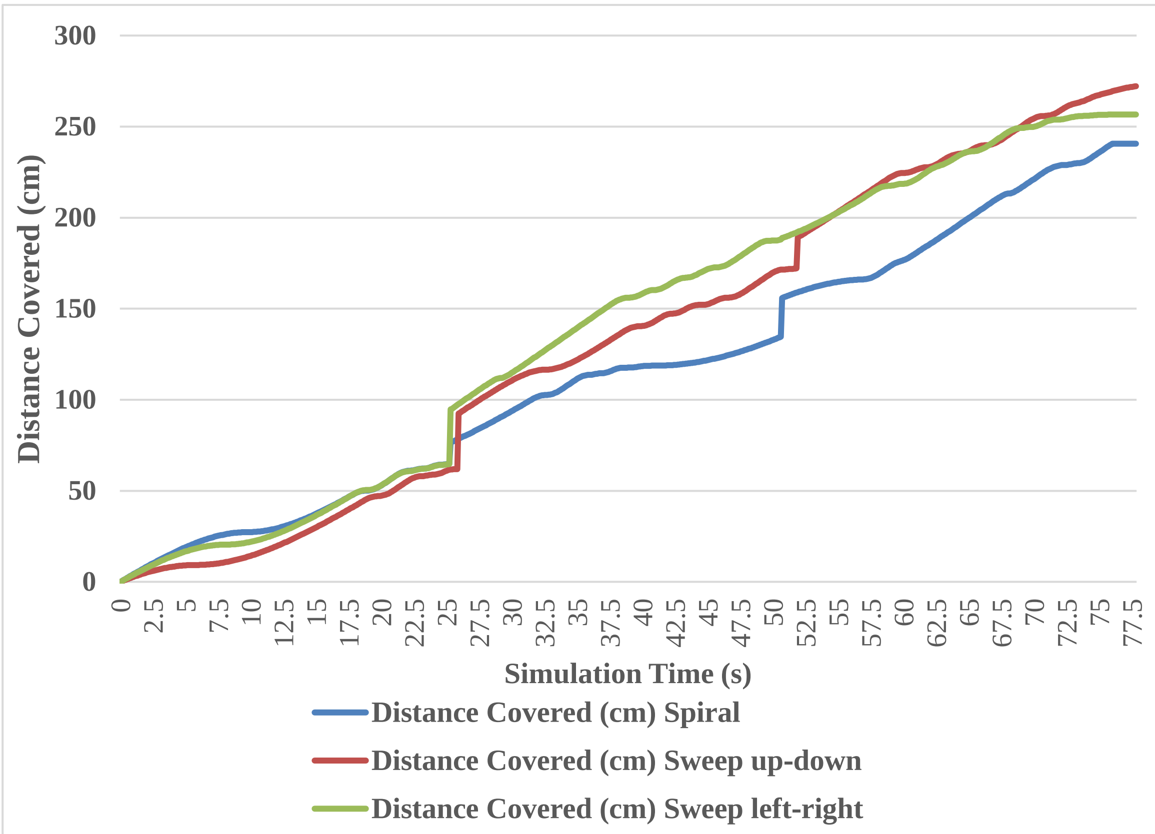

Figure 4.5: Three robots' distance-time graph.

The time taken to complete the total distance for three robots was compared between the three patterns: sweep up-down, sweep left-right, and spiral. In this instance, the left-right sweep and the spiral pattern took the same time to complete the distance. The sweep up-down pattern took 2.37% more time to complete the space coverage than the other two paths.

4.5 Four Robots Distance-Time Comparison

Table 4.4: Pattern comparison for four robots.

Patterns	**Single Robot Cumulative Distance Covered (cm)**	**Time (s)**
Spiral	255.166	35.8
Sweep up-down	252.513	37.8
Sweep left-right	247.449	35.8

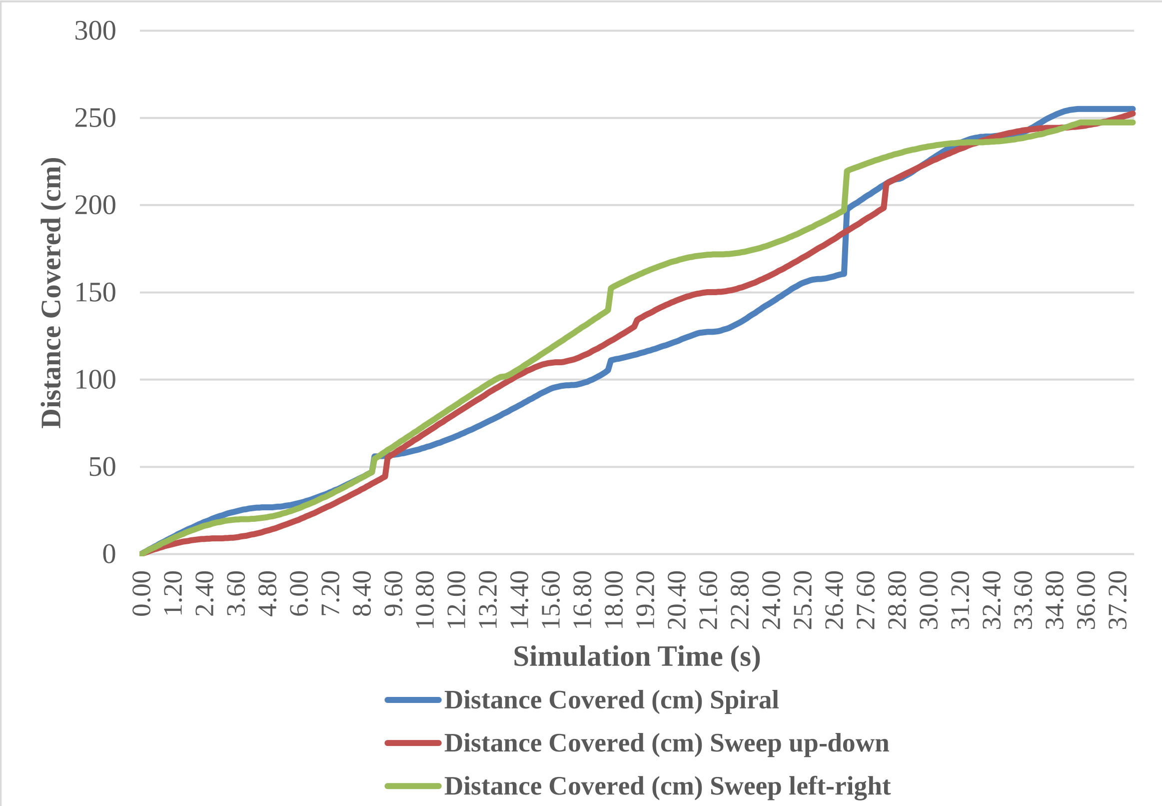

Figure 4.6: Four robots' distance-time graph.

The time taken to complete the total distance for four robots was compared between the three patterns: sweep up-down, sweep left-right, and spiral. Again, in this instance, the left-right sweep and the spiral pattern took the same time to complete the distance. The sweep up-down took 5.59% more time for complete coverage than the sweep up-down and spiral pattern.

4.6 Coverage Analysis

The coverage analysis of the sample site was also performed as follows.

Sum of Excavator Robot Areas = 20,754 ft^2

Total Area to be excavated = 15,490.56 ft^2

Coverage (%) = 133.97%

Overlap and offset (%) = 33.97%

The total area to be excavated was found from the site plan model in Revit. Sum of the excavator robots' area provided the excavation that was performed. This was calculated using the turning radii of the agents as given in the equation (3.1). Finally, the coverage and overlap percentages were calculated using equations (3.3) and (3.4).

Simulation-based validation of the complete coverage algorithm is discussed in this chapter. The distance-time graphs of one, two, three, and four robots for each of the three patterns are discussed, and the time efficiency of each is evaluated. In addition to this, coverage analysis was done which calculated the actual area that was excavated.

SUMMARY OF RESEARCH WORK

Earthmoving is a regular activity in the construction industry, but it is often plagued by a shortage of skilled labour and traditional excavation methods. This, in turn, leads to a decrease in construction productivity. Although automation technology has been applied to excavation operations, it has mainly focused on digging operations, while overlooking the aspect of complete coverage path planning. To effectively carry out excavation operations, it is crucial to cover the entire area under consideration instead of moving from one point to another. This study, therefore, aims to develop generative excavation coverage path planning strategies using BIM.

The generative parameters used for creating the excavation paths include the size of the area, the size of the excavator/robot, and the number of excavators/robots. The path assessment criteria are the completeness of coverage and time. To prove the concept, the coverage path planning algorithm was created in Revit Dynamo and exported to MATLAB via Microsoft Excel to simulate differential drive robots that use the pure pursuit algorithm.

The simulation results showed that the excavation coverage was complete and had an overlap of 20-30% for the area of slope stability. The sweep pattern required 3-5% less time than the spiral pattern. The variation is due to the different sizes of the excavators and the number of agents involved. This approach provides greater flexibility to the planners by allowing them to devise the excavation strategies beforehand. It would also help improve excavators' on-site manoeuvrability and productivity that, for years, have relied on operators' judgement and experience. Furthermore, these paths can be transferred directly to robots to perform excavation leading to the automation of the whole process. The use of generative excavation coverage path planning strategies using BIM is, therefore, a significant step towards the automation of excavation operations.

CONCLUSION

Excavation is a crucial process in construction. It involves the use of excavators to remove dig soil on a construction site. However, the excavation process is quite time-consuming and expensive, with constant issues related to its productivity. The productivity concerns can be addressed by automating the process. One way in which this process can be automated is by modelling the excavators' coverage paths through BIM, and then using multiple excavators or robots to perform excavation while travelling those paths. By determining the completeness of the coverage, it is possible to develop an excavation strategy that maximizes efficiency. This can be achieved by implementing different path patterns and analysing their time effectiveness. By comparing the productivity of different excavation patterns, it is possible to select the most effective approach. To further improve efficiency, this offline coverage algorithm can be used to coordinate between different excavators or robots.

This algorithm can help manage the excavation process, ensuring that each excavator or robot is working in the most efficient manner possible by dividing the excavation area among them and assigning each its set of waypoints. By working together, the excavators can manoeuvre the site more effectively, reducing the time and cost of the excavation process. Furthermore, planners can especially benefit from this strategy since it provides a picture of the excavation operation before the actual work which can greatly increase their understanding of the process, hence streamline the excavation plan for the construction works.

Limitations

There were also some limitations of this study that are described in this section. Firstly, given the financial limitations, the study used simulations instead of real-life robots. This approach was chosen due to the prohibitive costs of using multiple robots or excavators. The simulations provided a cost-effective alternative to test the coverage algorithm.

However, the simulations can only partially capture some of the complexities of real-life scenarios. Additionally, implementation costs were not factored into the study that, if included, would have significantly exceeded the scope of this study. Despite these limitations, the study's findings based on simulations provide a solid foundation for further research and development in the field.

FUTURE RESEARCH RECOMMENDATIONS

1. Real-world testing on a physical robot can enhance the algorithm. This would entail putting the algorithm on a robot and evaluating how it functions in a real-world setting. Researchers can use this testing to identify any shortcomings in the system and improve its accuracy and dependability. Furthermore, the testing would provide useful information about how the algorithm might be optimised for real-world applications.

2. To enhance the accuracy of the study, it is recommended that complete cycle times for an excavator are incorporated. This will enable the evaluation of the total time taken for excavation, including the time taken to load and dump the excavated materials. By analysing these complete cycle times, one can make informed decisions regarding the productivity of the excavation process. This will not only ensure better resource allocation but also help in identifying areas where improvements can be made to increase the overall efficiency of the excavation process.

3. When considering different scenarios, cost can also be considered as a generative parameter. This means that the cost aspect could be included in the analysis to determine the cost-effectiveness of each scenario. By doing so, one can better understand the financial implications of each option and make an informed decision based on the available resources.

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