AUTOMATED EXCAVATOR NAVIGATION USING BIM GUIDED ROBOT

Final Year Project UG 2018

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Islamabad, Pakistan.

2022

CERTIFICATION

This is to clarify that thesis entitled

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Has been accepted towards fulfillment

Of the requirements

For Bachelors in Civil Engineering

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Acknowledgment

We are extremely grateful to Allah Almighty for giving us the strength, courage, and opportunity to complete this research document. This research would have been incomplete, had it not been for the constant guidance and support from our Project Advisor Dr. Muhammad Usman Hassan, and all the respected faculty of the CEM Department of NUST Institute of Civil Engineering.

We would also like to thank Mr. Abdullah Bin Ahmed, a PG student of batch 2020 in CEM at NICE who had been guiding us along the way with his knowledge and constant support.

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LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

G**DP**	Gross Domestic Product
B**IM**	Building Information Modelling
L**UCIE**	Lancaster University Computerised Intelligent Excavator
G**NSS**	Global Navigation Satellite System
ANT	Artificial Neural Tissue
PID	Proportional Integral Derivative
L**IDAR**	Light Detection and Ranging
P**TP**	Point to Point
C**CPP**	Complete Coverage Path Planning
V**PL**	Visual Programming Language
B**RAN**	BIM based Robot for Autonomous Navigation
S**TL**	Standard Triangle Language
C**SV**	Comma Separated Values
D**C**	Direct Current
P**WM**	Pulse Wave Modulation

ABSTRACT

Local paths for excavation purposes need to be automated for improved accuracy and efficiency. Excavation path planning can help monitor and manage conditions on-site. So, a robot can work in all conditions when given a path without the need of labour. Construction industry is reliable on conventional methods and has been slow to embrace IT, whose substantial use can boost efficiency, cut costs, and improve safety level. To make paths more efficient or safe, Building Information Modelling (BIM) can be used to increase safety measures, improve efficiency, and reduce time by automating work on construction sites. BIM can stimulate all framework models and construction processes on a site for better work understanding and efficiency. The following study focuses on the integration of Building Information Modelling (BIM) with automation/simulation and a time comparison of local navigation of an excavator. This was done in a simulation software known as CoppeliaSim. A prototype was also developed using Raspberry Pi as a proof of concept for the BIM Integrated Excavator dubbed as BRAN (BIM based Robot for Autonomous Navigation) which was able to take the coordinates exported from BIM using Dynamo and navigate itself by creating a path using those coordinates. The system aims at automating the process of excavation navigation using BIM by minimising human efforts.

1. INTRODUCTION

1.1 Background

As we can see from our surroundings, the world is now evolving at a faster rate than ever before, with more and more construction projects springing up all around, making the construction industry one of the most prominent sectors of a country. It makes a significant contribution to both emerging and developed countries, both in terms of share and scope, by providing the necessary infrastructure for public and private activities such as trade, services, and utilities. Due to its products and also due to a large number of employees directly and indirectly related to the construction industry (Hampson & Sanchez, 2018), it adds 3-8% to a country's GDP (Arditi & Mochtar, 2000).

1.2 Construction Processes Overview

A building's construction process is often divided into four phases: planning, design, construction, and operation. The construction phase is the most essential of these phases since the success of a project is determined by how successfully the construction phase is carried out. So, to carry out construction stage operations successfully, efficient equipment and economic solutions are required. Building site operations are the most important overarching issues for both customers and contractors, as the construction period tends to create the most delays on a site. For years, the construction industry has attempted to enhance its efficiency through a variety of programs, resulting in fragmented approaches to improving construction efficiency (Meadati, 2007). Following the planning and design stages, the construction phase begins with the excavation of the building site. Excavation operations generally includes digging, removing soil, and stockpiling at site. Earthmoving and excavation process is not possible without the use of machinery and these processes require skilled labor to carry out operations at site. General machines used at almost every site include bulldozers, excavators, wheel loaders, scrapers, and graders. Excavator is the most common machine used at sites where trenching, cuts and removal of soil is required (Ha et al., 2002).

1.3 Automation in Construction

Construction industry usually depends upon conventional equipment and methods due to conservative approach of industry experts, but due to delay in project completion, shortage of manpower and quality of work to be executed, industry is looking for mechanized robots to increase productivity. A robot results in higher efficiency in terms of pay load, reach, degrees of freedom and quality of products. Automation in construction has been one of the most interesting topics for researchers in the last three decades. Despite the use of some autonomous and teleoperated machines in construction industry, a fully automated site is still a dream of many research developments and construction engineers (Elattar, 2008).

1.4 Problems In Conventional Earthmoving

General footing excavation and trenching requires precise excavation. Excavators are among the earthmoving vehicles utilized on all construction projects. Earthwork comprises of construction cost and operation time more than any other type of construction. Therefore, earthworks have more impact on a site's construction work productivity. Increasing the productivity of the excavation process is very difficult in conventional systems because it is a labor-intensive process. Success or failure of a construction site can be predominantly influenced by the excavation process because of the use of heavy machinery and shortage of skilled labor (Jung Hwan and Jong won, 2011).

Safe environment is a major need at a construction site because it is a high hazard industry. Workers can get hurt, injured, and may also die in some scenarios. These actions may cause extra expenditure, time delays and loss of lives. Working in safe and sound environments is the need of time otherwise the outcome may not be what is expected if safety issues keep arising (Akmal Shamsuddin et al., 2015). Major accidents that may occur onsite are falling from heavy equipment, being struck or crushed by the machinery and electrocution from parts of equipment. These accidents may occur due to poor communication, crowded work areas, load instability on machines, poor equipment and lack of safety features (Kavya & Pradeep, 2019). In the case study by (Choudhry & Fang, 2008), inexperience, inappropriate conduct, and deviations were the leading causes of injuries, accounting for 54.4 percent of total injuries. It is also predicted that construction industry may face a shortage of skilled labor in upcoming times because of variations in construction industry itself, difficulty of work, handling of heavy objects which shows a high rate of accidents compared to other industries (Jung Hwan and Jong won, 2011).

Moreover, the skill and expertise of labor also plays an important role in execution of project which affects the performance of a project. Unskilled labor is a major problem that results in loss of time and money. Projects sometimes do not meet their standards due to labor unskillfulness (Hussain et al., 2020). Lack of skilled labor reduces the productivity of construction projects and less experienced labor is more prone to accidents due to lack of familiarity with safety procedures (Karimi et al., 2016).

1.5 Problem Statement

Local paths for excavation purpose need to be automated for improved accuracy and efficiency. Excavation path planning can help monitor and manage conditions on site. So, robot can work in all conditions when given a path, without the need of labor. Construction industry is reliable on conventional methods and has been slow to embrace IT whose substantial use can boost efficiency, cut costs, and improve safety level. To make paths more efficient or safe, Building Information Modeling can be used to increase safety measures, improve efficiency, and reduce time by automating work on construction sites. BIM can stimulate all framework models and construction processes on a site for better work understanding and efficiency.

1.6 Objectives

- To integrate BIM with excavation by exporting excavation data using Dynamo
- To simulate an excavator model in CoppeliaSim using BIM data to showcase the capabilities and limitations of the robot
- To perform time comparison analysis between different navigation paths on CoppeliaSim
- To build a small-scale prototype to perform autonomous navigation

1.7 Research Significance

Construction industry being a huge economic force when compared to other construction industries still lacks technological advancements. Construction industry has even lacked efficiency improvements with only managing the increase of only half of efficiency improvements as compared to other industries in the last 50 years (Hampson & Sanchez, 2018).

A construction project is considered successful if it is completed at the lowest feasible cost, with the highest possible quality, and with no accidents. Success means bringing the performance indicators to an optimum level. Automation and robotics in construction can achieve a number of advantages i.e., higher safety for both public and workers by letting machines do the work, uniform quality and higher accuracy than labor, increasing productivity and efficiency with reduced costs and improving work environment by eliminating noise and dust related works (Elattar, 2008).

1.8 Research Gap

Many automated robots have been developed using coded scripts for repetitive cyclic processes. BIM integration for automated excavation is not used till now leading to an underutilization of huge reserve of data accumulated in BIM platforms.

Secondly, there exists minimal research on the time comparison analysis between different excavation navigation paths. This is essential in showcasing the different options for navigation and then reviewing their efficiencies.

Table 1: Summary of Literature Review

Research	**BIM**	**Robotics**	**Excavation**	**Navigation**	**Autonomous**
(Jung Hwan and Jong Won, 2011)	✓	✓	✓	✓	✓
(Mrad *et al.*, 2002)		✓	✓	✓	
(Thangavelautham et al., 2017)		✓	✓		✓
(Jud *et al.*, 2019)		✓	✓	✓	✓
(S. K. Kim et al., 2012)		✓	✓	✓	✓
(J. Kim et al., 2020)		✓	✓	✓	✓

2. LITERATURE REVIEW

2.1 Advancement in Robotics

Robots and robotic systems must be able to work with less and less direct human control in order to advance in the field of robotics without jeopardising their effectiveness and, more significantly, the safety of the people who deal with them (Ad et al., 2009).

Fifteen years ago, robots were static, simpler, slower, that were programmable and just used to work on factory floors. They were the machines which used to increase the productivity in comparison to humans (D.A. Bradley, 1990). Since then, robotics has advanced drastically with the introduction of new types of robots that take many forms like industrial robots, medical robots etc. (Davenport, 2005).

In early 1980s, investments slowed down because investors thought that robots lacked flexibility. Robots have gained senses and intelligence since then, and flexible manufacturing has become a focus of robotics research (D.A. Bradley, 1990). Now a days, robots are working in industry not only because it helps in keeping the workspace safe, which reduces injury risks but also because it helps in fast work and accurate production (Bayram & İ, n.d.).

2.2 Necessity of Robotics for Civil Engineering Students

Engineering training plays an important role in the development of engineers. Automation and robotics studies in academia has been widely increasing since 1985. Current studies have been yielding partial positive results to some problems of industry such as productivity, labor shortage, safety, quality, and cost. However, the field of education has not yet adopted the technological advancements at the same pace as other industries. Therefore, there are still a majority of technologies that are yet to be explored. Fields in which labour force is required, technological advancement plays a pivotal role (Hernandez-de-Menendez et al., 2020).

2.3 Robotics in Construction

Factory based manufacturing industry have been enjoying the automated technologies for a long time now. However, field-based technologies such as the construction industry with severe environmental conditions have been behind in adopting these technologies and have scarcely been touched by these technologies (Paulson, 1985).

Construction typically involves several earthmoving machines including excavators. Most of the excavation operations consist of digging, levelling of earth and sheet piling to remove particles that are large. It also includes all the highly accurate actions for trenches and footing formation (Ha et al., 2002).

Construction work is a labor-intensive process which involves working in dangerous situations and conditions. Therefore, robots are widely used to help humans on construction sites. They are getting involved increasingly on sites to carry out highly accurate actions and reducing hazardous actions, thereby, achieving control and safety of the sites (Elattar, 2008).

2.4 Automated Excavation in Construction

Based on robotic applications in conventional manufacturing, the use of robotics technology to automate the excavation process appears to be a possibility that could boost machine utilisation and throughput. Furthermore, the automation of the earth removal process may be viewed as delivering other benefits such as a lesser reliance on operator competence and a reduced operator workload, both of which are expected to contribute to a more consistent, and thus higher quality output (David A. Bradley & Seward, 1998). Although, fully automated excavation is still a dream for researchers, but recent developments and work has shown promise that developments can occur soon. Several robots with a bucket in front have been used for experimental purposes (Ha et al., 2002).

In general, the automation of excavation processes is expected to be highly rewarding and feasible because improved quality, labour cost savings, increased productivity and precision is required for the work that is to be performed (Mrad et al., 2002).

2.5 Excavation Simulation using MATLAB

An excavation simulation package was developed using MATLAB to test the path which was to be followed. The package offered a wide range of robotic analysis and design tools. These tools were dedicated to excavation configuration. Autonomous excavation cannot be done without sensors since they are used to detect obstacles whether they are small boulders or large rocks. These are necessary for safety and proper operation as they can be dangerous for worksite as well as the robot itself (Mrad et al., 2002).

2.6 Automated Excavators already developed

2.6.1 LUCIE Excavator

The Lancaster University Computerised Intelligent Excavator (LUCIE) exhibited automated and robotic excavation by using an artificial intelligence-based control system and a motion control method to move the excavator bucket through the ground. In this system, a velocity vector is generated which moves the target point the distance which is required and in the required direction. The tip of bucket is used to sense this target point as it moves in the required direction (David A. Bradley & Seward, 1998).

2.6.2 Warynski K-111 Excavator

The backhoe of this excavator worked on OS-9 operating system. It had flow regulators, pressure regulators, hydraulic cylinders, and force regulators which were used to record data, as shown in Figure 1. This data was then transferred to MS Excel using software trajectory path which was used to calculate the amount of soil that was to be excavated. This was done by calculating the area of path crossover. The angle with which the arm and bucket would attack the surface was determined, which was required as it would give the time it would take to excavate (Szlagowski, n.d.).

Figure 1: Warynski K-111 - Szlagowski, J. (n.d.)

2.6.3 HEAP Excavator

HEAP was built specifically for the purpose of autonomous landscaping. It is based upon the commercially available 12-ton Menzi Muck M545 which was customized with numerous adaptations and additions such as GNSS with correction system, Lidar and arm actuators etc. The mapping algorithm is based on work done by (Frankhauser et al.). This creates a 2.5-dimensional elevation map from distance sensors and a corresponding pose estimate (Jud et al., 2019).

HEAP combines excavation path planning with local navigation to form a completely autonomous excavator, but it lacks the integration with BIM.

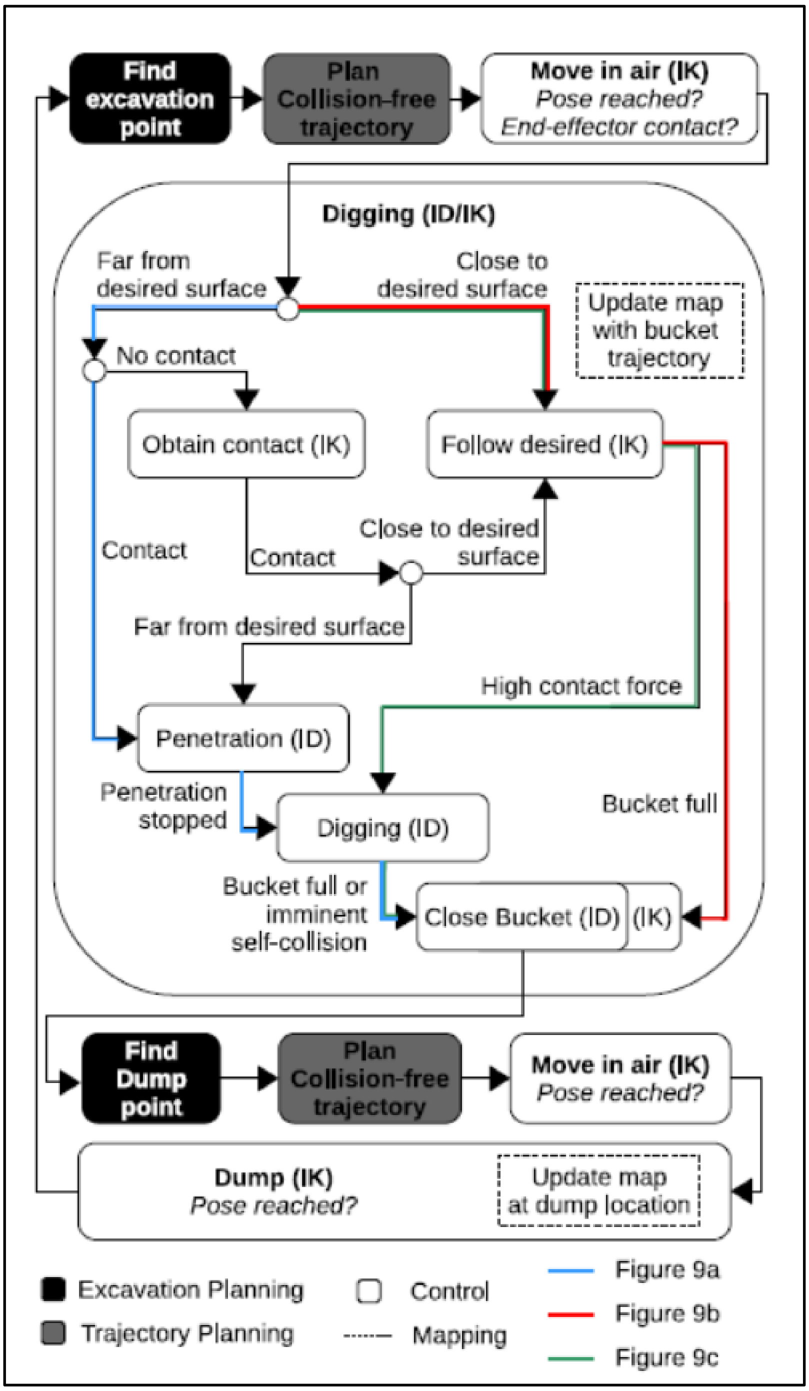

Figure 2: Building Blocks of HEAP Excavator - (Jud et al., 2019)

2.6.4 Multirobot Excavation for Lunar Base Preparation

The research by (Thangavelautham et al., 2017) explores the ANT (Artificial Neural Tissue) framework which uses a neural network approach for multi robot excavation. The proposed approach is suitable for off planet excavation as it is both a combination of autonomous and tele operated operation. The mundane operations will be automated whereas a teleoperator would be required for monitoring and intervention in case of unexpected obstacles. ANT was tested on multiple small-scale robots in a 50m dome, containing loose sand, which were monitored through the use of an overhead camera. The robots were equipped with all kinds of sensors, Lidar lasers and 1DoF bulldozer blade as shown in Figure 3. Fine adjustments could be made to this blade using PID control. These field studies show that by utilising low-cost vision devices like webcams and a laser range finder, ANT may be used to do multirobot excavation for lunar applications. There are challenges that are being faced in scaling up the rovers for a field demonstration.

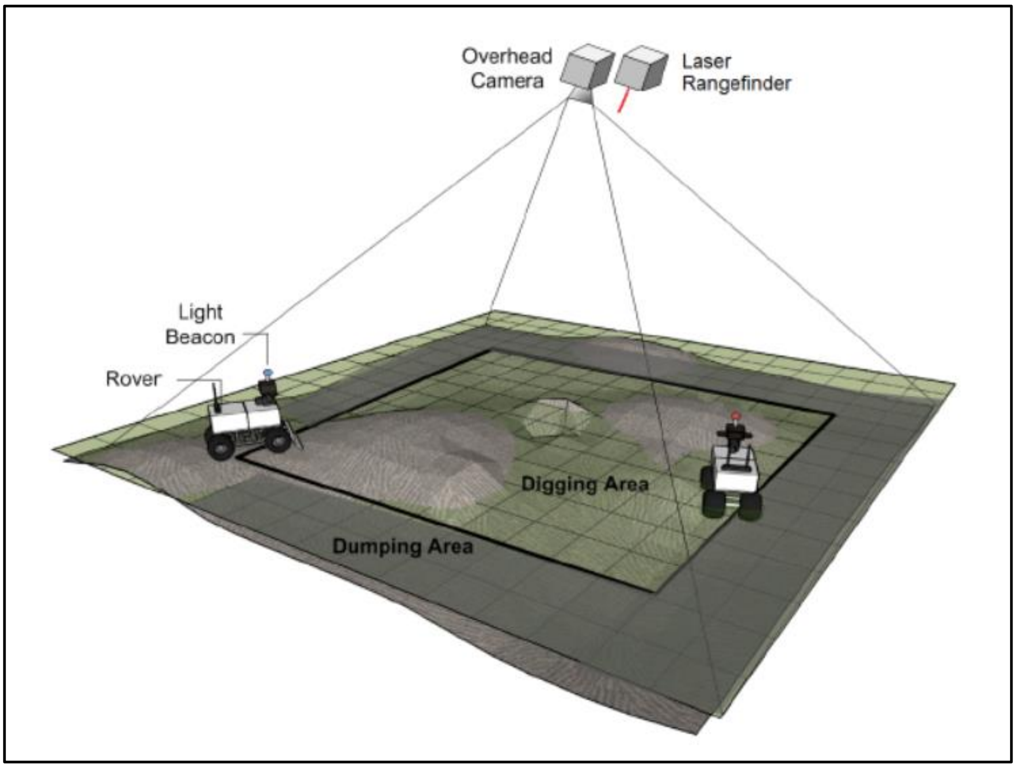

Figure 3: Excavation System - (Thangavelautham et al., 2017)

2.7 Path Planning Strategies

2.7.1 Algorithm for Path Planning

Path planning strategies previously computed a relatively longer path to arrive at the target in an environment with which it was not familiar or when it encountered a complex obstacle (S.-K. Kim et al., 2003). Therefore, an extension of the algorithm was developed for complex and unknown paths. The algorithm generates a path in 2D unknown environment which has obstacles. It uses four processes. (1) move toward the target; (2) move toward the hit point mode; (3) move along the boundary of an obstacle; and (4) stop (S.-K. Kim et al., 2003).

2.7.2 Types of Path Planning

Path planning can be of two types. i.e., static and dynamic. In static, there is no movement of obstacles on the path, while in dynamic, the objects on path can move (S. K. Kim et al., 2012). Path planning can also be classified as Point to Point (PTP) method and the complete coverage path planning (CCPP). CCPP finds out the efficient path during the entire cycle while PTP finds out the efficient path from Starting point to the Target point (S. K. Kim et al., 2012).

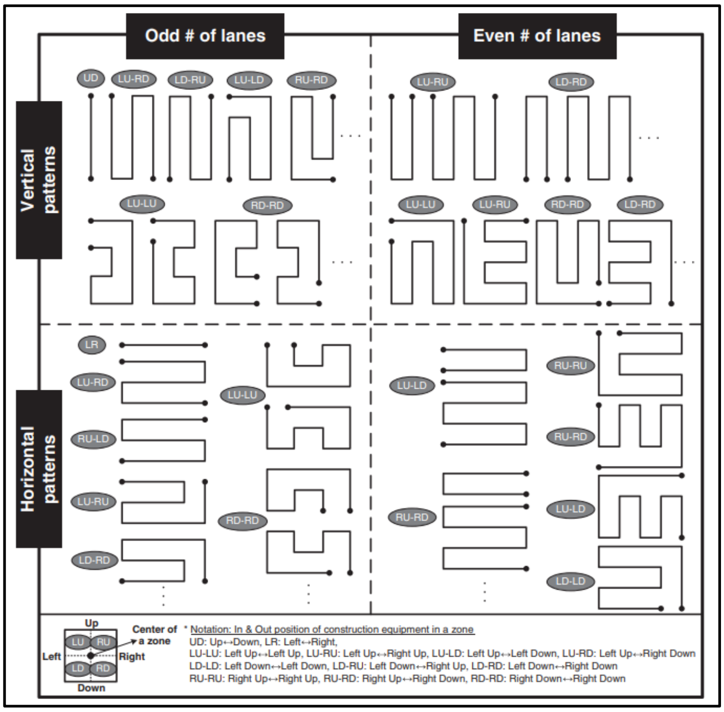

Figure 4: Path Planning Strategies - (S. K. Kim et al., 2012)

The excavator and the truck needs to work side-by-side to achieve greater efficiency. Figure 5 shows the CCPP algorithm would be required that would assure that the truck is accessible for the excavator and reduces the working distance which should be near the entrance area. Therefore, these four factors were considered during the proposed problem; accessibility of the dump truck, distance between cells, distance from the entrance, and isolation (J. Kim et al., 2020).

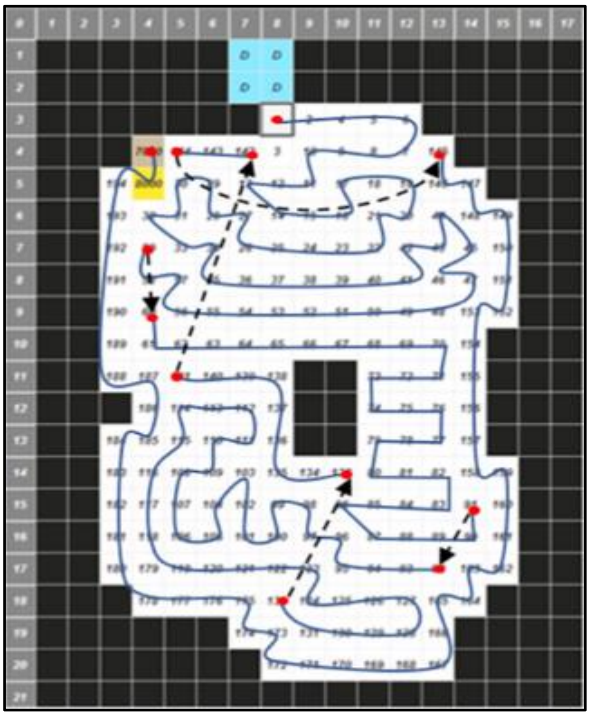

Figure 5: CCPP Algorithm - (J. Kim et al., 2020)

2.7.3 Teleoperated excavators for Path Planning

Teleoperated excavators, in which operator and excavator work side by side, are used for path planning, and they are used in those situations where the site is dangerous for humans. The starting point is figured out by the operator and then the excavator takes over from there by firstly filling the bucket using force. Then, in the next step, there are systems that automatically select where to dig. In such system, there are ranging sensors that measure the topology of the path and determine the digging trajectory that would maximize the volume and lessen the time required (Stentz et al., 1999).

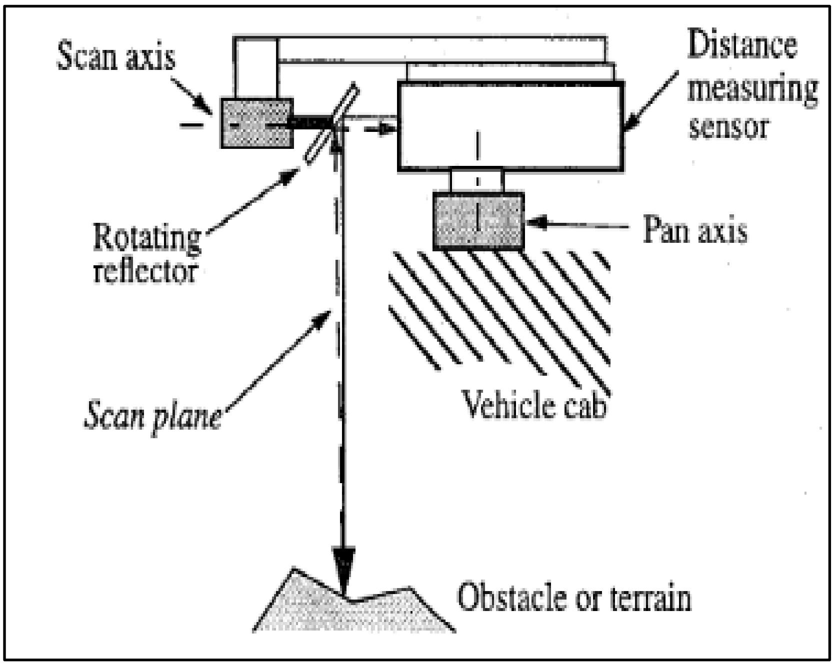

Figure 6: Teleoperated Excavator - (Stentz et al., 1999)

2.8 Application of BIM and Associated Simulation tools in Construction Industry

2.8.1 BIM in Construction Industry

Building Information Modeling (BIM) has the potential to revolutionize the construction industry by allowing for significant changes in the way projects are planned, built, and operated. Therefore making people more "BIM aware" and "BIM competent" rather than being "BIM expert" (Doan et al., 2019). Building Information Modeling (BIM) integration in daily recurring construction operations has greatly aided construction industry to prevail over challenging problems related to understanding site operations before they begin. This integration has also helped to improve the construction operational activities and improved trust among the project teams. Automation of construction sites provides more information, helps engineers understand their weaknesses and enable immediate work reports (Meadati, 2007). According to Mitropoulos and Tatum (Re-, 2000) a major source of improvement in construction industry have been due to technological advancement. Hence, adaption of these technological improvements in construction industry could be crucial in overcoming most of the recognized problems in construction industry. At the moment, BIM is quickly gaining traction and is being mandated by the construction industry around the world as a feasible solution for resolving the majority of the industry's recurring and persistent issues (Khoshnava et al., 2012).

Building Information Modeling (BIM) has introduced element technology which can help create work plans autonomously and control equipment so that autonomous excavation is possible. The effectiveness and efficiency of work can also be increase by real-time monitoring and updated technology in BIM with more promising construction (Jung Hwan and Jong won, 2011).

2.8.2 Dynamo as BIM tool

Dynamo is plugin that works closely with BIM based software such as Revit, which can be used to create programs for 3D BIM components automatically using certain parameters. It has a visual programming language (Chang et al., 2018).

It is an open-source add-on for Revit. With the help of visual programming, masses can be created via Dynamo. The logic of scripts is based on customer’s requirements. Visual programming languages (VPL) are 2D representation of standard textual programming languages. Due to high computational capacity of BIM, its usage has been growing in recent years (Salamak et al., 2019).

2.8.3 CoppeliaSim

Robotic system is a complex system that is very hard to construct and use, as it is very difficult to program the robot. It is a time consuming, cumbersome and high level of expertise is required for it (Bogaerts et al., 2020) to overcome these drawbacks. Thus, there is a need of certain technologies which will help in designing and implementation of hardware (Rooban et al., 2021).

CoppeliaSim is a robotic simulation software used to develop, prototype, and verify the robotic systems and algorithms (Bogaerts et al., 2020) with the following advantages:

- It has many applications like e-factory automation systems, remote monitoring, hardware development basis, easy verification, safe monitoring, algorithm development etc.
- It has many modules like path planning module, obstacle detection module, forward kinematics module, minimum distance calculation module.
- It has the ability to execute a variety of functions (Rooban et al., 2021).

3. METHODOLOGY

3.1 Research Methodology

The research methodology for the project is shown in Figure 7, showing that the project was completed in 3 phases:

1. Problem Identification:

   Literature review was performed to find out the research gap in papers regarding autonomous BIM based excavation navigation.

2. Solution Development:

   A BIM model was prepared in Revit, which was then used to export the site coordinates using Dynamo. The coordinates were then used by a simulation software named CoppeliaSim and our small-scale prototype.

3. Evaluation and Testing:

   Navigation path planning of 5 paths were performed on CoppeliaSim, along with the testing and demonstration of prototype navigation.

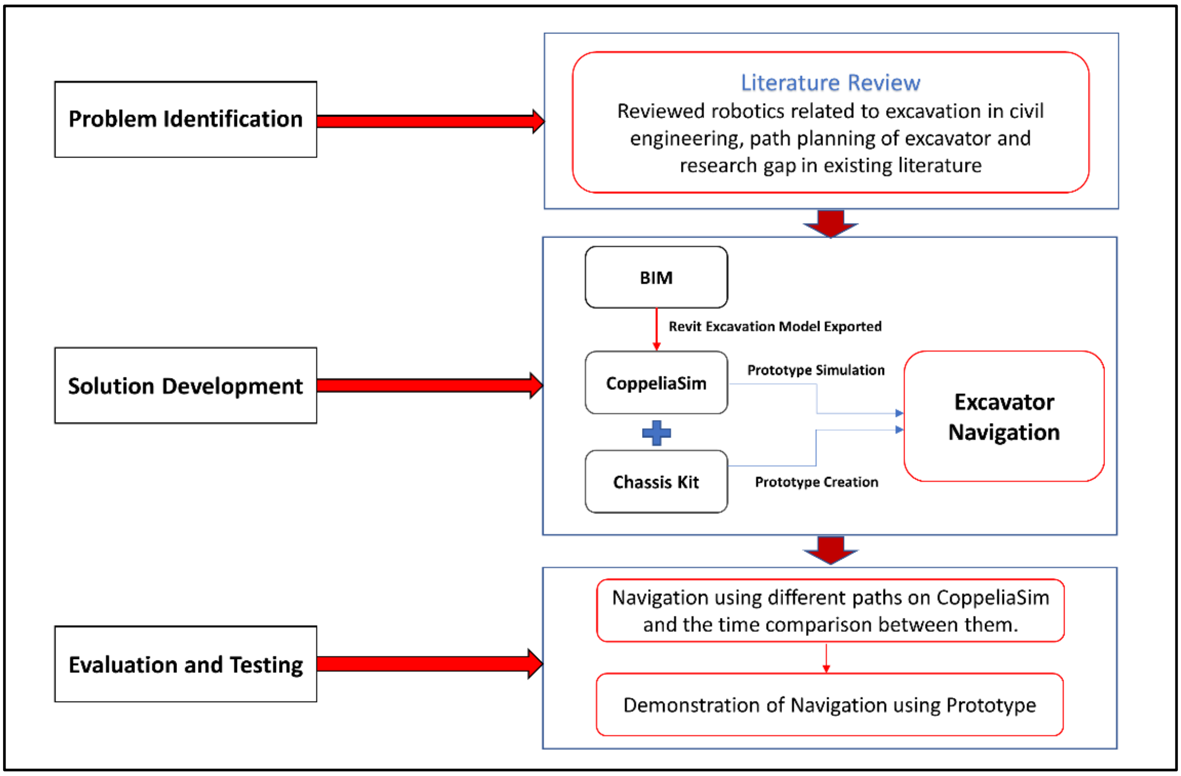

Figure 7: Research Methodology

As shown in Figure 8, the initial input for our dynamo script was the BIM model. Dynamo is a Revit plugin which uses visual programming to manipulate and edit BIM models. This Dynamo script was used to export coordinates into a csv file. This csv file was used in our BRAN robot for local path planning, following path 1 of our 5 proposed paths. BRAN is a Pi based prototype which works on

Raspbian OS and is controlled through a web interface known as PiCockpit, shown in Figure 9. BRAN is capable of movement through the help of 4 DC motors connected through an H bridge (L298N Driver). The distance travelled is measured through odometry with the help of 2 optical wheel encoders. These work together to let BRAN move autonomously with only the csv file serving as the required input.

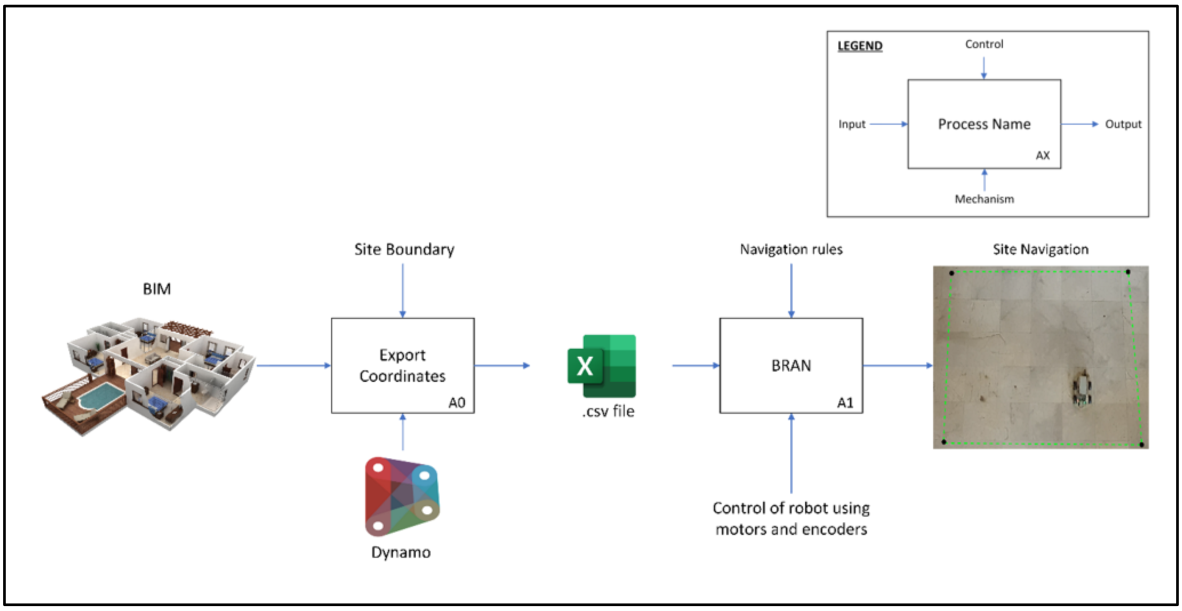

Figure 8: BIM Based Excavation Navigation System

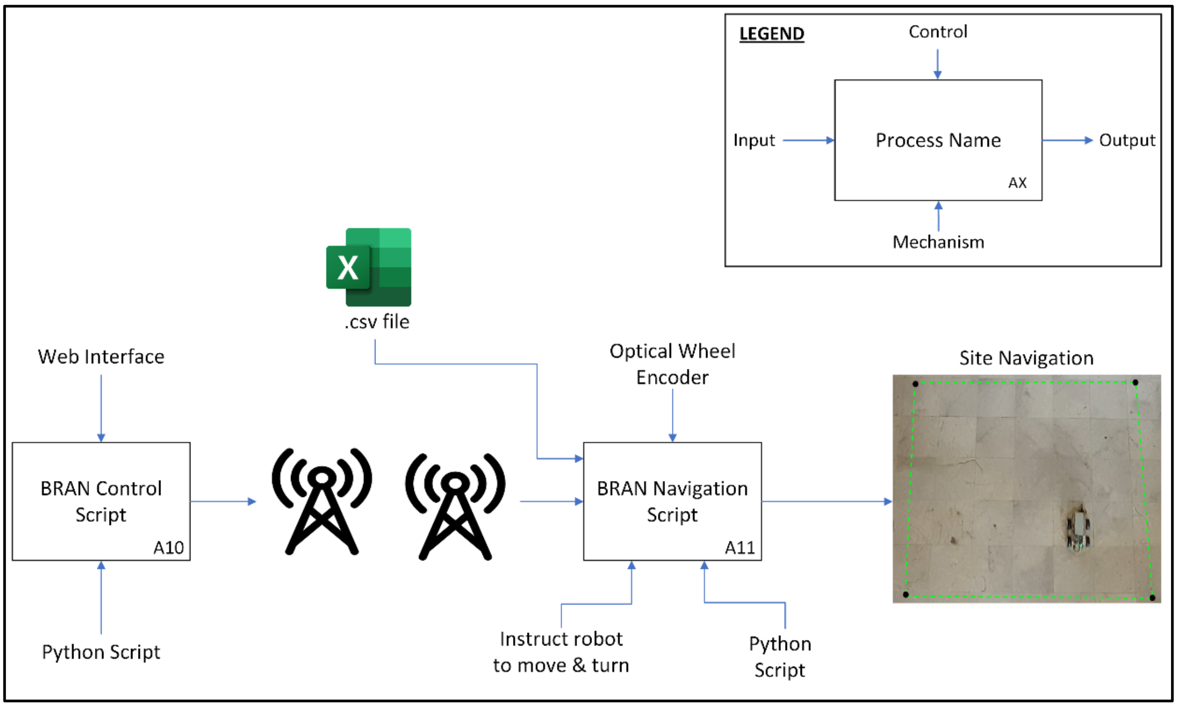

Figure 9: BIM based Robot for Autonomous Navigation (BRAN)

3.2 Revit & Dynamo

First of all, a model of a building was prepared in Revit, as shown in Figure 10. The model was made over an approximate area of 1240ft^2. Figure 11 shows a section view of the model to view the interior. After that, an excavated pit was created using building pads from "Massing & Site" menu of Revit. Figure 12 shows how the site would look once excavation would have been performed.

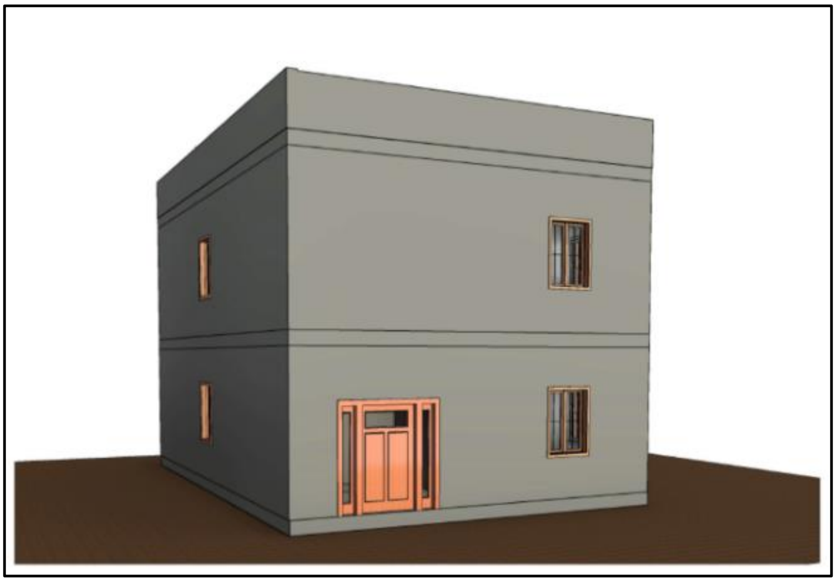

Figure 10: BIM Model

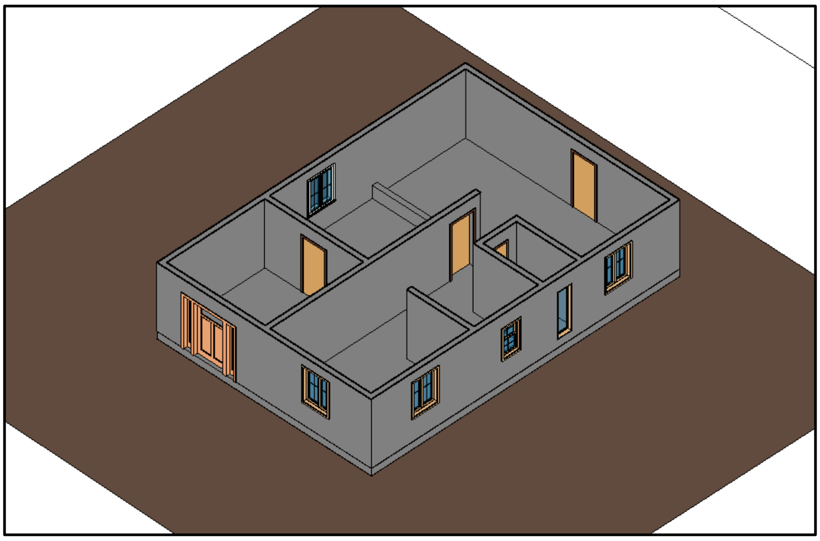

Figure 11: Section View of BIM Model

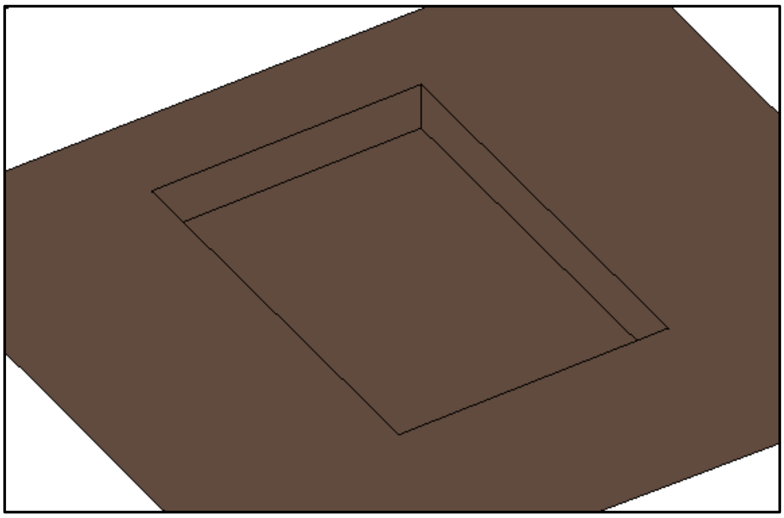

Figure 12: Excavated Site

Dynamo was used to export the coordinates of the pit into a csv file, which was later to be used by CoppeliaSim and the prototype. Figure 13 shows the complete view created in Dynamo for exporting the coordinates of the four corners of the site.

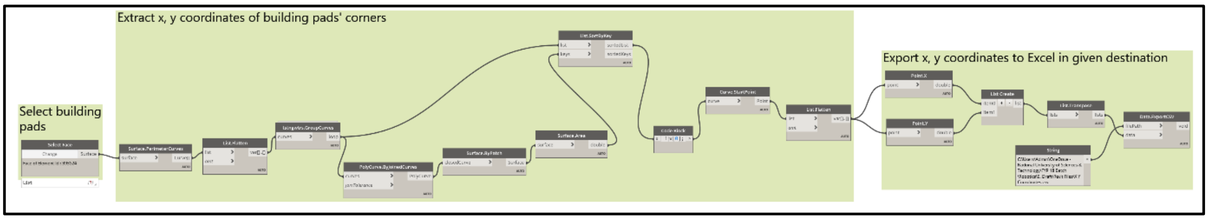

Figure 13: Dynamo Script

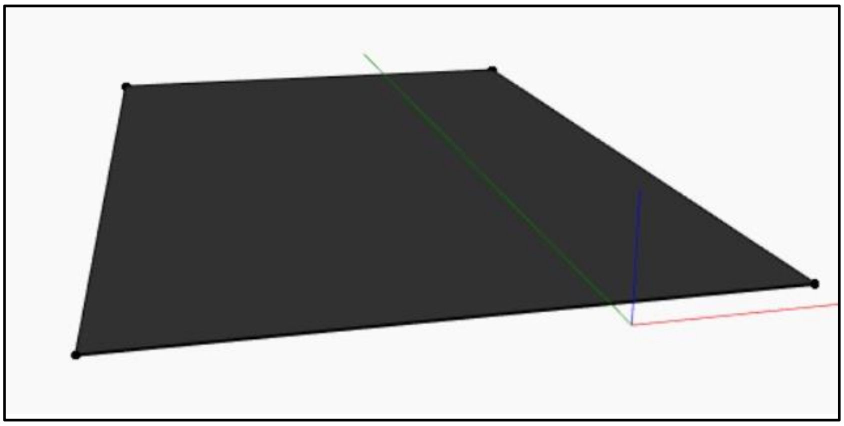

Figure 14: Dynamo Result

3.3 CoppeliaSim

Initially, students familiarized themselves with the environment of CoppeliaSim. A dummy and a test coordinates file were used to test the path following capabilities of CoppeliaSim, as shown in Figure 15.

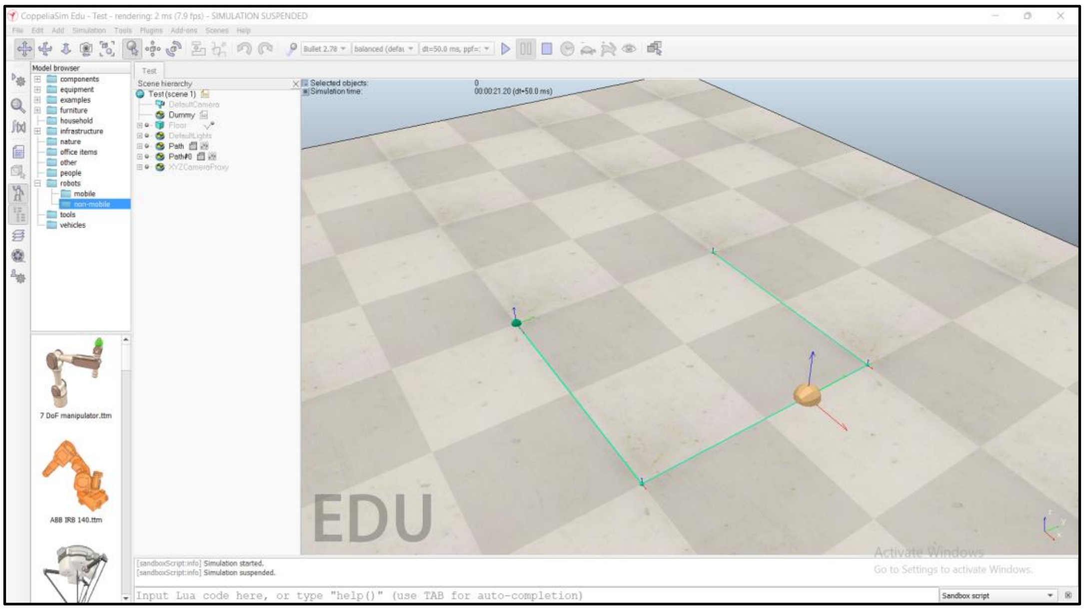

Figure 15: Test File for CoppeliaSim

After that, an STL file was exported from Revit, which was then imported into CoppeliaSim. The file was a mesh for the excavated topography, which was used as a reference during the coding process, as depicted in Figure 16. The csv file exported from Dynamo was also imported into the scene. For depicting the excavator, the "Youbot" vehicle from CoppeliaSim's non-mobile robots library was used, it was modified to remove the arm actuator as shown in Figure 17.

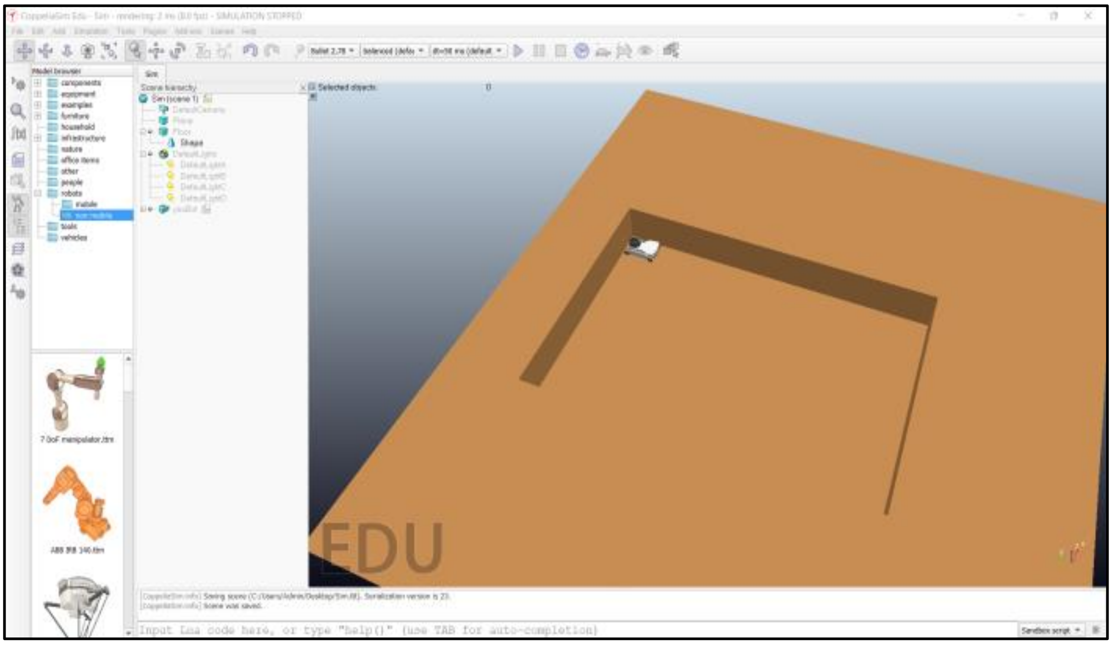

Figure 16: CoppeliaSim View

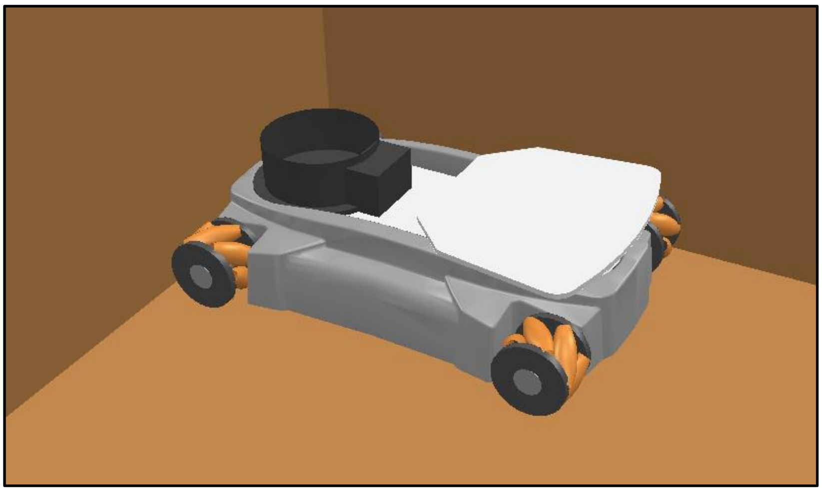

Figure 17: YouBot

3.4 Navigation Paths

The paths described below are performed only for local path planning.

<u>Paths 1 & 2:</u>

The **pseudocode flowchart** for the navigation of the prototype in paths 1 and 2 is shown in Figure 18:

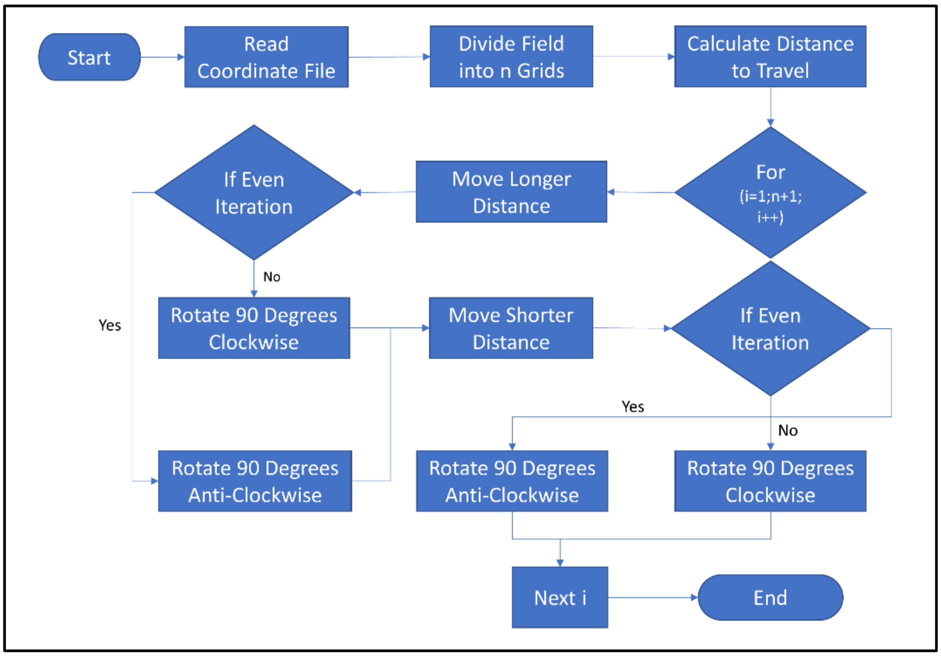

Figure 18: Pseudocode Flowchart 1

Figure 19 shows the path that would be taken by the prototype in **path 1**:

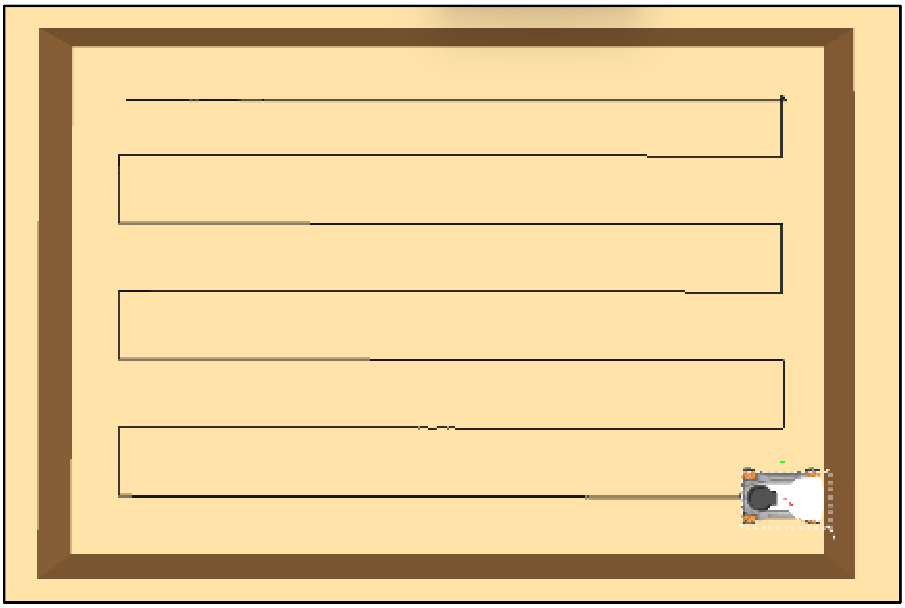

Figure 19: Path 1

Figure 20 shows the path that would be taken by the prototype in **path 2**:

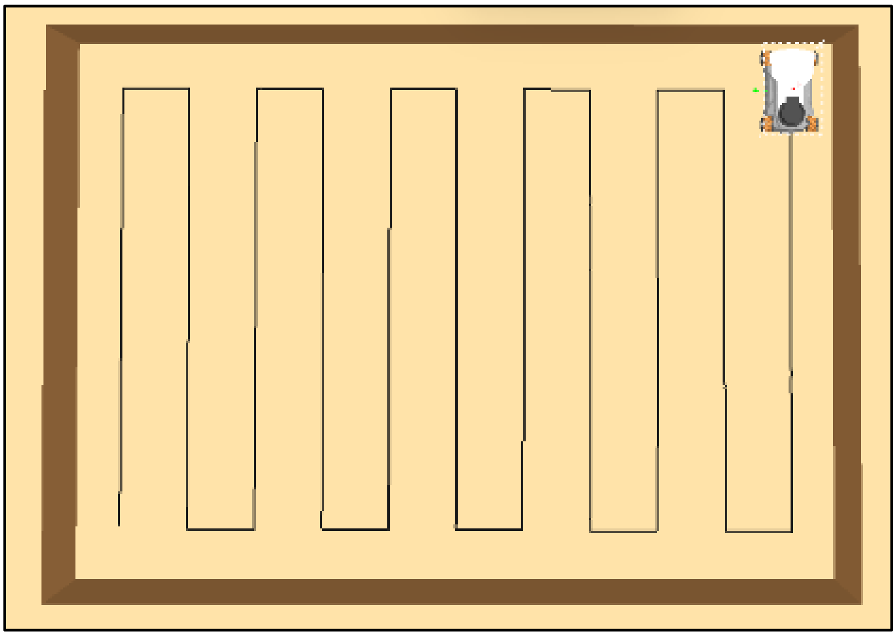

Figure 20: Path 2

Paths 3 & 4:

The **pseudocode flowchart** for the navigation of the prototype in paths 3 and 4 is shown in Figure 21:

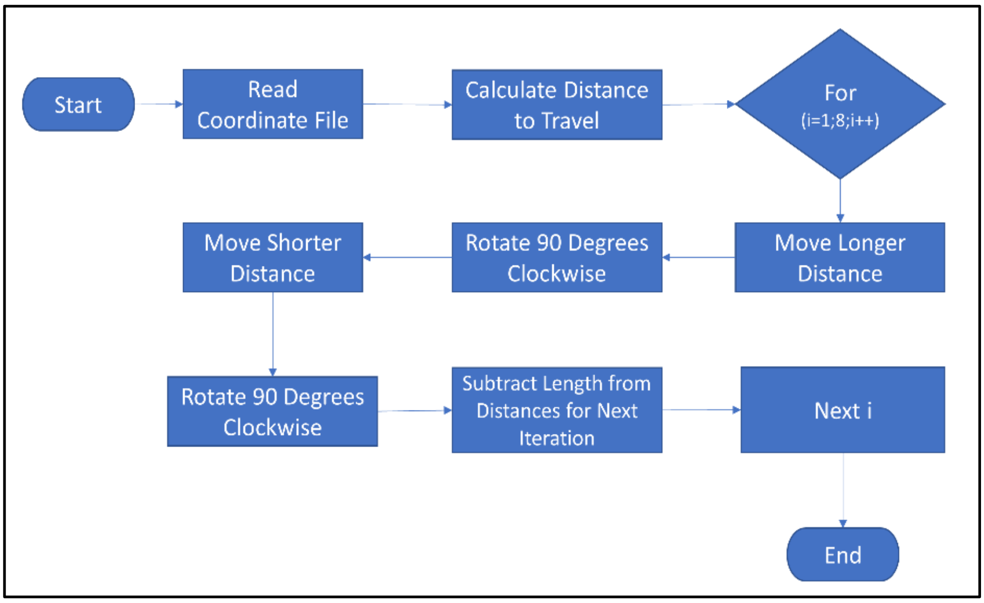

Figure 21: Pseudocode Flowchart 2

Figure 22 shows the path that would be taken by the prototype in **path 3**:

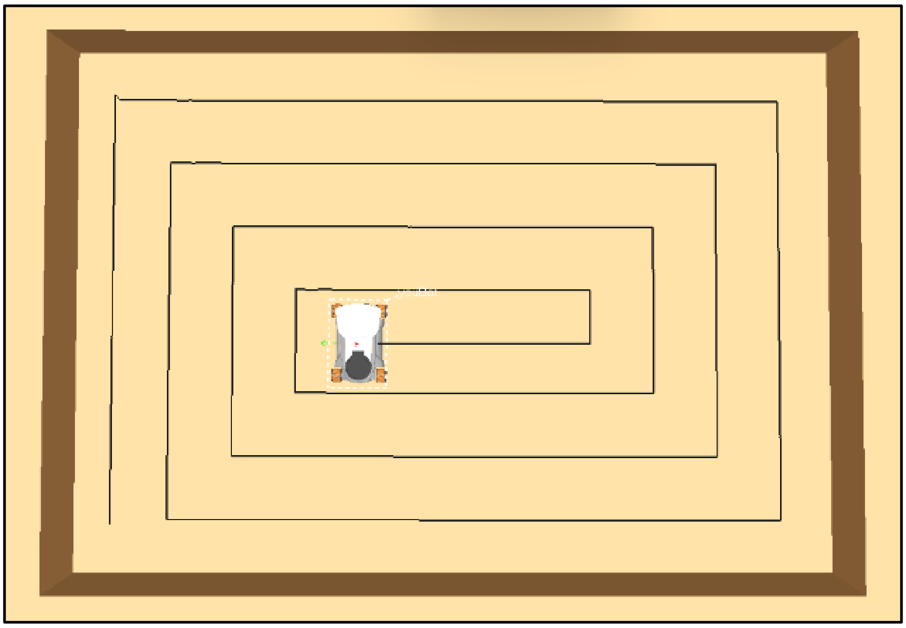

Figure 22: Path 3

Figure 23 shows the path that would be taken by the prototype in **path 4**:

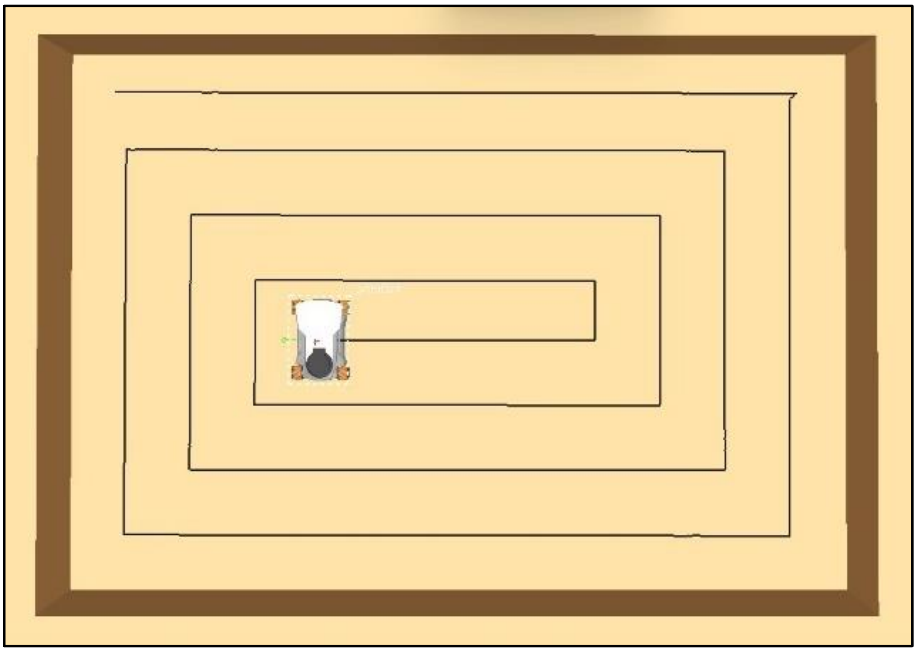

Figure 23: Path 4

Path 5:

Figure 24 shows the path that would be taken by the prototype in **path 5**:

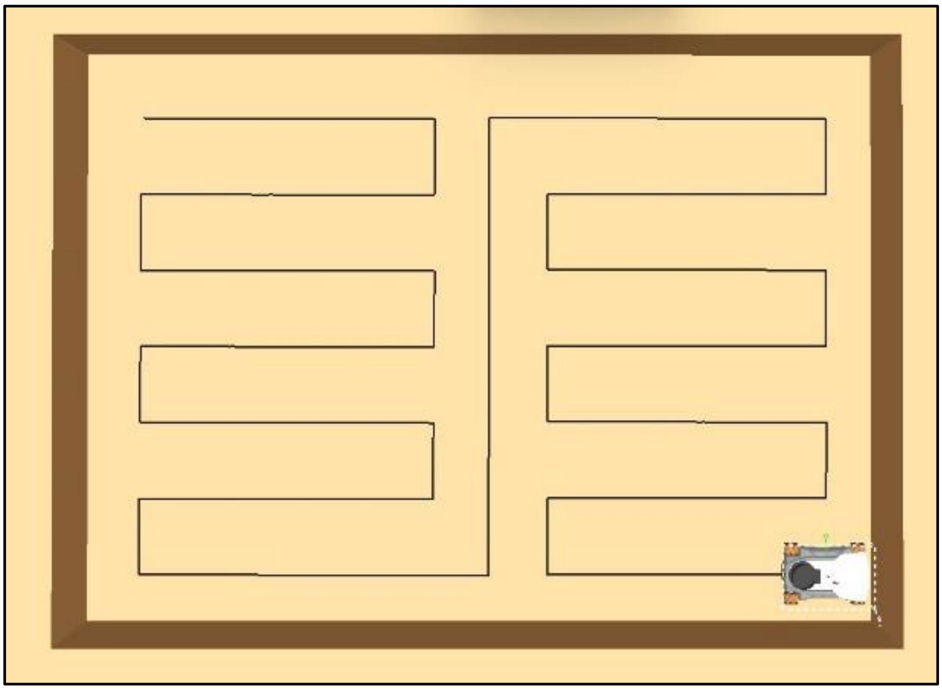

Figure 24: Path 5

3.5 Prototype work

To present the proof of concept using a prototype, a small-scale chassis was assembled for the task of navigation. The following items were used for achieving this objective:

1. Raspberry Pi 3B+
2. Acrylic glass chassis
3. L298N motor driver
4. Four DC motors
5. Two optical wheel encoders
6. A power bank, two 3.7V cells and a cell holder
7. Jumper wires

Raspbian OS was installed on the Raspberry Pi, using a 32GB SD card. The function of each component is summarized in Table 2.

Table 2: Components and Functions

Component	Function
Raspberry Pi 3B+	The central computer of our prototype – 1.4GHz Processor
L298N Motor Driver	To control and drive the motors
DC Motor	To drive the prototype
Optical Wheel Encoder	To measure the wheel rotations for odometry
Power Bank & 3.7V Cells	To provide power

The pseudocode for path 1, which was written in Coppeliasim was implemented onto the prototype with minor adjustments due to language differences, as the simulation was written in Lua and Python was used on the Raspberry Pi. Figure 25 shows the final prototype, with the components labelled accordingly.

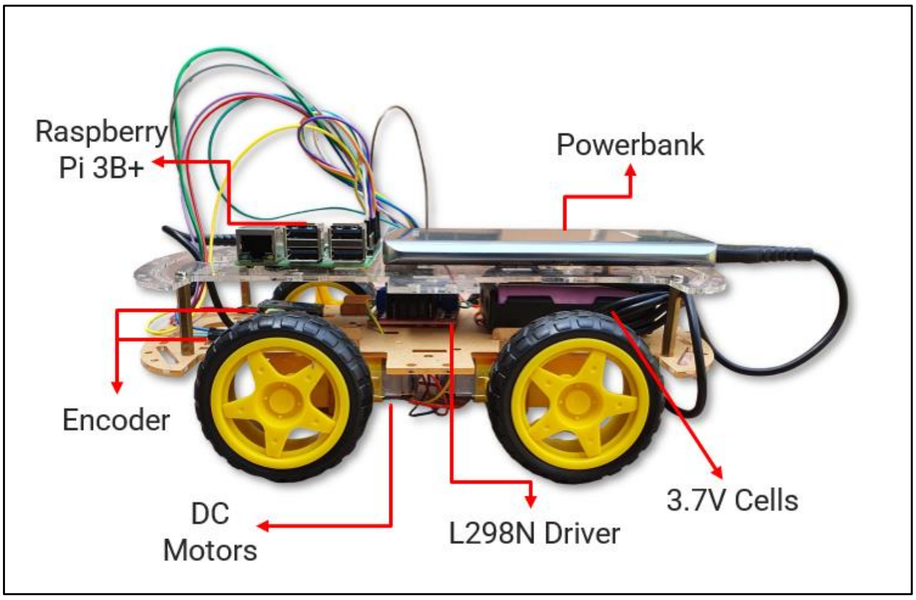

Figure 25: Prototype

Figure 26 shows the protype demonstration, performing the navigation task of path 1.

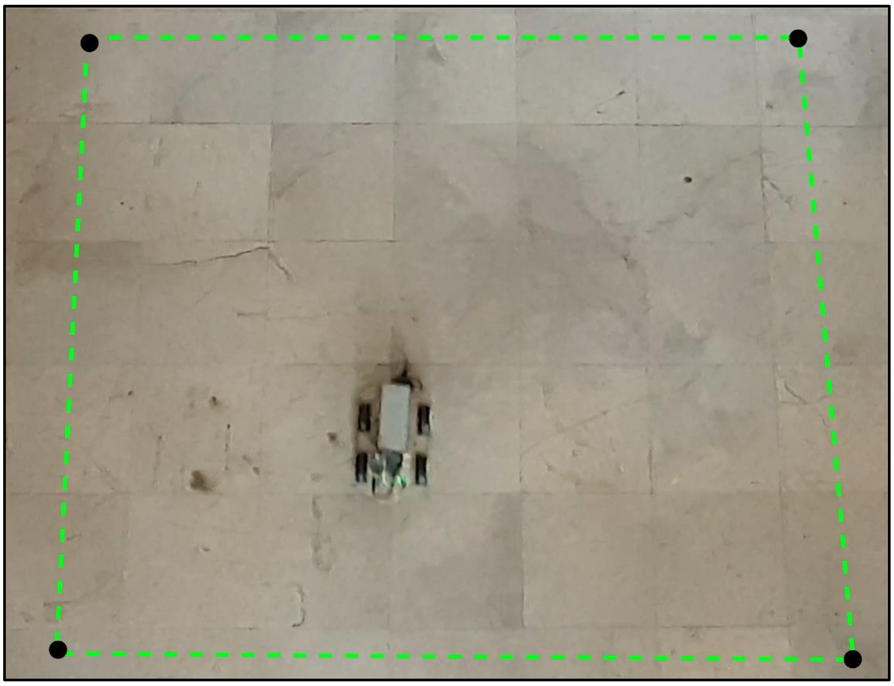

Figure 26: Prototype Demonstration

Initially remote desktop was used to access the Raspberry Pi from a computer and perform the coding. Later onwards a web interface named PiCockpit was used to control the Raspberry Pi, as shown in Figure 27. Four scripts were created for the web interface. ‘Start Navigation’ node starts the main navigation file. ‘Stop Navigation’ stops the main navigation file. The remaining two nodes are for calibration purposes. Using the web interface, the Raspberry Pi can be accessed over the internet to control the prototype.

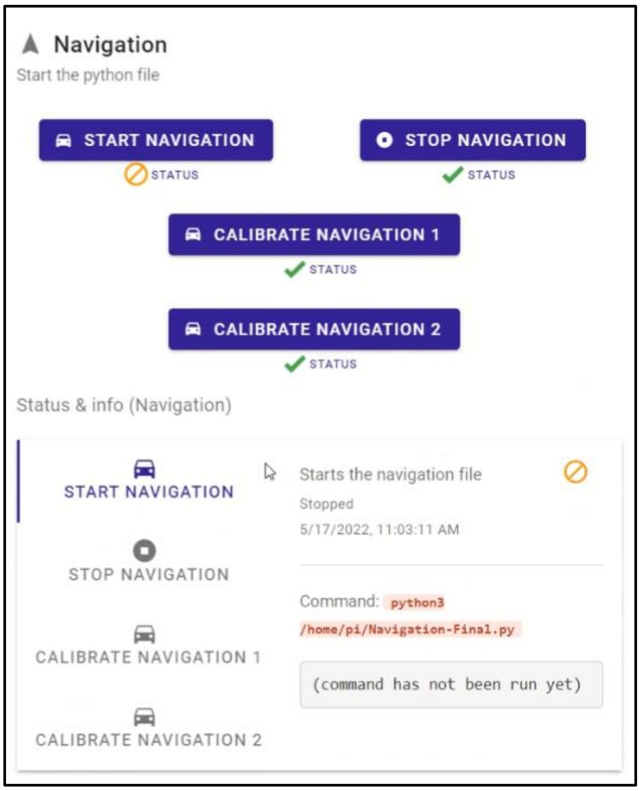

Figure 27: Web Interface

4. RESULTS AND DISCUSSION

4.1 Dynamo Export

A csv file was exported from the script created in Dynamo, which contained the coordinates of the four corners of the proposed site. The coordinates were in (X, Y) format, as shown in figure 28, which were later imported into CoppeliaSim and the Raspberry Pi.

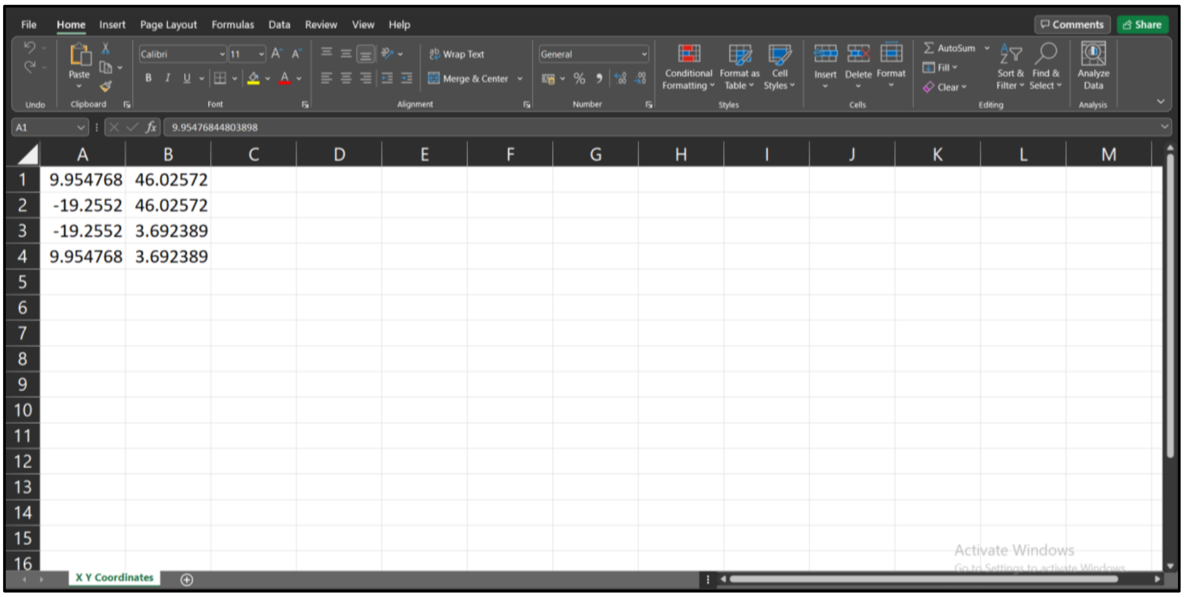

Figure 28: CSV File

4.2 CoppeliaSim Simulation

Table 3 summarises the results obtained from the simulation of different paths. It is to be noted that the simulation time is different from real time.

Table 3: Simulation Results

PATH	SIMULATION TIME *(Min: Sec: Msec)*
1	24:42:30
2	28:45:77
3	28:25:94
4	27:44:85
5	30:14:25

Figure 29 shows the speed comparison between the paths, with path 1 being the fastest and thus set at 100 percent. The remaining data represents speeds in percentage of the remaining paths with respect to path 1.

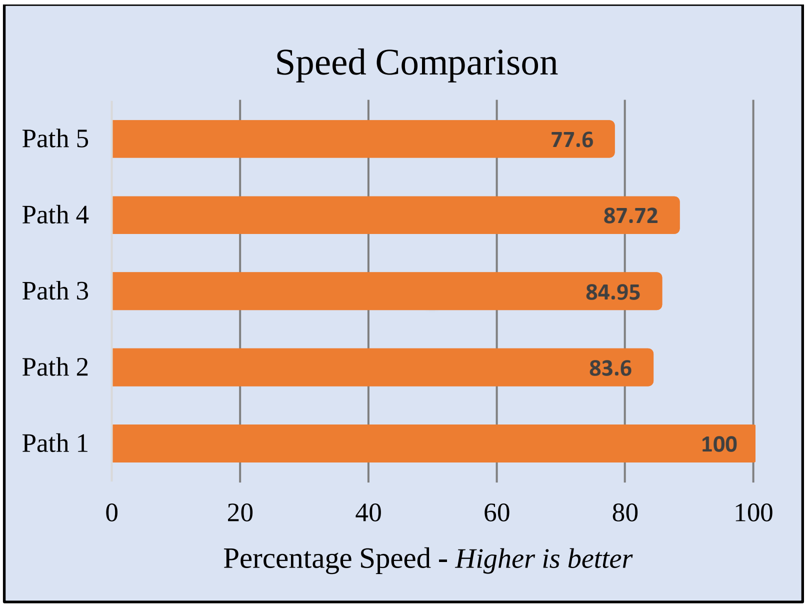

Figure 29: Speed Comparison

Thus, it can be concluded from our findings that, the number of rotations is directly proportional to the time taken i.e., greater the number of rotations, greater would be the time taken to navigate through the site. Due to the rotations in the shorter direction, path 1 took the shortest time to navigate the entire site, as compared to path 2 which has rotations in the longer direction.

After path 1, path 4 was the fastest, followed by path 3 and then path 2. Path 5 was the slowest amongst all with the greatest number of rotations.

4.3 Issues faced in Prototype Navigation and their Solutions

Several issues were faced during the coding and the demonstration of the prototype. Most noticeable issue faced was that the prototype was deviating from its straight path. Over small distances the deviation was not visible, but over larger distances, it was quite noticeable. The reason behind this issue is the inconsistent amount of power across the DC motors, as no two motors are ever the same. This results in one motor having more/less power than the other motor, thus making the prototype travelling more/less in one direction and thus deviating. To fix this issue, we used PWM (Pulse Wave Modulation). PWM is a technique which allows the variation of motor speed by increasing and decreasing the amount of power across the motors. With this solution, the deviation of the prototype was reduced to some extent.

The second issue which we faced early in the testing phase was that the prototype moved an incorrect amount of distance. The two reasons behind this issue were: (1) wheel slippage (2) incorrect number of ticks from the encoders. Due to these reasons, the prototype was falling short of the actual distance it was supposed to travel. It was observed that till 10cm, the prototype travelled the distance accurately. After 10cm, for every 10cm, the prototype fell short of a distance of 0.8cm. This error increased once the distances increased. To fix this issue, we applied a correction factor, thus bringing down the error to a negligible amount.

4.4 Assumptions

One of the basic assumptions is that the excavator is performing the excavation in one go. This means that the excavator is only excavating the soil and not returning to the dump site to dump the excavated soil. As a result, it's expected that either a dumper is following the excavator, conveying the soil that the excavator has excavated, or that the excavator has an unlimited capacity to hold the material.

The second assumption is that the excavator is traversing on level ground with no obstacles in its path.

The last assumption is that a ramp is provided in all paths for the excavator to enter or exit the pit.

5. CONCLUSION AND RECOMMENDATIONS

The construction industry is lagging behind when it comes to automation and robotics, thus lacking the necessary integration with BIM tools to make construction sites more efficient and safer. The implementation of such technologies is the need of the hour and should be the direction for research for future studies.

Much research has been done on the path planning for the excavation process but not much focus has been placed on the navigation of the whole excavator. This has caused the local navigation process to still be inefficient and highly reliant on the operator rather than pre planned.

This research has focused on local navigation and path planning of an excavator. A BIM model was designed and exported, later to be used for simulation and by the prototype. The simulation software was used to test different paths and perform time analysis on them. Furthermore, the prototype was developed to generate a clear understanding of how an actual excavator would perform the navigation process in real world conditions.

The study concludes that the number of rotations in a navigation path dictates the time taken for site navigation. Thus, to make site navigation more efficient, the number of rotations for an excavator should be limited where possible.

For further recommendations, BIM tools should be able to interact with sites having complex geometry and terrain. Such tools have to be then integrated with path planning software which exports the shortest path to navigate the site for excavation purposes. Along with this data, a simulation software needs to be used which is capable of handling the complex geometry and terrain exported from BIM.

The prototype developed for this research was at a rudimentary level. Hence, it should only serve as a guideline for future studies. It is recommended that for better results, future prototypes should be capable of performing actual excavation and precise navigation on complex terrains.

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