OPTIMIZING ROBOTIC SWARM BASED CONSTRUCTION TASKS

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Oct 2020

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DECLARATION

I declare that this is my own research proposal and this proposal does not incorporate without acknowledgement any material previously published submitted for a Degree or Diploma in any other university or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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Signature of the supervisor:................... Date:

ABSTRACT

Construction is a field that grows with technological advancements by the day. The field has always adapted novel and innovative technologies to create marvels of engineering which were thought to be impossible before their time. Having many challenges in the physical construction tasks, there are researchers all over the globe trying to innovate and improve construction related technologies. With the advancements in technology, some construction projects have already adapted robotics in some aspects of the construction process. In this research, we try to introduce a novel approach for construction using swarm robotics.

Behaviour of a robotic swarm is collective and aimed at solving a problem using the collective behaviour. This is similar to the natural animal swarm behaviour of bees/ ants/ termites...etc. Even though there are many researches and developments done in the field of swarm robotics, the concept has not yet made its way into industrial environments.

Many researchers in the field of construction using swarm robots have come up with successful algorithmic approaches for constructing simple shapes. However many of them lack practicality due to the usage of pheromone trails / building blocks with communication capabilities / bots having a real time global view of the state of the construction...etc which are difficult to achieve in the real world with the existing technologies. Furthermore, most similar researches show a serial behaviour in the construction instead of parallel behaviour seen in nature.

In this research we propose a novel and a practical approach for swarm robots for optimizing construction tasks in 2D using swarm robotics concepts. The swarm consists of a set of robots that are practical to implement, with limited visibility and limited communication skills. Having only the local view of the terrain, robots in the swarm construct a given shape in 2D in collaboration with the other robots in the swarm. With the application of swarm concepts in an improved manner, the swarm is able to construct the given shape displaying true parallelism which in turn will improve the construction time.

Constructions using swarm robots is proposed as one of the most practical methods of constructing buildings/ shelters specially for colonizing space where sending skilled workers is too expensive. The implications of this research can be an initiative to such applications.

DEDICATION

To my parents for their dedicated partnership in the success of my life

ACKNOWLEDGEMENTS

I would like to send my deepest thanks to Dr. K.S.D. Fernando, who ignited my passion for research and provided help and wisdom at every step of the way of this research. Her guidance was unequivocally crucial to this work, and I owe a great deal of its success to her.

I would like to extend my thanks and appreciation to the staff members of the Department of Computation Mathematics, for their interest in, and consideration of, my research work.

Lastly, I would also like to express my heartfelt appreciation to all my family and friends, who supported me in this long endeavor and through all my life. Though they may not know it, the impact they have had upon me is substantial, and I would have never made it to where I am now without them.

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Chapter 1 - INTRODUCTION

1.1 Prolegomena

With the emergence of new technologies, constructing things has become more advanced and less human involved. In the past manual labor was the norm for almost every industrial task. But with the advancements of technology, robotics has begun to replace humans in many tasks. With the advancement in Artificial Intelligence, many industries have hurried into adapting AI technologies in order to perform complex tasks more efficiently

Constructing a physical structure needs many workers working in collaboration. Building a structure with building blocks requires placing those blocks in the correct places in a systematic order. This order and the workers efficiency determines the time to construct the building. Similar construction behaviors can be observed in nature in ant/ termite colony building.

The performance of a collective construction task done by a robot swarm depends mainly on the systematical order of placing the building blocks and the task distribution within the swarm. A robot in such a multi robot system needs to fetch building blocks from the environment and place them in a suitable position in the desired structure so that collectively the structure is built within a minimum time and a minimum distance traveled collectively.

1.2 Aim and objectives

The aim of this project is to develop a simulation of a robot swarm that is optimized for 2D construction tasks. The swarm of robots will have a better performance in power usage and build time compared to the existing approaches to the problem. In order to reach this aim, following objectives are identified

1. To evaluate existing approaches for construction tasks using swarm robots.
2. To critically review AI concepts relevant to swarm robotics and their applications.
3. To design and develop a swarm robot construction simulation environment in which swarm concepts can be implemented and task execution can be observed.
4. To compare and contrast the results of the simulation swarm controllers with the characteristics of existing approaches.

1.3 Background and motivation

Swarm robots have numerous applications in the real world. Many researches have been carried out related to swarm robotics where researchers have proposed methods for performing various tasks using various algorithms. Space exploration is a key area which is considering using robotic swarms [1] for various tasks since it is easier to get a large number of small structures into space than sending a small number of large machinery. There are many proposals for colonizing mars and moon which require building large structures on them [2]. Huge automatic construction tasks like that may require a swarm robotic construction approach since it is not practical to use one large 3D printer of the size of the building.

Proposals for constructing habitable buildings on mars and moon includes creating shelter structures at first for protection from radiation and small meteorites. Lunar regolith or mars regolith processed into building blocks are proposed to be used for these shelters. A swarm of robots can then use the regolith blocks to build the 3D structures needed. In this research, we will focus on building 2D structures as an initiative to such tasks [3]

1.4 Problem in brief

Currently there are multiple proposals for building structures using swarm robots. In the case of building structures in an unmanned terrain with actual robots, it is necessary to find a practical method of doing it. With the existing technologies, a swarm robot created for a construction task will be a small unit capable of self navigation while avoiding obstacles including other swarm bots. It can be capable of detecting, picking up, carrying and placing a building block. However it is not possible to implement capabilities like pheromone trail detection with the existing technologies

In an unmanned environment, building blocks for construction can be created by robots or automated machines. Stationary machines can act as building block factories using the regolith from the ground to create building blocks. The task of the swarm of the robots will be building a predefined structure on the ground on a predefined location using the said building blocks. Furthermore, the structure might change from one construction site to another.

1.5 Summary

Existing research in this field not being practical to build in the real world, a practical method for construction using swarm robotics is needed. The swarm needs to build the structure within a minimal time and travelling a minimal distance so that they save power and time. In this research we will present a method to construct 2D shapes using swarm robots for an environment as described above.

Chapter 2 - LITERATURE REVIEW

2.1 Introduction

As described in the previous chapter, using swarm robots for construction tasks is not a new concept. However, existing solutions for the unmanned construction using swarm robots not being very efficient as similar construction seen in nature done by ants/ termites. This chapter discusses the existing research that can be useful in achieving the proposed objectives in this research.

2.2 Early developments in swarm robotics applications

Not being a very old field of technology, swarm robotics has come a long way in the recent past. Bonabeau et al. [4] depict phenomena in social insects that had been transferred successfully to algorithms. Biological swarm behaviors from which a number of computational algorithms were developed are also discussed by Parpinelli and Lopes [5]. Camazine et al. [6] discuss general self-organization aspects in biological systems. Moreover, Garnier et al. [7] provide a good overview of the biological principles of swarm intelligence. Floreano and Mattiussi [8] discuss swarm intelligence alongside evolutionary computation, artificial neural networks, and bio robotics. Blum and Li[9] and Krause et al [10] address swarm intelligence algorithms for optimization. Hassanien and Alamry [11] depict the natural inspirations of swarm intelligence–based optimization algorithms. Swarm intelligence–based optimization algorithms are analyzed by Yang et al.[12], the link between swarm intelligence–based optimization algorithms and self-organization is examined by Yang et al. [12], Rossi et al. [13] classify existing multi-agent algorithms according to their underlying mathematical structure.

2.3 Collective construction with swarm robots

The advantage of a system of cooperative swarm robots is that they operate locally with minimal resources and without need to understand the complexity of the whole system. Such decentralization of work provides a great robustness and flexibility as no single failure can cause overall system or task failure [14]

Swarm robotics at Harward [15] shows how a multi robot construction system inspired by the behaviour of termites mound building capabilities. They try to understand and mimic the low level rules that govern the behaviour of termites resulting in coordinated construction of very large structures compared to the size of the individual building entities.

Research by Justin Werfel [16] compares and contrasts multiple approaches for collective constructions with robot swarms. It shows that simple algorithmic approaches with robots having only basic senses will result in incomplete constructions. The proposed solution in the paper is having advanced building blocks with programming and communication capabilities. It has demonstrated how such blocks can be used to build 3D structures successfully by a robot swarm.

An extended research on the above by Werfel et al [17] gives a better insight at the two approaches and shows mathematically that using communicative blocks are more efficient. However in this setup, the robots do not have a communication system among them. Robots figure out the real time status of the construction using the data broadcasted by the building blocks. Another research by Werfel et al [18] evaluates how a robot swarm can build predefined patterns of blocks using communicating blocks and multiple simple robots.

A novel approach for construction by bulldozing gravel is suggested by Parker et al [19]. This method is using minimalist robots with limited sensory capabilities to push material outside their desired area of construction so that the area becomes clear and material forms a wall around the area. The bots have only a pressure sensor. When they push gravel outside, they know when to stop by measuring the pushing force. This basic control method has resulted in a successful way of clearing an area.

A more practical approach has been suggested and tested by Stewart et al [20] for wall construction. The research paper has suggested an algorithm based on a distributed feedback mechanism to regulate the construction and the researchers have tested it successfully in the real world using a set of small bots.

2.4 Swarm concepts in construction

2.4.1 Blind bulldozing

Collective construction can have two main strategies. Construction by accumulating material and construction by removing material. Blind bulldozing is a proposed swarm robot construction method for the second strategy.. A swarm of robots having minimal sensory capabilities can adapt this method.

Parker et al [19] uses blind bulldozing method to construct a nest-like structure by removing rubble on the environment using a robot swarm. The robots in this case are equipped with basic pressure sensors attached to their fronts. Once the task is started, they try to push the material outside of their initial position. The pushing stops once a pressure threshold is detected. With evenly distributed gravel on the ground, a swarm of robots can clear a circular area in this manner.

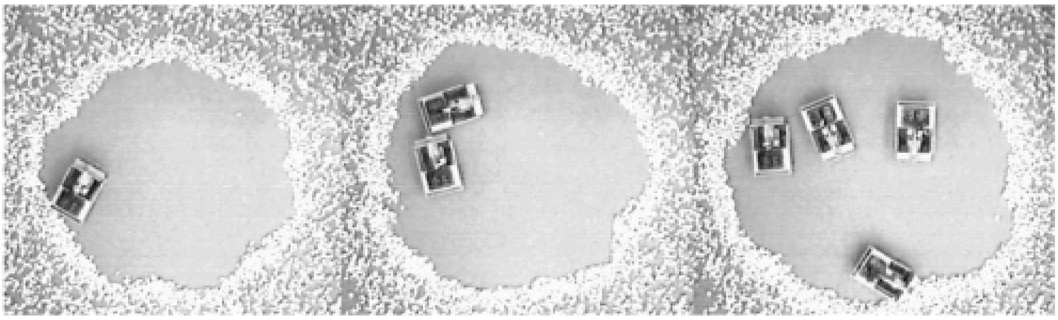

Figure 2.4.1: Nests constructed by blind bulldozing by one, two and four robots

With very simple instructions, the robot swarm manages to construct a structure in this method. The circular nest shape emerges from the simple action of pushing out material until a pressure threshold is measured. This kind of robot swarms can easily display true parallel construction behaviour because of them having a very simple instruction set.

The research furthermore evaluates the efficiency of the construction with the number of robots in the swarm. The time taken for the construction drops with the increase of the number of robots in the swarm with the parallel nature of construction

2.4.2 Leader based construction

A robot swarm can have a leader to help guide the task that it is intended to do. In nature, some swarm forming animal behaviour can be seen centered around leaders. Ants store their food and keep the eggs close to their leader. Bees create hives centering their leaders [7]. A similar approach is taken when a leader based robot swarm is designed [21].

Russell et al. [20] propose a method for wall construction guided by a light beam from a leader. The swarm bots follow the light beam emitted by the leader and do the construction at places where the light intensity is at a particular level. With this method, a stationary leader with a light can guide a swarm to construct a wall around the light at a distance where the intensity is at a specific value. The leader can move while swarm robots do the construction and guide the robots to build arbitrary shaped walls.

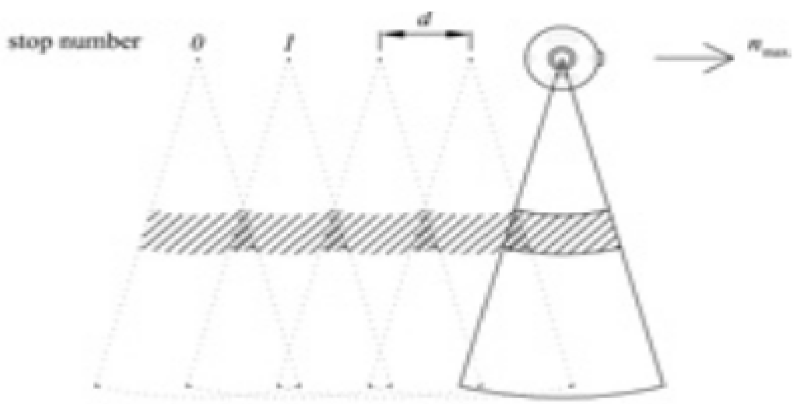

Figure 2.4.2: The leader robot moves at the direction of the arrow. The dark area shows the area where similar light intensity can be detected as the robot moves, where swarm robots are supposed to do the construction creating a wall like structure

Furthermore, there are several other researches that use a leader like behaviour. The self assembling kilobot robot swarm [22] employs an overhead camera to have a global view of the assembly at all times in order to determine when to release the next swarm bot to the formation once the previous bot is positioned.

2.4.3 Rule based construction

Some insects that show swarm behaviour are observed to be following simple rules for building structures. Inspired by wasps like insects, some researches are done with swarms to build coherent nest-like structures. However, with only rules to guide the swarm robots, there are no predetermined shapes fed to the swarm. Instead the build shape emerges from the rules

Theraulaz et al. [23] shows that such rule based construction systems can produce coherent biological like architectures. Furthermore, they show that the swarm entities need specific coordination properties to produce such architectures.

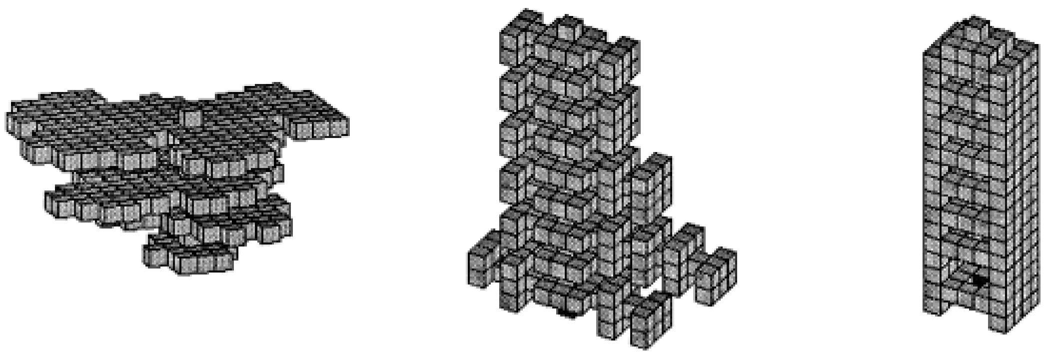

Figure 2.4.3: Some shapes constructed by rule based lattice swarms

Pollack et al [24] combine rule based approach with stigmergic cooperation between the robots to produce more complex constructions. However this still does not aim at creating pre determined shapes.

2.4.4 Stigmergic cooperation

Swarms observed in nature coordinate their behaviour stigmergically. Communication and coordination between entities of the swarm happens through the changes in the local environment they observe. This is adapted heavily for swarm robotic behaviour in various ways [24]. Stigmergic cooperation allows robots in a swarm to have information without heavy communications between robots. This allows simplistic swarm robot designs while having coordination between the robots and the robot task of the swarm.

In a construction task, stigmergy happens from the changes in the structure that is being constructed by the swarm. Small changes one makes in the construction is new information to the other robots when they perceive the change. Then they can modify their next behaviour for the task completion depending on this stigmergic information

Without direct interactions between the robots, stigmergy makes the construction task independent of each individual entity, which means an increased number of entities only help speed up the construction but not the outcome of the process. This in turn introduces a massive redundancy to the system since the failure of one/ few entities does not affect the task of the swarm system [24]

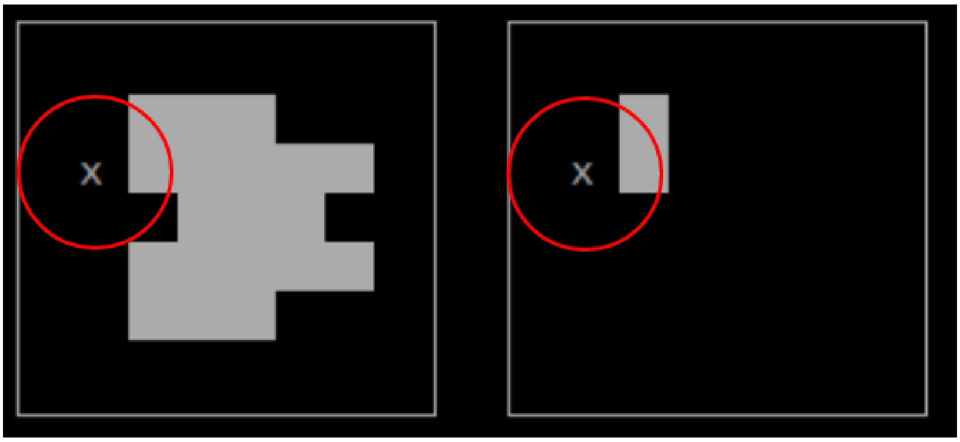

Figure 2.4.4: Global map of a construction (left) and perceived local map (right) of a robot (marked x) at a particular time. Red color circle shows the maximum sensory distance of the robot

The popular kilobot swarm robots [25] are capable of self assembling into given 2D shapes. The robots can perceive the immediate environment and decide on where to assemble themselves in the given shape in order for the collective robot swarm to construct the shape. The state of the local environment which gives robots a partial view of the state of the construction is used for the stigmergy in this research

Some researchers have used extended stigmergic techniques by enhancing the perceivance of nature by various means. Werfer et al [17] has proposed an extended stigmergic method which uses building blocks that have communication capabilities. This allows robots to have a global view of the construction in real time without directly perceiving the entire construction. This is achieved by enabling the building blocks to communicate between each other and the robots. As building blocks can determine their relative position in the construction, robots can use information from the blocks to determine the real time state of the construction. However this is not practical in constructing large structures with hundreds or more building blocks since the cost can get very high and the failure in building block communication can lead to large errors

2.4.5 Using AI with swarms

Using evolutionary algorithms with swarm robotics is a challenge because instead of evolving single agents, clusters of multiple agents need to be co-evolved despite the fact of them each having only a local view of the global environment. The swarm needs to be scored using a criteria considering the collective performance instead of the individual performance in this case.

A research by Dorigo et al. [26] proposes a method to develop controllers for robot swarms using co-evolution of the swarms. They study and evaluate the aggregation and coordinated motion of the swarm bots with a simulation of a robot swarm. They have found that the evolved controllers are having a generality in the sense that they show similar behaviors for configurations that they were originally evolved for.

Robots in simulations perform differently than robots in the real world. Robots behaving perfectly in simulation might not work in the real world. O'Dowd et al. [27] present a distributed co-evolution method for robot swarms taking the aforementioned 'reality gap' into account.

2.5 Summary of past related researches

Research	**Brief**	**Features**
Blind bulldozing- multiple root nest	Constructing a nest like structure with robots with	1. Minimum robot sensory and processing

construction [19]	bulldozer like behaviour	capabilities 2. Building by clearing out material
Controllability Characterizations of Leader-Based Swarm Interactions [21]	Investigation into network topologies for controlling swarms of mobile robots	1. Swarms controlled by humans; commands are given to the leader 2. A networked command and control system for robots
A Distributed Feedback Mechanism to Regulate Wall Construction by a Robotic Swarm [20]	Construction of walls with a guided leader in the swarm to mark the area where the construction needs to happen	1. Leader guides the swarm using light as a signal 2. Feedback between robots and the leader to understand the state of the construction
Modelling the Collective Building of Complex Architectures in Social Insects with Lattice Swarm [23]	Building 3D structures with swarm robots governed by simple rules	1. Rule based construction 2. No predetermined shape of construction
A Stigmergic Cooperative Multi-Robot Control Architecture [24]	A robot swarm architecture for stigmergically construct 3D shapes initiated from a seed block	1. Started from a seed block 2. Limited sensory capabilities 3. No predetermined shape of construction
Construction by Robot Swarms Using Extended Stigmergy [17]	A robot swarm constructing using building blocks that have communication capabilities	1. Building blocks communicate with robots 2. Robot have a real time view of the construction
Kilobot: A low cost robot with scalable operations designed for collective behaviors [22]	A low cost small robot capable of swarm behaviours such as self assembly	1. Very small build 2. Simple algorithmic approach for self assembly
Designing Collective	Construct structures by pre	1. A compiler creates

Behavior in a Termite-Inspired Robot Construction Team [15]	determining control rules for the swarm depending on the shape of the construction	instructions for robots prior to the construction 2. Robots use local sensing to coordinate activities to a limited extent

2.6 Limitations of the existing similar research

Most observable and common problem that is present in the existing approaches is the lack of true parallel behaviour opposed to what we see in nature. Many swarm approaches make the swarm entities move in parallel. However, the most critical step, which is placing building blocks, happens serially in most cases. This is caused by the algorithmic approaches that are adapted for controlling swarm robots. The algorithm described needs to know the state of the previous block placing to determine the next block placing strategy.

Some approaches show a non redundant swarm system. In a swarm system, redundancy is a major expectation since there are multiple entities working at the same time. Failure of one entity should not affect the collective task and should not cause the task to fail.

In this research we aim at constructing given shapes. In that sense, some of the considered existing approaches are not successful since they do not aim at constructing a particular shape. The constructed shape emerges from the collective behaviour governed by the specified rules for controlling entities in those systems.

Some more limitations can be identified in several researchers such as the need for a seed block to start construction (need an external input for starting the task), need for a global real time view of the system and communication between swarm robots which limits the independent nature of swarm robots in the collective environment.

2.7 Problem definition

Existing research in the field of swarm robotics not having practical implications in the real world, an optimized method for construction using swarm robotics is needed. The robot swarm needs to build the structure within a minimal time and travelling a minimal distance so that they save power and time compared to the previously proposed approaches. In this research we will present a method to construct 2D shapes using swarm robots for an environment as described in the previous section.

2.8 Summary

Using swarm robots for construction tasks is not a new concept. However, the literature suggests that there is no practical usage of the technology due to the lack of performance compared to the conventional approaches. Not seeing swarm robots being used commercially at the moment supports this claim furthermore. Therefore, researching for approaches with better performance is a must for the development of the swarm technology.

Chapter 3 - TECHNOLOGY

3.1 Introduction

In chapter 2, a lengthy review has been done on swarm technologies used in the field of construction. The problem has been identified and potential technologies that can be used to resolve the problem has been discussed as well. This chapter presents the technologies that are adapted in this research such as rule based swarm control and stigmergic cooperation

3.2 Swarm robot design

In the literature review, one problem that was highlighted in the existing research was impracticality of many methods that are proposed. Therefore in this research the robots designs are developed such that the they are practical to be implemented with existing technologies

3.2.1 Sensors

Swarm robots are designed to have low cost hardware which is readily available at the time of doing this research. A small robot in a swarm can have a single board computer running with its controlling software and a set of low cost sensors.

The swarm robots have sensory inputs such that they can perceive their immediate environment. This limits their visibility to a local area and thus not having a global view of the real time construction which is the case for a real world robot. Robots are assumed to be able to identify other robots (for collision avoidance while navigation) and identify blocks that are placed within the expected construction. It is practical for the robots to initially give the locations of the building block factories since they are stationary.

With the current technology, pheromone trails are not practical to be used by robots. Considering the fact that building blocks are in the numbers of thousands or more when building a real world structure, it is not practical for each of the blocks to have a device with communication and localization capabilities either. In the real world, it is safe to assume that the inter robot communication has a limited range. Therefore, having a global view of the real time construction is not possible.

3.2.2 Building block factories

Factories are stationary places in the environment. Robots will have to go to the factories to get new building blocks once a block is placed in the construction site.

3.3 Stigmergic cooperation

In nature, animals that show swarm behaviour communicate using changes they do to the environment. Changes one entity of the swarm does is observed by others and that information helps them adjust/ reorganize their tasks.

3.3.1 Stigmergy from the local view of the construction

The sensory view of robots is information for the robot to determine the state of the construction. Even though this makes the robots have a partial view of the construction, it is practical in the real world to have such a view instead of a global view [28]

A robot can not have a global up to date map in this manner. Therefore, a local map is maintained by each robot. As the robot explores new areas, the map is updated.

When the robot has a building block, it determines where to put the block based on the data it has on the environment which is its local map. However, once the determined place is reached, it might be already filled by another robot since the robots are working independent of each other. As the local map gets updated with this new information, now the robot can determine a new place to place the block

3.3.2 Stigmergy from the environment

When multiple robots work together in the environment, they can cross each other's paths. Practically, the robots should not collide each other since it can be damaging to the robot hardware.

Once a robot in the simulation sees another robot in its vicinity, the new robot is perceived as an obstacle in the map. WIth the robot’s capability of differentiating between blocks and robots, it should know that this obstacle is not a permanent one. This information is used to not include the detection in the local map for calculating the next block placement

Furthermore, a path planned to place a block can be obstructed when the robot returns to a particular place since it has previously been there. The construction by other swarm bots has been going on while the robot went to fetch the block.

When a robot sees another robot obstructing its path, or when the planned path is obstructed by the latest building blocks placed, a new path is planned again using the local map. This time, the local map is updated with the new data before planning the path and hence it will avoid the newly identified obstacles

3.4 Rule based controllers

Inspired by wasps and similar insects, structure construction can be done with construction entities having simple rule sets to determine how to place building blocks relative to the environment and the current state of the construction. In such systems, the final shape of the construction is an emergent feature of the rules the swarm robots have. Such a system does not need to possess large computational capabilities or communication capabilities between robots. No global view of the final outcome is needed for the robots to do the construction either.

With the added stigmergy, rule based controllers can be improved. The rules are introduced to the swarm robots so that,

1. They will escape edge cases such as making another robot stuck in a enclosed part by placing a block blocking the other’s escape path
2. Do not harm each other by colliding while in operation
3. Update tasks based on the new information from the environment

A simple set of rules govern the robot controllers above their control algorithm

1. If travelling and another robot is crossing the travel path, reroute the path considering the other robot as an obstacle
2. If the target location to drop the building block is filled, find a new suitable place to drop the building block and reroute to there
3. If there is another robot in the vicinity and the next block that is going to be dropped blocks the other’s path and make it stuck inside the construction, find a new suitable place to drop the building block and reroute
4. If placing a block makes an empty space in the construction which is not

reachable after placing this block, place the block in the empty space instead of the planned location

3.5 Summary

In this chapter, the technologies that are used for this research are discussed. We use the stigmergic and rule based controlling concepts to develop our robot controllers for the robots in the swarm. In the next chapter, the approach to adapt these technologies is discussed extensively

Chapter 4 - Approach

4.1 Introduction

The precious chapter described the technological concepts that are adapted for this research. This chapter extensively describes our approach for implementing those technologies in terms of input, output and process

4.2 Hypothesis

We hypothesize that the performance of robot swarms can be enhanced and optimized using evolutionary concepts so that robot swarms can complete construction tasks using less power and time compared to the existing approaches.

4.3 Input

The input for the robot swarm is the shape to construct. Each robot in the swarm will have inputs from their sensors which in turn will give them information on their immediate surroundings

4.4 Output

A robot controller that can be used in robots in a robow swarm such that the robot swarm can perform 2D construction tasks with a optimal performance compared to the existing such approaches

4.5 Process

The swarm robot simulation having an environment depicting the terrain and the robots with their sensory capabilities, a sequence of simulations will be run, evolving the robot controllers at each step to better perform the construction task. The construction image fed to the swarm will be different at each simulation to avoid the controllers specializing and overfitting to a single construction shape

Each robot having a neural network evolving with neuroevolution, converts the inputs they have to decide the next position to place the building block. Collectively this will construct the full shape that is fed to the robot swarm

4.6 Users

Researchers can use the results of this research for extended research or for specific construction tasks. Robot manufacturers and construction firms can use the results of this research to create a swarm of robots for real world construction tasks

4.7 Features

The swarm robots hypothesized for this research have specific features which are described in the beginning of this chapter. The expected environment for the robots will have building block factories. The terrain needs to be selected by a 3rd party based on the shape of the construction needed

4.8 Summary

This chapter shows our approach for the research. The hypothesis of the research with input, output, process...etc. components are described in detail here. In the next chapter we discuss the design that implement the technology described in the previous chapter with the approach described in this chapter

Chapter 5 - Design

5.1 Introduction

In the previous chapter the approach for this research is described. In the chapter before, the technological concepts that are adapted for this research are discussed. This chapter extensively dives into the design of the research implementation using the discussed technologies and the approach

5.2 High level architecture

The simulation environment will have robots, building blocks and building block generators as mentioned in the previous section. The modules in the system are connected as follows

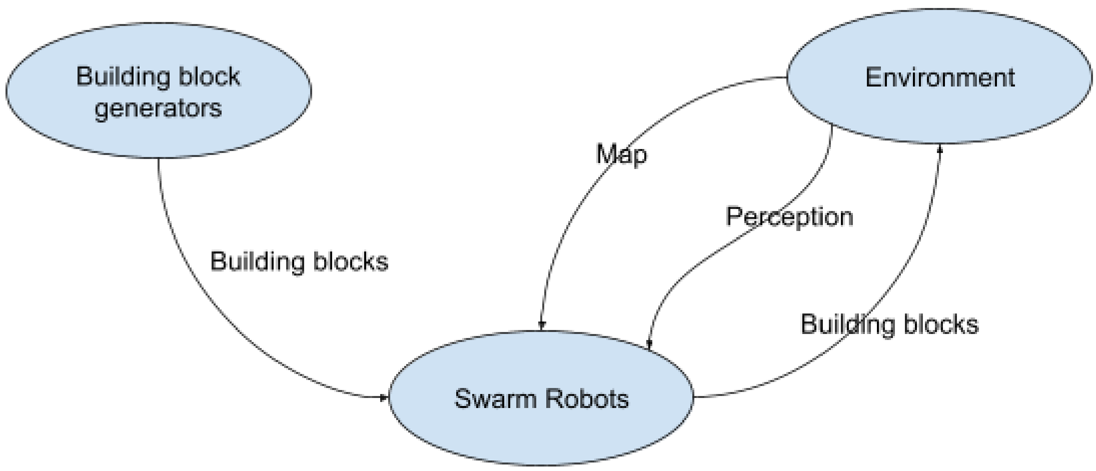

Figure 5.2: High level architecture of the simulation

1. **Swarm robot**

   Swarm robots will have sensory inputs such that they can perceive their immediate environment as described in the previous sections. This limits their visibility to a local area and thus not having a global view of the real time construction which is the case for a real world robot

2. **Environment**

   Environment contains all the modules and enables perception for the robot sensors in the simulation environment

3. **Building block factories**

   Static objects that provide building blocks for the construction. The positions of these are given to the robots. However, the positions vary from simulation to simulation. Robots need to return to the factories to get a new building block after placing a block for construction

The design for the simulation divides into two parts as mentioned in the previous section. First is the 2D simulation that will be used for initial training of the robot swarm. For the second part, ROS gazebo simulator environment will be used with adapted robot controllers from the part one

5.3 Design of swarm robots

In order to test a construction robot task, a swarm of robots is needed with defined capabilities and limitations. Due to the practical limitations, the research will be done using a simulation ensuring a minimal reality gap. In the scope of this research, we assume a bot in the swarm to have specific abilities and limitations which are practical for small low cost robots with the current technologies

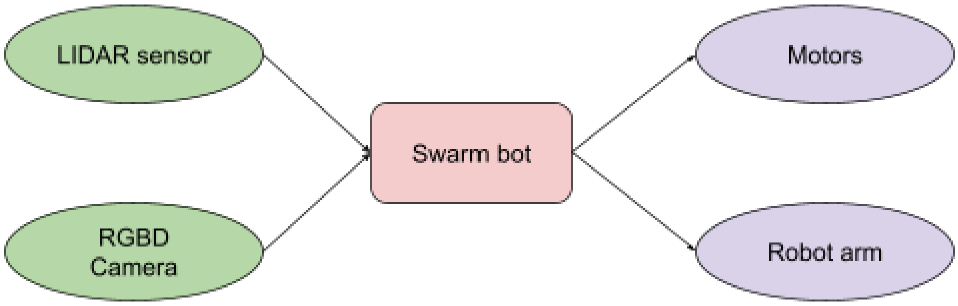

Figure 5.3: Swarm bot inputs and outputs

With the existing technologies, a swarm robot created for a construction task will be a small unit capable of self navigation while avoiding obstacles including other swarm bots. It will be capable of detecting, picking up, carrying and placing a building block. The bot will have a simple communication method to exchange information with other robots in its neighborhood. There will be a GPS receiver on board each swarm robot so that the robots know their location on the global map. These can be listed as follows

1. Able of carry one building block at a time
2. Able to navigate avoiding other robots and obstacle
3. Have a simple inter-robot communication system which is able to exchange information with robots in its neighbourhood
4. Have a GPS receiver enabling to know one's location on global map
5. Can identify and differentiate objects in its vicinity (blocks/ bots)

Given a shape to construct, the builder robots in the swarm basically have to place building blocks within the shape. The challenge in this research is to make the robots place the blocks in an optimized pattern making the construction time minimal.

In an unmanned environment, building blocks for construction will be created by robots or automated machines. They will be stationary and will use the regolith from the ground to create building blocks. The task of the swarm of the robots will be building a predefined structure on the ground on a predefined location using the said building blocks. Furthermore, the structure might change from one construction site to another.

5.4 Simulation design

The 2D simulation is designed to simulate the evolution of the robot swarms in a computationally optimized way, making the progress faster. The environment will basically consists of the terrain, swarm bots and building block factories

The simulation environment implementation is straightforward. Environment keeps track of all the robots and blocks placed. When a robot asks about a position in the environment, it replies with the information of the occupancy of the position. (Occupied by a block, a bot...etc)

As the construction goes on, the progress of the construction is monitored by the environment. If the construction is finished or the maximum time is elapsed, the simulation is finished

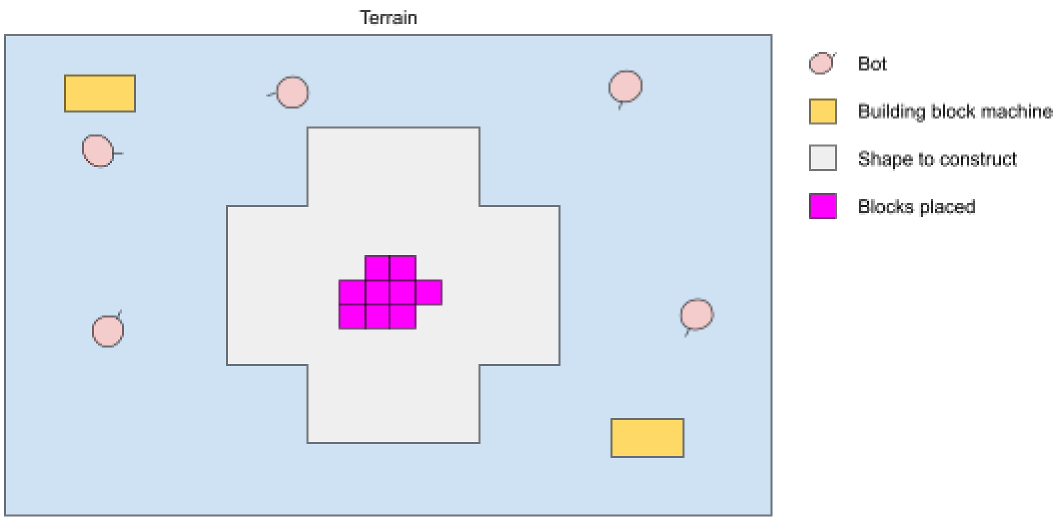

Figure 3.3 -2D simulation environment structure

The grid environment will help robots map the terrain and determine the block positions for the shape that needs to be build

5.5 Summary

This chapter described the design of the simulation environment for testing our hypothesis. The architectural designs and mathematical details were discussed extensively. In the next chapter we go into the details on the implementation of this design

Chapter 6 - Implementation

6.1 Introduction

Implementing the simulation for testing the hypothesis is described in this chapter. We go into the details of the concepts and mathematics used for implementing the proposed design in this chapter

6.2 Simulation framework

There are many frameworks present for 2D environment simulations. Python pygame [1] is one of the most widely used such a framework that is very flexible and easy to use.

Pygame is a fast 2D graphic library which is implemented in C at the core in order to make it very fast at rendering and simulations. Since it is very commonly used for visualization related applications, reference material is also widely available which makes it easier to use

6.3 Simulation Environment

The terrain is represented by a canvas of size $W \times H$ where W is the width and the H is the height in pixels. In the canvas, we define a building block size of $w_b \times h_b$ where w_b is the width of a block and h_b is the height of a block. The shape is constructed by the blocks of this size. Therefore, the shape is resized into a suitable size that can be fitted into the canvas

[1] https://www.pygame.org/

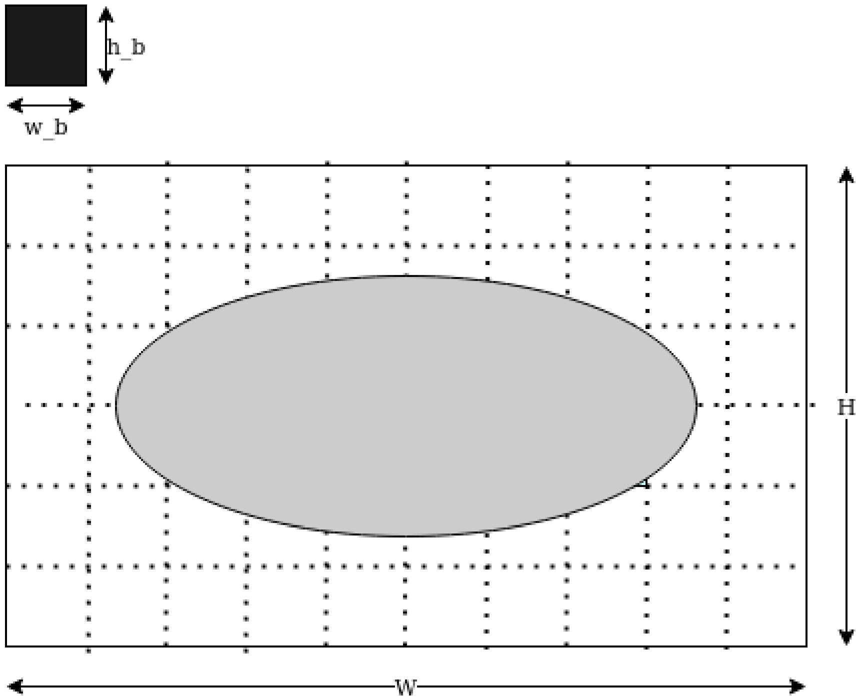

Figure 6.3.1: A building block (top) and environment canvas (bottom). Grayed area depicts a construction shape. The ellipse overlapping squares marked by dotted lines are to be filled with building blocks to complete the construction

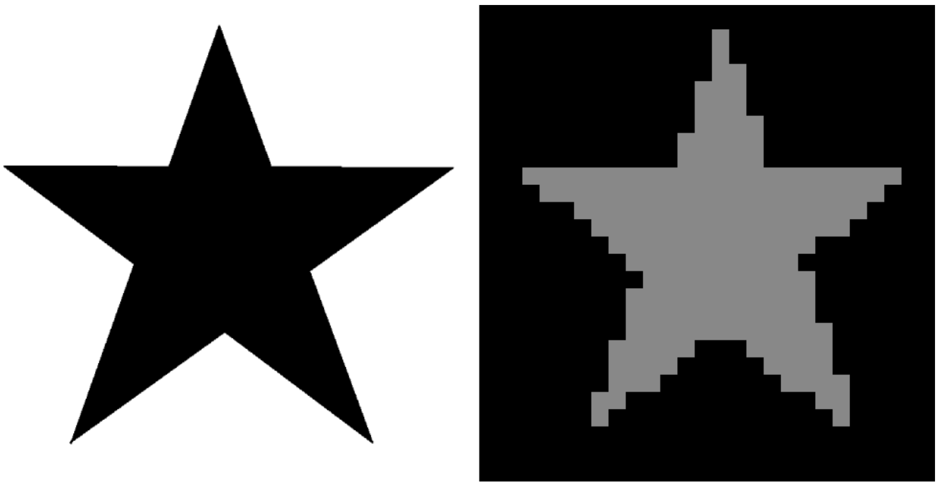

Figure 6.3.2: A start shape given to construct (left) and a resized image (right) to match a block size of 20x20 in a canvas of size 800x600

6.4 Robot controller

6.4.1 Navigation

The robot work environment is a map with each pixel depicting a block sized chunk. Each robot plans its action on this map which is smaller than the canvas size. This simplifies the navigation and related processing

E.g. For a canvas of size 800×600 with block size 20×20, each block depicting a pixel, the local map of each robot is of size 40×30

Robots need to navigate to and fro building block factories and the construction site. At the beginning, each robot needs to get a building block from the nearest block factory. The block factory locations are fixed and are fed to the robots at the start of the construction task. When a new block is needed, robots go to the nearest block factory and fetch a block

Robots use A* path planning for planning the navigation path

6.4.2 Sensor data processing

Robots perceive only their immediate environment by their sensors. This data is used to update each robot's local map at each step of the simulation. Until new information comes on a particular pixel on a map, the old data is used for calculations

6.4.3 Calculating next block drop position

The most critical task for a successful construction is the systematic order of block placing in the shape for construction. We have created an algorithm where robots try to build the shape from its center to the outside. This allows robots to construct from inside to the outside of the shape which is the behaviour we see in ant/ termite mound construction

The steps of this algorithm can be broken down as follows

1. Set next block position to the center of mass of the given shape

   This gives the approximate center of the area distribution of the given shape to begin with. It can be considered the center of the shape. The centroid is calculated by taking the pixels inside the shape having a weight of 1 and others weighing 0

$$Center\ of\ Mass\ =\ (\frac{\Sigma m_i x_i}{\Sigma m_i}, \frac{\Sigma m_i y_i}{\Sigma m_i})$$

   Where m_i is the mass of each pixel and (x_i, y_i) is the row and column of the pixel

2. When placing a block, observe the surrounding blocks and remember the free pixels to be used as next placing candidates

   This encourages bots to stay in one area since the next block is probably picked from near where the previous block is placed. However, these locations can be later found filled when the robot arrives with the next block after placing this block and picking up a new one

3. If the center of mass pixel is occupied in the local map, get the closest pixels to the occupied pixels in the map

   Now that there are one or more blocks in the shape, the next block must be placed near existing blocks. We take the empty pixels that has one or more neighboring occupied pixels in the shape

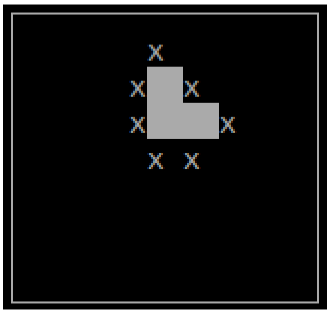

Figure 6.4.3.1: If white pixels are occupied, we need to place the next blocks at the locations marked by xs

4. If any of the candidate pixels are in the previously stored candidates, drop the others. Otherwise (if all previously marked candidate pixels are now occupied) do nothing

5. If all the candidate pixels have the same number of neighboring occupants, select the one closest as the next block position

   Navigation time is lower for closer blocks

6. If different candidates have different number of neighboring occupants, select the ones with the highest number of occupant neighbors and select the closest one from them

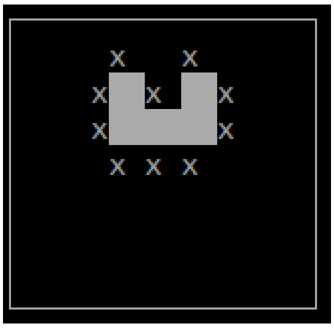

Figure 6.4.3.2: The pixel stuck inside the u shape has 3 occupant neighbors while others have one each. Therefore priority must be given to the one that is closer to be getting trapped inside the shape

6.4.4 Control algorithm

```
While not all bots finished:
      For each bot:
            Update local_map with sensor data
            If stuck or build_shape finished:
                  Set bot finished
            Elif no block:
                  Set path to nearest block factory / navigate
            Elif reached block factory:
                  Load block
                  Calculate next drop position
                  Reroute
            Elif reached drop position:
                  If drop position is filled:
                        Calculate next drop position
                        Reroute
                  Elif drop blocks another bot:
                        Calculate next drop position
                        Reroute
                  Elif drop creates empty unreachable
position:
                        Reroute to unreachable position
```

```
Elif obstacle on path:
     Reroute
```

6.5 Simulation outcome

Here a simulation of the swarm system is demonstrated further describing how the swarm concepts and the implemented control algorithm works to create a star shape given

1. All bots start at random locations. Four red circles at corners are building block factories. The bots are numbered and their paths are shown in the respective colors. Initially all are going to place their block at the center of gravity of the shape

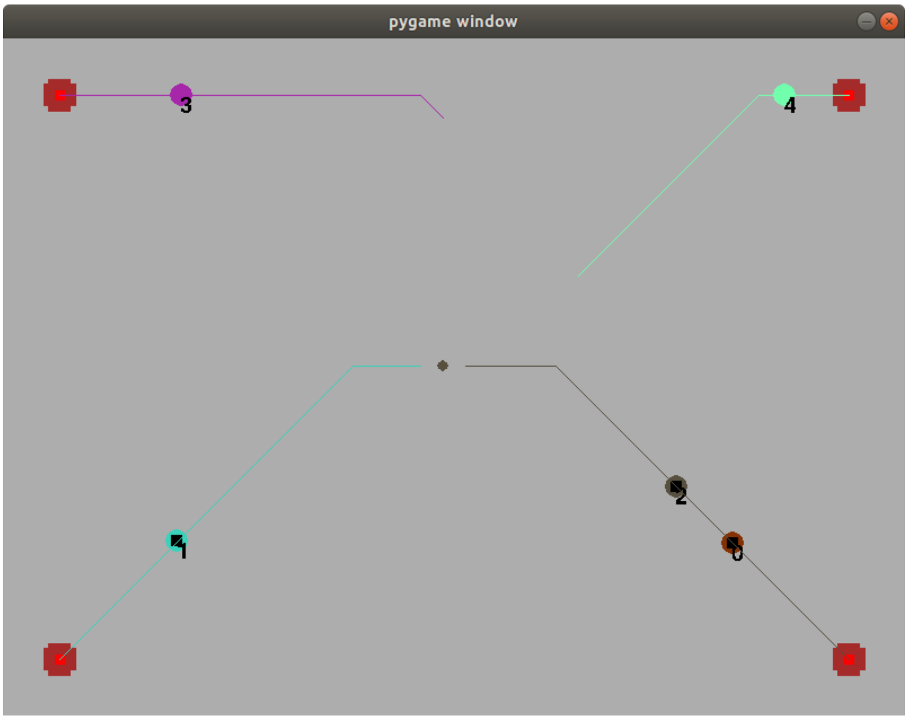

Figure 6.5.1: Initial robot behaviour

2. After placing a few blocks

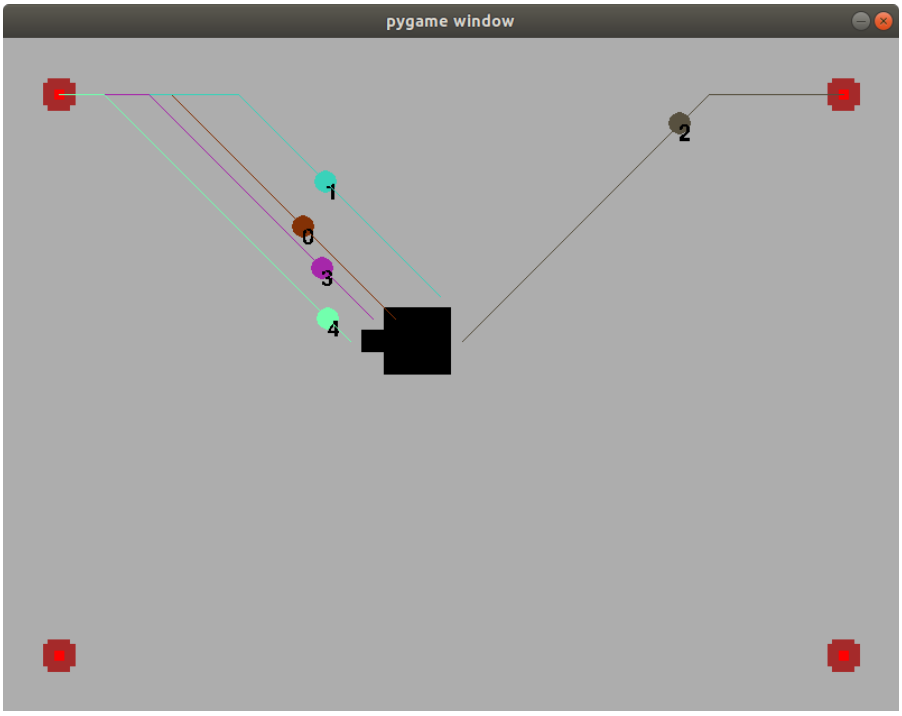

Figure 6.5.2: After a few blocks placings

3. The small colored dots show where bots are going to place their blocks. Notice how number 2 bot is going for an already filled location. It was empty when the bot last saw the location

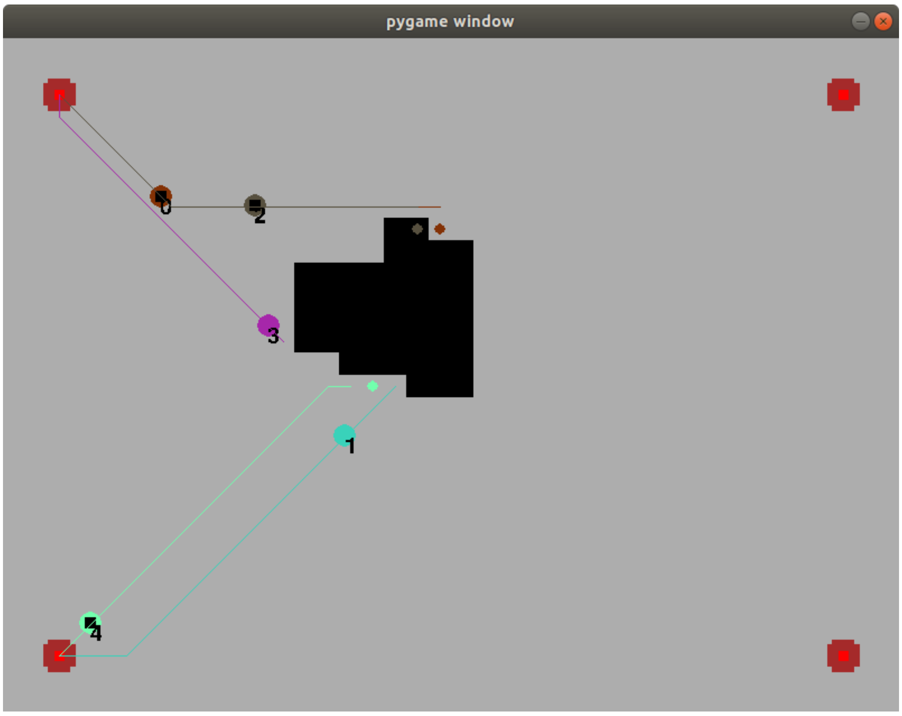

Figure 6.5.3: Number 2 bot going to fill a filled position

4. After coming close to the intended location, number 2 has seen the location was filled and changed the target to the next pixel. However number 0 bot is on the way to fill in that position

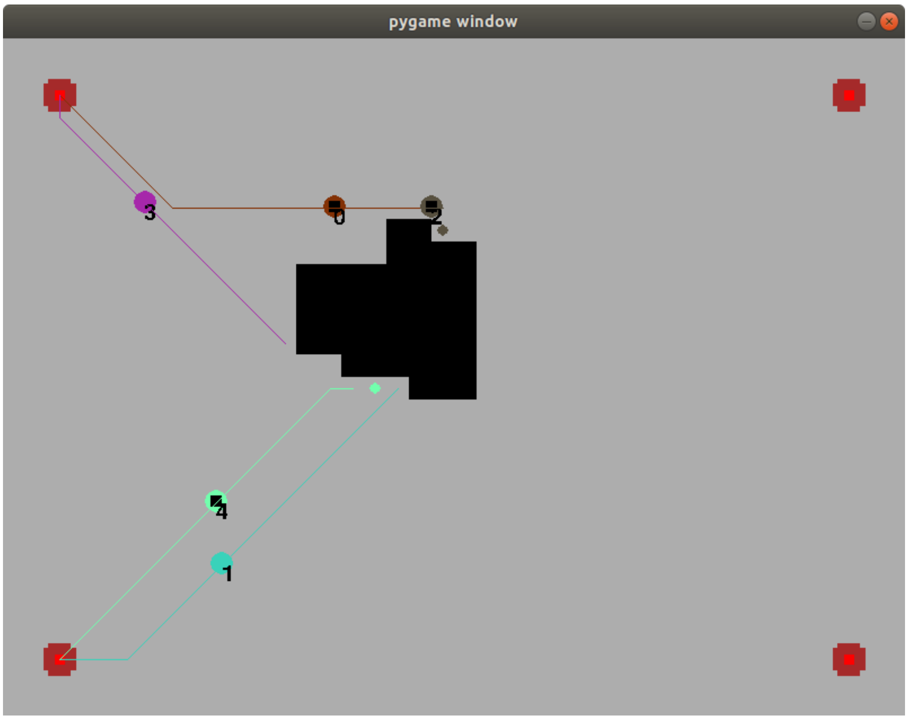

Figure 6.5.4: Number 2 changed its target location to the next location

5. Now number zero is coming to fill a filled position while number 2 leaves

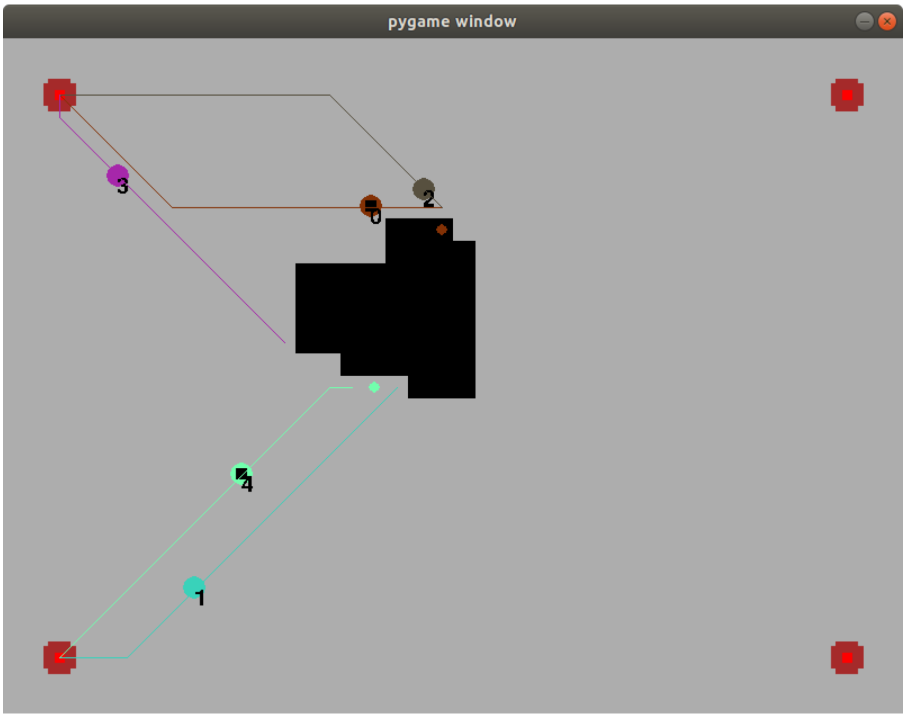

Figure 6.5.5: Number 0 bot coming to fill the position filled by number 2 bot

6. After seeing the filled location, number 0 changes its target to the next empty pixel

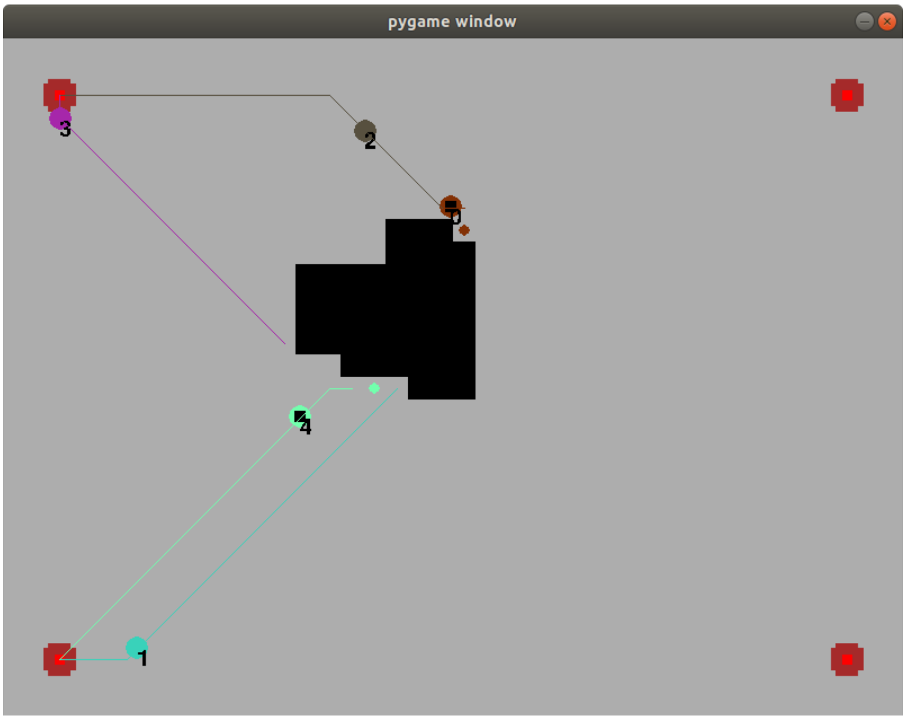

Figure 6.5.6: Number 0 has changed the target

7. After a few more steps, the final shape is constructed successfully

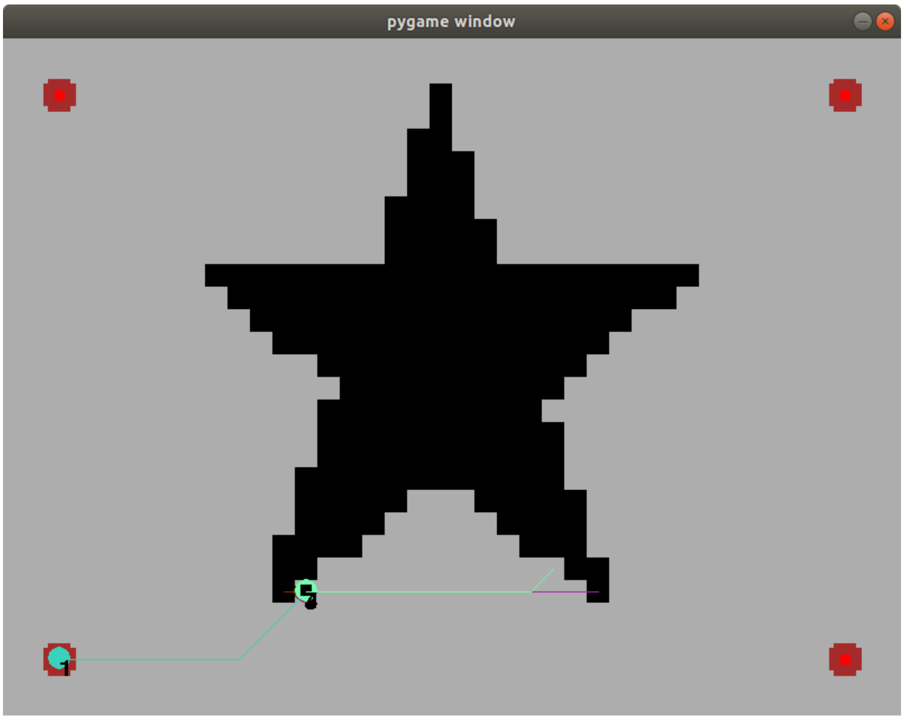

Figure 6.5.7: Final shape is constructed

6.6 Summary

This chapter described how the robot controllers and environment are implemented for simulating a real world 2D swarm construction task. The developed control algorithm alongside with the adapted swarm concepts are evaluated in the next chapter

Chapter 7 - Evaluation

7.1 Introduction

In this chapter we evaluate the swarm robot controllers designed and developed by this research. Here we discussed whether the objectives mentioned in earlier chapters are met and to what extent.

7.2 Evaluation procedure

The aim of the research was to propose a system for an optimized robot swarm. However, for a direct quantitative comparison, very similar researches are needed and no such researches has been found in the literature review. Each approach proposed in each research tries out a different set of concepts of swarm robotics and tries to improve/ research a different aspect of the field. A summary of the most related researches can be found in table 1 on section 2.5. These vary within self assembly, 3D construction, wall/ nest construction and beyond

Major difference between the most similar (construction related) researches and our one is they have done the construction without a predetermined shape, allowing the emergent property of a swarm to determine the shape. Our aim in this research was to construct a given shape.

Considering the above, a qualitative comparison is done and the proposed approach is evaluated on the following aspects which are the limitations identified in the existing researches:

1. True parallel behavior in construction.
2. Redundancy of the system.
3. Final outcome of the system.

7.3 Parallel behavior in construction

The approach developed has shown true parallel construction with multiple robots of the swarm simultaneously constructing the shape, placing building blocks. This is not observed in existing research which constructs given shapes [13,15,17] or self-organizes into given shapes [22,25]. Simple methods like blind bulldozing [19] shows true parallelism but with very limited decision making capabilities which does not suit for complex construction tasks such as the tasks we aim for in this research.

7.4 System redundancy

Usage of stigmergy has helped make the robots in our proposed system independent of each other. This makes the process of construction independent of the number of robots working. Only the speed of the construction is affected by the number of robots. In other existing methods, there are many methods with redundant swarms in both construction and self organizing. However those do not show parallel construction behaviour. Some do not have redundancy such as Werfer et al [15] method since it depends highly on the precompile instructions for each robot in the swarm.

7.5 Final outcome of the system

Our proposal has shown that it can deliver an outcome as expected. It can construct a given 2D shape with multi robot collaboration. Similar researches that adapt swarm behaviour for construction are successful in rule based shape generation [23,24]. However their problem is the outcome not being pre determined. Simple methods like blind bulldozing [19] are highly dependent on the environment and cannot be used for creating arbitrary shapes. The others which satisfies the final outcome, specially self organizing in kilobot swarm [22], they do not display at least one property we consider in this comparison

7.6 Performance vs number of bots

In a swarm system, performance is increased with the number of swarm entities in general. However, overcrowding can cause performance to drop as the interactions between swarm units increase too much.

In our proposed system, the swarm bots take time to resolve inter robot interactions. Robots have to take longer paths to their goals to avoid collision with other bots which are obstructing its pre planned path. With this, after a certain number of bots in the system, the swarm system loses performance. This behaviour can be observed in the graph below

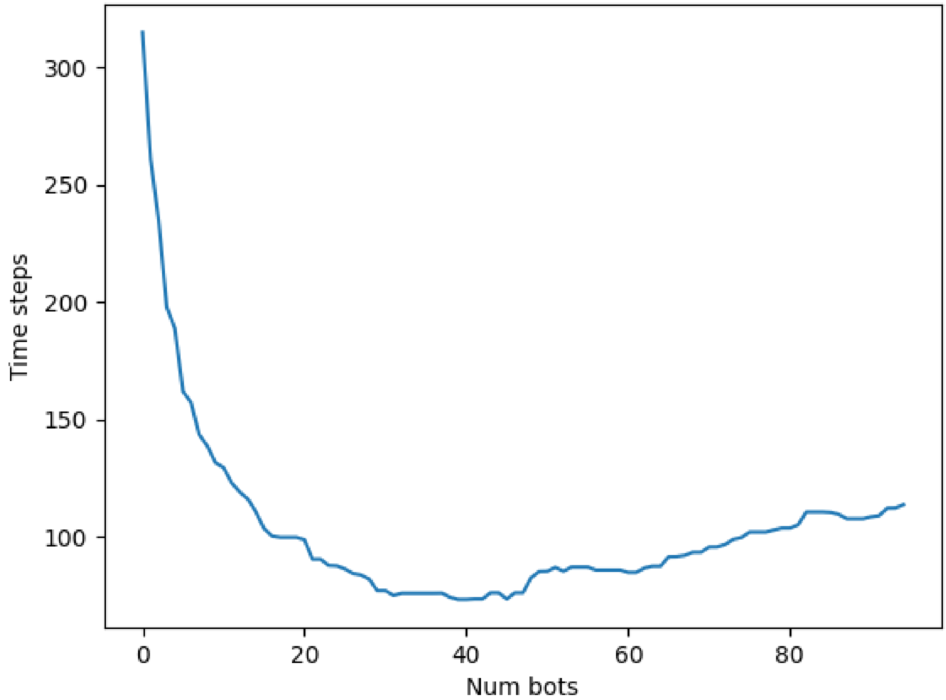

Figure 7.6.1: Time taken to finish a given shape vs number of bots in the swarm system

The graph shows the time steps that the swarm system spent on constructing a given shape vs the number of bots used in the system. For the particular shape used, the best performance can be observed at around 40 robots in the swarm.

The number of bots for best performance is dependent on the shape constructed, building block size, terrain and the bot interaction handling criteria. However, it would be possible to pre-determine this number by realistic enough simulations in the real world application.

7.7 Use cases

As explained in section 1.3, swarm construction is heavily discussed in the field of space exploration. With the existing technologies, swarm construction is financially sound considering the fact that the payload that is sent from earth is considerably smaller compared to the payload needed for any other means of construction.

Landing on a foreign planet is a challenging task for a rocket. There should be a land pad constructed for a spaceship to land since otherwise, landing would create a large crater on the site making it impossible to land [29]. A landing pad for a rocket should be a large flat hard surface which does not blow ejecta when a rocket engine exhaust plume is directed at it. A 2D construction robot swarm can be sent to a foreign terratin for constructing such a structure using regolith or similar in situ material [30].

If a robot swarm is less costly than a conventional construction crew/ machines, a robot swarm is more advantageous for 2D construction tasks in the real world such as brick laying for pavements and walking paths/ areas.

Most construction tasks that are seen in the real world are 3D constructions. However, there are 2D construction applications present within those such as floor tiling or brick laying for floors. These can be done with a swarm of robots efficiently with the results of this research.

7.7 Summary

In this chapter we have evaluated the developed robot controllers using proper experiment mechanisms. We have qualitatively compared the success of the approach and presented the results. The results shows that indeed, the proposed method is optimal compared to the existing 2D construction methods

Chapter 8 - Conclusion

8.1 Introduction

This thesis presents results that show that it is possible to optimize swarm construction tasks using AI methodologies. Even though there is research done on construction using swarm bots, we expect to suggest a novel method for construction using more practical swarm bots in this research.

8.2 Conclusions

In this research we have identified the limits of existing methods that are proposed for swarm construction tasks. Our proposed method was aimed at mitigating these limits identified resulting in a better and optimized swarm robotic system.

We simulated a swarm robotic system which does 2D construction tasks. We have used concepts of stigmergy and rule based control for the robots in the swarm and have developed a control algorithm for the robots to perform their individual tasks so that collectively the shape given is constructed

The observation with all the existing researches for similar problems is that they suffer from one or more limitations identified in the literature review in section 2.6. Our solution has overcome the identified limitations by the introduced new approach for the problem. Furthermore, we have achieved all four objectives set at the start of this research.

Finally we can conclude that by introducing stigmergy with rule based control to a swarm robotic system with a carefully designed control algorithm can result in an optimized robotic swarm for construction tasks.

8.3 Future work

The research has focused on 2D constructions as a starting step to the real world 3D constructions. Furthermore, the shapes that are tested for construction are enclosed and did not have open areas in the middle (e.g. doughnut shaped or similar) or multiple separated construction areas

For real world applications, 3D construction optimized robots are needed in most cases. And complex shapes need to be built. Therefore the research needs to be extended into that area. Novel concepts can be introduced into the research in order to improve the optimization as well. More research needs to be done with various improvements to the robot controller algorithms. Introduction or more swarm concepts into the system might help improve the system as well

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