Swarm Robotics: Exploration and Mapping in Simulated testing Environments

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Interim report
Computer Science and Artificial Intelligence BSc

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1 Introduction

Swarms exist everywhere in life. Nearly all organisms exhibit some form of swarming behaviours within their communities. Starlings display impressive organisational behaviour, positioning themselves with respect to the movement of their neighbours [1]. Humans show swarm behaviours when moving in crowds, for example, moving around sports venues or exiting buildings in emergencies. No matter how hard you look, regardless if the context, swarms are typically present.
These behaviours can also be artificially created in robotics [3]. Within the realm of computing, parallelising processes is breaking barrier after barrier - swarm robotics brings the same benefits. Being able to divide and conquer a problem has the ability to massively increase the rate of work by employing multiple robots. Therefore, it would be wasteful not to properly dedicate the time which this discipline deserves.
For my project, I am going to try and reproduce some of these behaviours artificially. I will start by simulating robotic agents in a 2D environment. The agents will be placed within close proximity inside a simulated environment and then allowed to explore and combine their findings; ultimately creating a visualization map of its environment. The agents will need to both navigate the environment and avoid collisions, whilst creating an internal representation of its surroundings. The best-case scenario for the agents within the swarm is to be fully independent; creating a decentralized system.
I will initially explore this problem by creating SLAM simulations, and then attempting to apply similar techniques to a centralised system. These initial simulations will employ techniques such as graph-based SLAM, random walks and other elements of swarm behaviours in order to create a base-line representation of the environment. This project will also have the flexibility to potentially implement physical robots, given time permits.

2 Professional and Ethical Considerations

My project maintains compliance towards all ethical considerations, as there is minimal external involvement from humans. The majority of my project will be carried out in simulation, therefore no ethical approval is required. Should my project progress to physically implementing agents, considerations such as safety around the robots, will be considered. All tests will be carried out in an environment where people cannot be hit, therefore mitigating any trip hazards.

To ensure all elements of the BCS code of conduct are met, I have summarised each section and how I meet certain criteria.

2.1 Public Interest

As mentioned previously, my project has due regard for public health, as there is minimal external involvement from humans. Furthermore, no major privacy, security or wellbeing considerations are required due to the nature of this project. Third parties will be respected throughout the project with consistent citations and there will be no discrimination against anybody involved. Finally, I will promote equal access to the benefits of IT by open-sourcing my research once I have graduated. This will be accessible on my Github profile: https://github.com/CharlieAnthony/

2.2 Professional Competence and Integrity

My project is within my professional competence, as it significantly relies upon knowledge obtained from modules such as "Acquired Intelligence and Adaptive Behaviour" and "Fundamentals of Machine Learning." Furthermore, I will develop my professional knowledge, skills and competence through communicating with my supervisor and ensuring all relevant gaps in knowledge are explored through reading extensively. As part of my background reading, I have made myself familiar with the BCS code of conduct and surrounding legistlation. I will comply with this throughout when carrying out my professional responsibilities. There will also be no unethical inducements offered or accepted throughout the project.

2.3 Duty to Relevant Authority

As the relevant authority will be the University of Sussex, I will comply with all relevant codes of conduct and legislation. I will exercise my professional judgement at all times, including avoidance of any situation that may give rise to a conflict of interest between myself and the university. I will also make it my responsibility to ensure all colleagues work is properly referenced in a bibliography at the end of my dissertation.

2.4 Duty to the Profession

Finally, I accept my duty to uphold the reputation of the profession. I will work to the best of my ability to ensure my project is complete to the highest possible standard. As mentioned previously, I will seek to improve professional standards through communication with my supervisor. This dissertation will be written with integrity and respect towards all members of BCS and colleagues of the profession.

3 Related Work

3.1 SLAM

SLAM (Simultaneous Localisation and Mapping) is a technique used in robotics to create a map of an unknown environment [2]. It is an important area of research in robotics as it is heavily used in autonomous vehicles, drones and vacuum cleaners; allowing agents to understand and navigate their environment effectively. Figure 1 shows an example of a robot scanning its environment, with the sensors visually added to the image.
SLAM can be broken down into two sub-problems: localisation and mapping. Localisation is the process of determining the location of a robot in its environment, whilst mapping is the process of constructing a map of the environment. The maps are constructed using data collected from sensors, such as cameras and laser scanners; Figure 2 shows this. A lot of existing work in SLAM is based on single robot applications, however, there

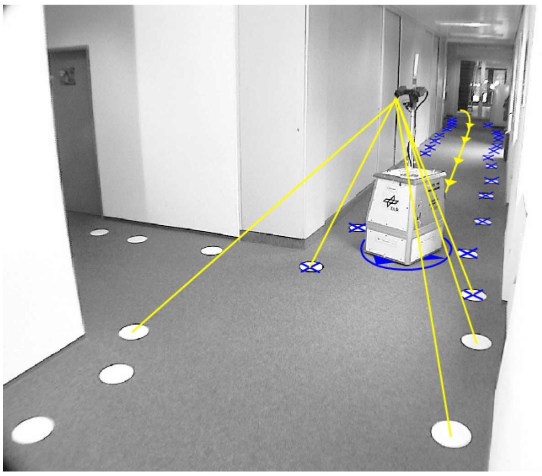

Figure 1: A visual representation of a robot scanning its environment [2]

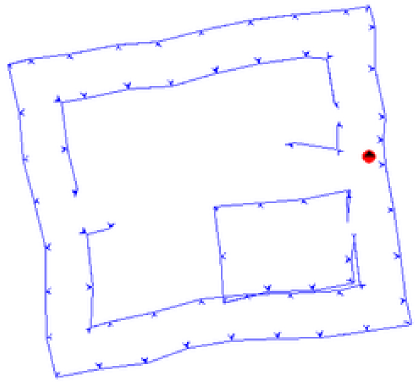

Figure 2: The map (after loop closure) produced by the robot's SLAM algorithm of its environment [2]

is a growing interest in multi-agent SLAM. One of the greatest challenges in SLAM is crossing the simulation to reality gap, as in the real world, sensor readings are noisy and environments are dynamic, which increases the complexity of the problem.

3.2 Graph-based SLAM

Graph-based SLAM is a technique used to create a map of an environment, by using a graph to represent the environment. It works by having a robot move around its environment, whilst taking measurements of its surroundings. These measurements are usually received by a sensor, such as a camera or laser scanner. The robot then uses these measurements to create a plot of where objects may be, by combining the measurements from sensors with its memory of the route it has taken. This technique is used in many applications, both in research and in the real world.
One limitation of graph-based SLAM is that it is computationally expensive, as it requires a lot of memory to store the sensor readings. Also, it is not very scalable, as the more sensors that are added, the more memory is required. Another limitation is that it cannot always be reliable, as the algorithm depends heavily on detecting loop closures, which when not detected, can lead to a lot of errors in the map. This, combined with even the slightest inaccuracy from sensors/motors makes it difficult to apply to the real world.

3.3 Particle Filters

Another technique used in SLAM is particle filters. Particle filters, also known as Monte Carlo localisation, is a probabalistic technique used to estimate the localisation of a robot in its environment. It starts with a set of particles randomly distributed across the environment, which represent possible locations of the robot. Each particle has an associated weight, representing the probability that the particle is the true location of the robot. As the robot moves around the environment, the particles weights are then updated based on an algorithm which takes the robots sensors as input. Overall, this technique is very effective, as it is able to localise the robot in its environment, even when the environment is dynamic. Also, this process is highly parallelisable, as each particle can be updated independently; which makes this a viable solution for real-world applications. However, particle filters are susceptible to the "curse of dimensionality", which means that as the number of dimensions increases, the problem's complexity rapidly increases.

3.4 Swarm

Swarm robotics [3] is a discipline which studies the coordination of large numbers of robots. It is largely inspired by biology, where social organisms achieve complex behaviours through simple interactions with each other and the environment. Swarm robotics is an important area of research in robotics, as it has many applications, such as search and rescue, exploration and mapping.

One of the benefits of swarm robotics is the scalability and flexibility of the system [4]. This is because the system is decentralized, meaning that each agent is able to make decisions independently. This allows for repeatability, as the system can be scaled up or down simply by adding or removing agents. Also, it allows for flexibility, as the system can be adapted to different environments, as each agent is able to make decisions based on its surroundings.

One of the biggest challenges in swarm robotics is the simulation to reality gap. This is because in simulation, the agents are able to easily share information with each other, whilst in the real world, this is more challenging. Furthermore, swarm robotics struggles with more complex environments, like outdoors. As a result, swarm robotics still has a lot of room for research and development.

3.5 Random Walks

Random walk exploration in the context of swarm mapping is a technique where agents individually map an environment, using methods like Graph-based SLAM, Particle Filters, etc. and them combine their findings to a single global map; this is an example of a centralised system [5].

A example of an implementation of random walk exploration is Brownian motion [6], which is a physics-inspired approach. It works by applying a random force to each agent, which determines its direction. The agents then move in this direction until they detect an obstacle, at which point they will change direction. This process is repeated until the environment is fully mapped. There is randomness provided from the environment, through detecting other agents or obstacles, and randomness in motion, as each path is determined by a random force. Overall, collective behaviour emerges from these simple rules, which lead to a global behaviour which efficiently maps an environment.

One of the biggest drawbacks of this approach is that it is not scalable, as the agents are not able to communicate their maps to each other, which can lead to a lot of redundant exploration. This is because equally, sharing their maps with each other would be very computationally expensive. Also, another limitation is that this approach doesn't guarantee effiency. This is because of the inherent randomness, which means areas of the environment may be unexplored.

4 Requirements Analysis

Table 1 shows the requirements for my project, along with their justification. Initially, I will create a simulation interface, where the user can see the agents, the environment and a representation of the agents internal map. After I will work towards implementing SLAM and swarm algorithms. As an extension, I will attempt to implement physical agents, which will act in the real world. This will require a lot of additional work, so will only be attempted if time permits. I have included a number of optional requirements below to compensate for this.
When creating the simulation interface, I will be using the Python programming language, along with the PyGame library. This will abstract away a lot of the complexity of creating a graphical user interface, allowing me to focus on the core functionality. I will also use various other scientific python libraries throughout my project, such as NumPy, SciPy and Matplotlib.

ID	**Requirement**	**Justification**
1	Simulation Interface	A graphical user interface, where the user can see the agent, the environment, and a representation of the agents internal map
2	SLAM Implementation	Implement a SLAM algorithm, which allows a single agent to localise and map the environment
3	Customise Environment	Allow the environment to be easily modified in the interface - perhaps by uploading a black and white image
4	Centralized Swarm	Implement a centralized swarm algorithm, where the agents individually collect data and then feed to a global map
5	Decentralized Swarm	Implement a decentralized swarm algorithm, where the agents communicate their findings and create individual representations of the environment
6	User Interface Interactivity	Develop a user interface with interactive elements, which allow the user to change the environment and the properties of the agents.
7	Single SLAM Agent	Implement a SLAM algorithm on a single agent system, using the Pose Graph Optimization Algorithm
8	Multi-agent Random Walk Agents	Implement a multi-agent random walk algorithm, where the agents move randomly around the environment
9	Centralized Multi-agent SLAM System	Implement a centralized multi-agent SLAM algorithm, where the agents individually collect data and then feed to a global map
10	Decentralized Multi-agent SLAM System	Implement a decentralized multi-agent SLAM algorithm, where the agents communicate their findings during exploration and create individual representations of the environment

Table 1: Table of requirements and their justification

Along with this table of requirements, there will also be a number of opportunities for optional extensions, should time permit. These include:

- Implementing physical agents
- User interface enhancements, such as adding a menu bar, easier ways to change the environment, etc.
- Develop a performance metric, allowing the user to compare SLAM algorithm performances

5 Project Plan

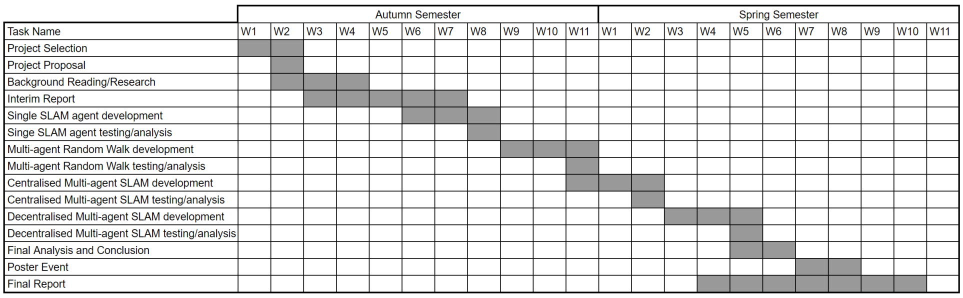

Figure 3: Gantt chart showing the project plan

The execution of my project will be split into various phases, where each phase will focus on an area of development. The majority of the project will be software development, therefore I have chosen to split this process into various stages. Figure 3 shows the project plan, where the grey bars represent the time spent at each phase. Should my project overrun, I will have contingency time built into both the Christmas break and the Easter break, which is currently unaccounted for in the project plan.

5.1 Phase 1 - Research and Planning

The first phase of my project involves researching and planning. During this period I will create a project proposal, research SLAM and swarm algorithms, and write this interim report. This phase will be completed by week 7. It is important to carry out this phase as it provides structure for the whole project, which will help ensure that the project is completed on time.

5.2 Phase 2 - Single SLAM Agent

The second phase of my project is where development will start. I will start by creating a basic simulation environment, where the user can see the agent and the environment. After, I will implement the Pose Graph SLAM algorithm seen in Figure 4, on a single agent system. This will give me the experience of implementing SLAM, which will be useful when implementing swarm algorithms as a good portion of the code will be reusable. This phase will be completed by week 8, and will allow me to follow on to multi-agent random walks.

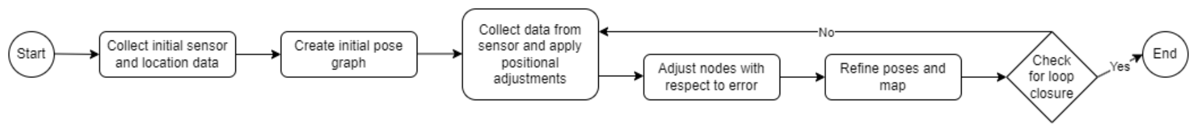

Figure 4: A flow chart of the Pose Graph SLAM algorithm

5.3 Phase 3 - Multi-agent Random Walk

In the third phase, I will implement a multi-agent random walk algorithm. This will allow me to explore the challenges of swarm communication and agent coordination. I plan to implement the Brownian motion algorithm as a starting point, then if time permits, I will explore other algorithms, such as Ballistic motion and Levy walk. I will complete this phase by week 11, which will allow me plenty of time to implement the more complex swarm algorithms.

5.4 Phase 4 - Centralised Multi-agent SLAM

The fourth phase will consist of implementing a centralised multi-agent SLAM algorithm. This will finally allow me to combine the knowledge I would've gained from the previous phases and apply it to a more complex problem. I will look to implement an algorithm like the multi agent map merging algorithm, which will allow me to combine the maps of single SLAM agents. Furthermore, I will bring in the communication system developed in Phase 3, which will help structure the agents. This phase will be completed by week 2 of the Spring semester.

5.5 Phase 5 - Decentralised Multi-agent SLAM

The fifth and final phase of development will see me implement a decentralised multi-agent SLAM algorithm. This will be the most complex phase of development, as it will require me me to combine the SLAM elements of the previous phase with the communication from Phase 3. I will look to implement an algorithm like C-SLAM (Collaborative Simultaneous Localization And Mapping) [7], and will analyse it's performance and how it scales. This phase will be completed by week 5 of the Spring semester.

5.6 Phase 6 - Analysis and Conclusion

The final phase of my project will largely consist of writing up my findings and analysing the performance of the algorithms. I will write up my final dissertation, along with creating a poster for the event. I may also spend some time creating visual representations of my findings, such as graphs and charts. This phase may begin as early as week 4 of the Spring semester and will be completed by week 10.

6 Supervisor Meetings

6.1 Meeting 1 - 11/10/2023

Discussed on the project idea and potential directions to take. Discussed the possibility of implementing physical agents, challenges that may occur and potential ways of implementing swarm algorithms. Need to focus on researching SLAM and swarm and looking into existing resources.

6.2 Meeting 2 - 27/10/2023

Discussed potential algorithms, such as particle filters and graph-based SLAM. We also discussed the logistics of the project, ensuring that it remains both realistic and achievable. We also discussed the possibility of implementing physical agents, and where relevant resources could be found.

6.3 Meeting 3 - 14/11/2023

Started with feedback on the interim report - discussing the structure and content. After we discussed how the project will move forward and the next steps to take. Given the interim report is now complete, we can focus mainly on development, following the project plan. As I have already developed a basic simulation interface, I can now move onto implementing my first SLAM algorithm.

6.4 Meeting 4 - 08/12/2023

In this meeting, we turned to ironing out the specifics of the implementation - including looking at existing resources, like Enki, and concepts that need to be considered, such as Differential Turning. The goal of this meeting was to guide me into starting to create my environment and first SLAM algorithm, which will be implemented over the christmas break.

6.5 Meeting 5 - 02/02/2024

We firstly caught up on progress made over the christmas break. After, we started to look forward to the next steps of the project, cdiscussing the projects overall direction and the next steps to take. One notable suggestion was the move away from swarm algorithms and perhaps the move towards multi-agent SLAM, as this would be more achievable in the time frame. Finally, we discussed how I should manage my time towards the end of the project and how I could start working on my dissertation.

7 Appendices

7.1 Project Proposal

Swarm Robotics: Exploration and Mapping in Simulated testing Environments

Charlie Anthony [candNo: 246537]
Supervisor: Dr Chris Johnson

Project Proposal
Computer Science and Artificial Intelligence BSc

Department of Informatics and Engineering
University of Sussex
October 2023

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1 Aims and Objectives

Aim:
To understand and showcase the principles of swarm robotics in the realm of navigation and mapping. This project is driven by a fascination with swarm robotics and its potential in autonomously navigating and mapping unknown environments.

Primary Objectives:

- Design and develop a basic simulation environment representing an unknown environment.
- Implement swarm intelligence principles to allow a group of agents to collaboratively navigate and map the environment.
- Evaluate and refine the agent behaviours for effective navigation and territory mapping.

Extensions (if time allows):

- Optimise agent behaviour for efficiency in discovering the quickest route to a goal point within a maze-like environment
- Investigate the challenges associated with transitioning from simulation to real-world application (the sim-to-real gap)

2 Relevance

This project integrates principles of artificial intelligence, robotics and simulation, making it highly relevant to my degree in Computer Science and Artificial Intelligence. The exploration of swarm robotics in navigation can provide insights into optimizing algorithms for real-world challenges.

3 Resources Required

This project will require the use of lab computers, and should the extensions be carried out, the occasional booking of seminar rooms/study rooms for carrying out physical experiments. Should it be required, the project will also be aided by a small degree of funding to allow purchase of physical components which may be required for constructing agents. While the purchase of such components may not be essential, it would allow a more in-depth and thorough review of the swarm behaviours implemented.

4 Timetable

Here is a simplified version of my timetable:

	Mon	Tue	Wed	Thur	Fri
9:00		project/cw	Lecture		project/cw
10:00		project/cw	Lecture	Lecture	project/cw
11:00		project/cw	Lecture	Lecture	project/cw
12:00					
13:00		Lecture			Lab
14:00		Lecture			Lab
15:00		Lab			
16:00					
17:00					

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