

Multi-Agent SLAM: Exploration and Mapping in Simulated testing Environments

Charlie Anthony [CandNo: 246537]

Supervisor: Dr Chris Johnson

Dissertation

Computer Science and Artificial Intelligence BSc



Department of Informatics and Engineering
University of Sussex
May 2024

Contents

1	Introduction	2
2	Related Work	2
2.1	SLAM	2
2.2	Graph-based SLAM	3
2.3	Particle Filters	3
2.4	Swarm	4
2.5	Random Walks	4
3	Requirements Analysis	4
4	Project Plan	6
4.1	Phase 1 - Research and Planning	6
4.2	Phase 2 - Environment Development	6
4.3	Phase 3 - Single-agent SLAM	6
4.4	Phase 4 - Multi-agent SLAM	7
4.5	Phase 5 - Analysis and Conclusion	7
5	Professional and Ethical Considerations	7
5.1	Public Interest	7
5.2	Professional Competence and Integrity	8
5.3	Duty to Relevant Authority	8
5.4	Duty to the Profession	8
6	Methods	8
6.1	Single-Agent SLAM	8
6.1.1	Feature Extraction	8
6.1.2	Identifying Landmarks	9
6.1.3	Data Association	9
6.1.4	Pose Graph	9
6.1.5	Graph Optimisation	9
6.2	Multi-Agent SLAM	9
7	Appendices	9
7.1	Supervisor Meetings	9
7.1.1	Meeting 1 - 11/10/2023	9
7.1.2	Meeting 2 - 27/10/2023	9
7.1.3	Meeting 3 - 14/11/2023	9
7.1.4	Meeting 4 - 08/12/2023	9
7.1.5	Meeting 5 - 02/02/2024	9
7.1.6	Meeting 6 - 09/02/2024	10
7.1.7	Meeting 7 - 16/02/2024	10
7.1.8	Meeting 8 - 23/02/2024	10
7.1.9	Meeting 9 - 29/02/2024	10
7.2	Project Proposal	10
8	References	15

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. 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. 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 Related Work

2.1 SLAM

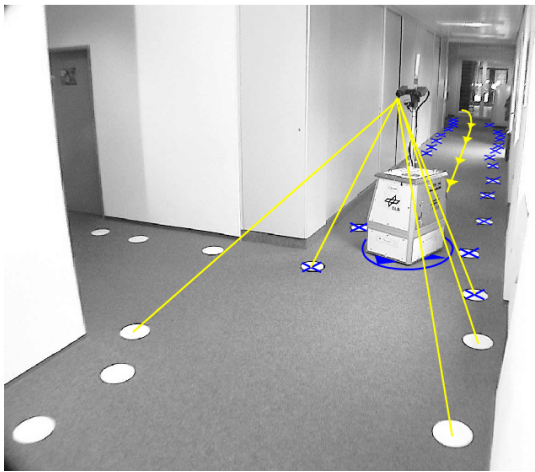


Figure 1: A visual representation of a robot scanning its environment [1]

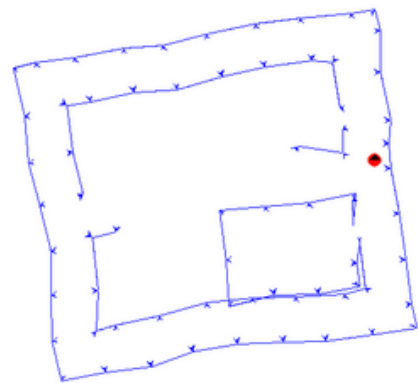


Figure 2: The map (after loop closure) produced by the robot's SLAM algorithm of its environment [1]

SLAM (Simultaneous Localisation and Mapping) is a technique used in robotics to create a map of an unknown environment [1]. 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 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.

2.2 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.

2.3 Particle Filters

Another technique used in SLAM is particle filters. Particle filters, also known as Monte Carlo localisation, is a probabilistic 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.

2.4 Swarm

Swarm robotics 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. 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.

2.5 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 then combine their findings to a single global map; this is an example of a centralised system.

A example of an implementation of random walk exploration is Brownian motion, 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 efficiency. This is because of the inherent randomness, which means areas of the environment may be unexplored.

3 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 single-agent and multi-agent SLAM algorithms. I have also added a couple optional requirements, which can be carried out should time permit but are not critical towards the

success of the project.

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 will allow me to visually see the agents behaviours, which will aid de-bugging. It will also help understand the algorithms in further detail by allowing me to see how they work live.
2	Single-agent SLAM	Implementing a single-agent SLAM algorithm will help provide the required knowledge to tackle the larger challenge of multi-agent SLAM. It will also give me benchmark figures to compare my multi-agent SLAM to when evaluating my project.
3	Multi-agent SLAM	This is the main goal of my project. Implementing multi-agent SLAM algorithm will allow me to explore the challenges of navigation and exploration.
4	Evaluation Metrics Integration	This will allow me to analyse the performance of my algorithm and make improvements. This requirement includes adding functionality to create graphs and charts, which will be used to visualise performance.

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 robots.
- User interface enhancements, such as adding being able to view each individual agents internal map.

4 Project Plan

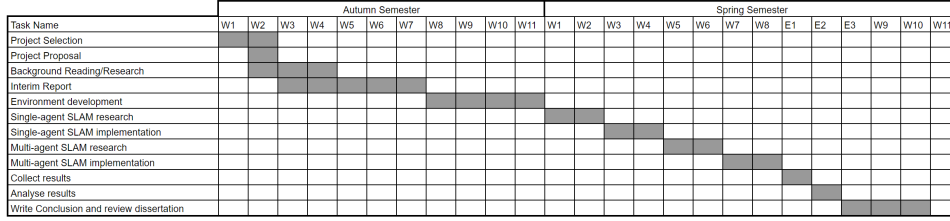


Figure 3: Gantt chart showing the project plan

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 prior to the due date, which is currently unaccounted for in the project plan.

4.1 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 single and multi-agent SLAM algorithms, and write my 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.

4.2 Phase 2 - Environment Development

The second phase of my project will be to develop the simulation environment. This will involve creating a graphical user interface, using the PyGame library, where the user can see the agent, the environment and a representation of the agents internal map. This phase will be completed by week 11 - putting me in a good place to work on implementing SLAM algorithms after the Christmas break.

4.3 Phase 3 - Single-agent SLAM

The third phase of my project will be to implement a SLAM algorithm on a single agent system. This will involve implementing graph-based SLAM, mentioned in my related work section. The algorithm will work by having the agent move around its environment, whilst taking measurements of its surroundings. These measurements will then be used to predict where objects may be, through feature extraction. Then, the features detected will be combined to define landmarks, which will be used to create a map of the environment. Finally, once the algorithm has been implemented, I will create a simple agent which will move around the environment, using a random walk algorithm. I aim to complete this phase by the end of week 4 of the Spring semester.

4.4 Phase 4 - Multi-agent SLAM

In the fourth phase of my project, I will implement a multi-agent SLAM. This will involve creating a centralized multi-agent SLAM algorithm, where the agents individually collect data and then feed to a global map. To achieve this, I will need to modify my single-agent SLAM algorithm to firstly allow for a central server to exist, and then I will need to implement a communication protocol between the agents and the server. To create a complete map, the server will need to combine the maps from each agent; implementing cross-agent feature matching. The server will also need to have a mechanism which resolves conflicts in data association, for example, when two agents have conflicting information about a landmark's position. This phase needs to be completed by week 8 of the Spring semester, which allows for a reasonable amount of time to work on the final report.

4.5 Phase 5 - Analysis and Conclusion

I will start the final phase of my project during the Easter break, where I will collect data which will be used to analyse the performance of the algorithm. I will then use this data to create a series of graphs and charts, which will be used to visualise performance and draw conclusions. After, a lot of time will be spent writing up my findings and analysing the performance of the algorithms. Finally, I will conclude my project by writing a conclusion, which will summarise my findings and discuss potential future work. Prior to submitting my report, I will also spend time proofreading and editing my work.

5 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.

5.1 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/>

5.2 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 legislation. 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.

5.3 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.

5.4 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.

6 Methods

6.1 Single-Agent SLAM

6.1.1 Feature Extraction

Feature extraction is the process of detecting and extracting features from sensor data. In the context of SLAM, features are points of interest in the environment, such as corners, edges and lines. These features can then be used to create a map of the environment. There are many different techniques for feature extraction, such as the Harris corner detector and the split-and-merge algorithm. My implementation uses Seeded region growing, which was heavily inspired by the work of [3].

6.1.2 Identifying Landmarks

6.1.3 Data Association

6.1.4 Pose Graph

6.1.5 Graph Optimisation

6.2 Multi-Agent SLAM

7 Appendices

7.1 Supervisor Meetings

7.1.1 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.

7.1.2 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.

7.1.3 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.

7.1.4 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.

7.1.5 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, discussing 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.

7.1.6 Meeting 6 - 09/02/2024

Started with me demonstrating my current progress, with my environment working, LIDAR sensor appropriately implemented and my work-in-progress feature detection. We discussed then how I could approach landmark detection and how I planned on implementing it. We ended the meeting with clearing up questions regarding the project presentation, poster competition and submission.

7.1.7 Meeting 7 - 16/02/2024

We discussed how my project was going; talking about feature extraction and landmark detection. As I had been having troubles with bugs in the previous week, Chris suggested spending more time writing test cases. We then discussed how I should approach writing the final report; considering structure and content. We agreed that there are parts of the report that I could start now, such as my literature review and methodology used in feature detection and landmark detection.

7.1.8 Meeting 8 - 23/02/2024

Started with showing my progress on landmark detection and random walk exploration. We then discussed different exploration algorithms that could be used, as random walk exploration isn't efficient. We discussed creating some form of wall-avoidance navigation, which would be far more efficient. We then reviewed my plan and reflected on how progress was going. We both agreed that progress isn't as fast as we would like, but we are still on track to complete the project on time.

7.1.9 Meeting 9 - 29/02/2024

We had a quick online meeting this week; discussing where the project is and the next steps. We started by talking about my implementations of exploration strategies and how I could improve them. We then discussed evaluation metrics and how I could gather and present data. Finally, we talked about how I could approach multi-agent SLAM, as it's an area I am concerned about due to its complexity.

7.2 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



**UNIVERSITY
OF SUSSEX**

Department of Informatics and Engineering

University of Sussex

October 2023

Contents

1	Aims and Objectives	2
2	Relevance	2
3	Resources Required	2
4	Timetable	2

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				

8 References

References

- [1] Frese, U., Wagner, R. and Röfer, T. (2010). A SLAM Overview from a User's Perspective. *KI - Künstliche Intelligenz*, 24(3), pp.191–198. <http://dx.doi.org/10.1007/s13218-010-0040-4>
- [2] Lajoie, P.Y. and Beltrame, G. (2023). Swarm-slam: Sparse decentralized collaborative simultaneous localization and mapping framework for multi-robot systems. *arXiv preprint*, arXiv:2301.06230. <https://doi.org/10.48550/arXiv.2301.06230>
- [3] Gao, H., Zhang, X., Fang, Y. and Yuan, J. (2018). A line segment extraction algorithm using laser data based on seeded region growing. *International Journal of Advanced Robotic Systems*, p.172988141875524. <https://doi.org/10.1177/1729881418755245>