

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

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Dissertation
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. 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 Literature Review

2.1 Introduction to SLAM

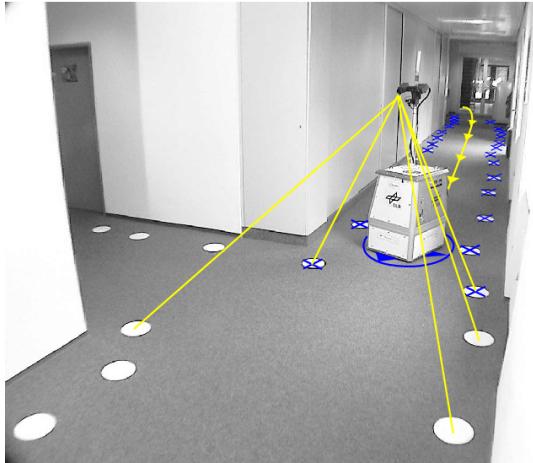


Figure 1: A visual representation of a robot scanning its environment [1]

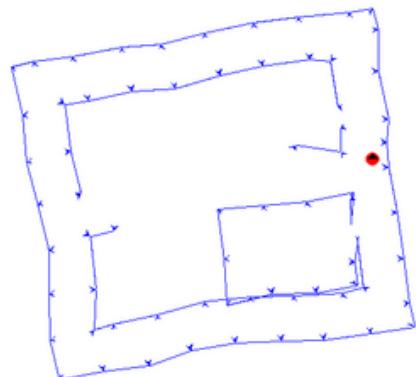


Figure 2: The map (after loop closure) produced by the robot's SLAM algorithm of its environment [1]

SLAM (Simultaneous localization 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: localization and mapping. localization 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.

Code implementations of SLAM usually divide the problem into the Front-end and the Back-end [2]. The Front-end is where the agent interprets the environment; it will receive data, which could be in the form of images, LiDAR scans or other sensor data. The Front-end will then process this data, extracting features and identifying landmarks. Furthermore, the Front-end will also perform data association, which will compare new features/landmarks to data that has been previously collected. The Back-end is where the agent will use the data collected from the Front-end to create a map of the environment and localise itself. There are a number of paradigms which may be used during this process, such as Graph-based SLAM, Particle filtering and Extended Kalman Filters. By combining the Front-end and the Back-end, the agent will be able to create an internal representation of its environment and its position in that environment.

2.2 Background and Evolution of SLAM

In the mid 1980s, SLAM concepts were first introduced by Smith and Cheeseman [3]. They initially laid out the foundations of the problem, which was to be able to reason about the position of an object with potentially inaccurate information about the environment. Their paper demonstrates a lot of themes which we now associate with SLAM, such as taking frames (poses) which have an associated positional uncertainty, taking measurements of the environment at each frame and then using these measurements to identify objects in the environment. Smith and Cheeseman used the Kalman Filter equations for static-state estimations, and then merged these state estimations to create a representation of the environment.

The next major developments in SLAM came shortly after, in the early 90s, from the work of Leonard and Durrant-Whyte [4]. In their paper, they identify further challenges in SLAM, such as the data association problem and environment dynamics. They also outlined one of the traditional problems with SLAM, which is the "chicken and egg" problem. This arises as to build a useful map, the robot needs to know where it is, and to know where it is, it needs a useful map. To tackle this, they proposed the use of an Extended Kalman Filter (EKF), which builds on the traditional Kalman Filter equations by allowing for non-linear state estimations. This was a significant development, as it allowed for the creation of more accurate maps; however they also concluded that the EKF was not suitable for large-scale environments, as data association becomes increasingly difficult.

Come the 2000s, SLAM had become a well-established area of research, with a number of different paradigms being used to approach the problem. One of which was FastSLAM, which was developed by Michael Montemerlo and Sebastian Thrun [5]. FastSLAM was an attempt to solve one of the fundamental flaws of EKF SLAM, which was scalability. FastSLAM works by using a particle filter to estimate the robot's pose, and then constructs a map of the environment using these poses. A particle filter is a probabilistic technique used to estimate the robots position, which works by having a set of particles randomly distributed across the environment, which represent possible positions the robot could be in. As the robot moves, the particles are adjusted based on measurements from the robots sensors; the position of the robot is then estimated by taking the average of the particles. FastSLAM main strengths are its ability to handle large environments and improve the computational complexity of EFK SLAM, however it's weaknesses are that it is not as accurate as EKF SLAM and it struggles with dynamic environments.

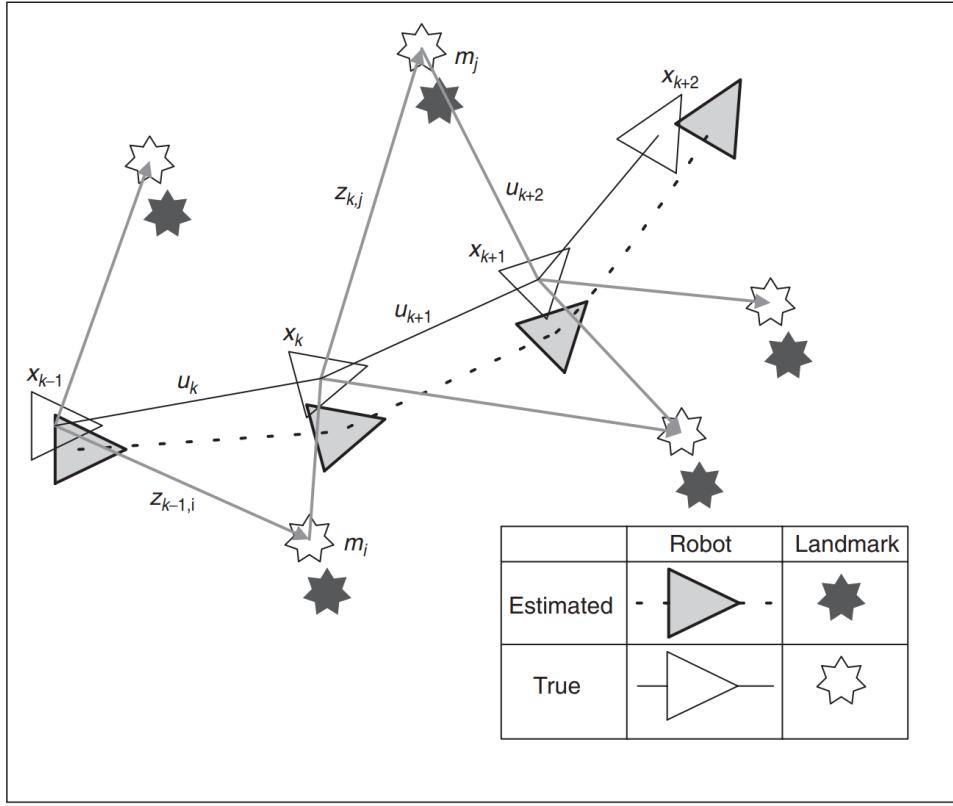


Figure 3: Formal representation of the SLAM problem. [6]

Finally, in 2006 Durrant-Whyte and Bailey wrote a significant paper outlining the future of SLAM [6]. They started by discussing existing approaches to the problem and then formally outlining the SLAM problem, shown in Figure 3. They then went into further detail on how both EFK SLAM and FastSLAM work, and then discussed the limitations of each approach. They also wrote a second paper, discussing the future of SLAM, including multi-agent SLAM, 3D SLAM and Dynamic environments [7].

2.3 Technical Frameworks and Models

2.3.1 Mapping techniques

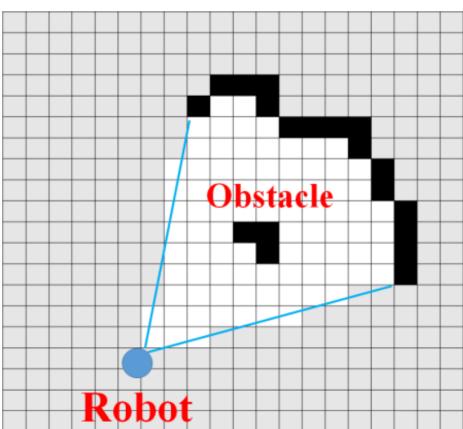


Figure 4: Simple visualization of an occupancy grids [8]

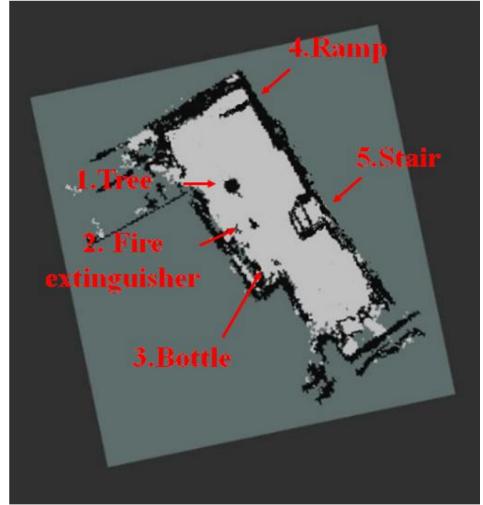


Figure 5: Complex example of occupancy grid in practice [8]

Mapping techniques are used by the agent to create a representation of its environment. There are a number of different mapping techniques commonly used in SLAM, such as grid maps, feature-based maps and semantic maps. Grid maps, or occupancy maps, are the most common type of map used in SLAM, as they are easy to implement and computationally efficient. They are typically represented as a 2D array, which simply stores a binary value for each cell, which represents whether the cell is occupied or not. Figure 4 shows a simple example of an occupancy grid, where the black cells represent occupied space and the white cells represent free space. Figure 5 demonstrates how an occupancy grid can be used to represent a more complex environment, such as the experiment environment used by Nam et al [8]. Occupancy grids are typically implemented in conjunction with distance sensors, such as LiDAR - this allows the agent to measure the distances to multiple points in the environment, which can then be used to update the occupancy grid.

Feature-based maps are another common type of map used in SLAM. They work by having the agent detect features in the environment, such as walls, corners and edges. These features are then used to define landmarks, which are then used to create a map of the environment. Landmarks are distinct features in the environment which can be used to localise the agent; a common metaphor used to describe landmarks is a distinctive skyscraper in a city, like the Shard in London, which you could use to figure out your location. Feature-based maps are also implemented with distance sensors, as the agent can use points detected by the sensor to detect features.

Finally, semantic maps are a more recent addition to SLAM, which work by allowing the agent to detect and classify objects in the environment. This is achieved using computer vision techniques, such as object detection and image segmentation. Figure 6 shows an example of a semantic map; you can see the image segmentation has identified various objects, such as the keyboard and the books. Semantic maps are used more frequently in

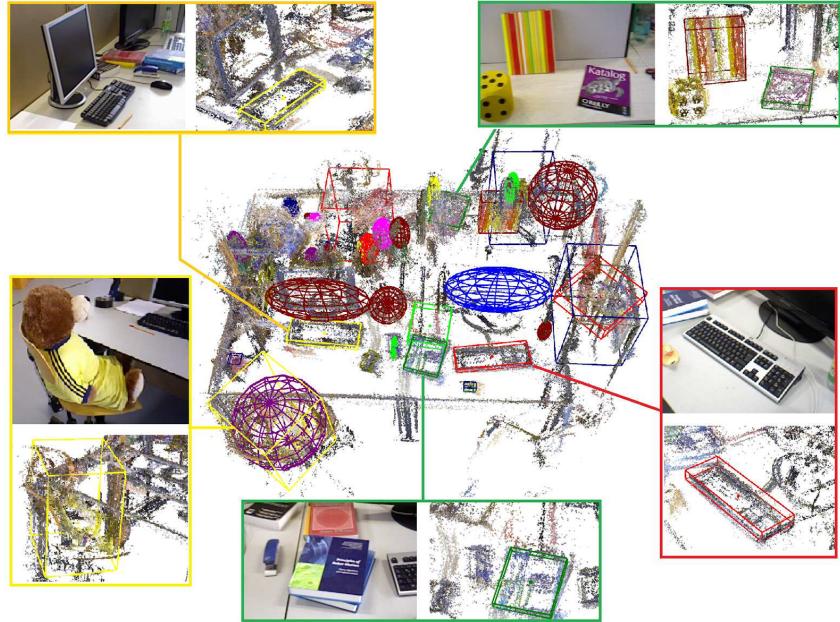


Figure 6: Example of a semantic map [9]

research, as they are more computationally expensive and require more complex sensors, such as cameras.

2.3.2 Localization techniques

Localization techniques are used to help the agent determine its position in a given environment. There are a number of popular techniques commonly used in SLAM, such as Extended Kalman Filters, Particle Filters and Visual Odometry. Extended Kalman Filters are a set of mathematical equations which are used to estimate the position of the agent given a set of noisy sensor readings. The equations are split into two main functions, the prediction function and the update function [10]. The prediction function is used to predict the agents position based on the previous state, which incorporates uncertainty from the agents movement. The update function is then used to update the agents position based on new sensor readings and update the uncertainty. The prediction functions are defined as:

- State Prediction Equation:

$$\hat{x}_{k+1} = f(\hat{x}_k, u_k, 0) \quad (1)$$

- Covariance Prediction Equation:

$$P_{k+1} = A_k P_k A_k^T + W_k Q_k W_k^T \quad (2)$$

The state prediction equation predicts the next state \hat{x}_{k+1} based on the previous state \hat{x}_k , the control input (the agents desired movement) u_k and the process noise (which is assumed to be zero here). The covariance prediction equation then updates the uncertainty of the agents position based on the state transition matrix A_k , the previous position uncertainty P_k , the control input matrix W_k and the process noise covariance matrix Q_k . The update functions are defined as:

- Kalman Gain Equation:

$$K_k = P_k H_k^T (H_k P_k H_k^T + V_k R_k V_k^T)^{-1} \quad (3)$$

- State Update Equation:

$$\hat{x}_k = \hat{x}_k + K(z_k - h(\hat{x}_k, 0)) \quad (4)$$

- Covariance Update Equation:

$$P_k = (I - K_k H_k) P_k \quad (5)$$

The Kalman Gain equation determines how impactful the new sensor reading z_k should be, based on the previous position uncertainty P_k . H_k is the Jacobian of the measurement function $h(\hat{x}_k, 0)$ with respect to the state, and V_k is the Jacobian of the measurement function with respect to the measurement noise. The state update equation then updates the agents position based on the Kalman Gain. Finally, the covariance update equation updates the uncertainty of the agents position based on the Kalman Gain.

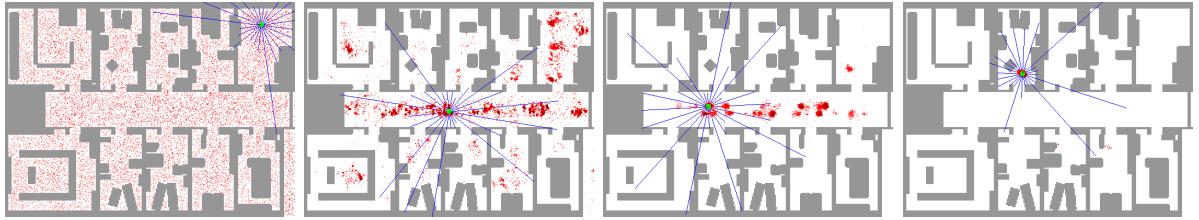


Figure 7: Example of Particle Filter in a 2D environment [11]

2.3.3 Sensor technologies

There are many different types of sensor technologies used throughout SLAM research, such as LiDAR, cameras and Inertial Measurement Units (IMUs). LiDAR (Light Detection and Ranging) is a distance sensor which works by shooting out a laser and measuring the time it takes for the laser to bounce off an object (up to a given distance) and return to the sensor. Typically, the sensor will rotate 360 degrees and take measurements at regular intervals, which is particularly useful in SLAM as it allows the agent to sense its complete surroundings.

Cameras are another common sensor used in SLAM, which work by taking images of the environment and then using computer vision techniques to extract features and landmarks. One of the advantages of cameras is that they can capture a lot of information about the environment, such as objects and textures; which make data association easier. However, cameras are also a lot more computationally expensive in comparison to LiDAR, as feature extraction and landmark detection have a lot more complexity.

IMUs are used to measure the orientation, velocity and gravitational forces of the agent; this makes them useful in SLAM as they help record the agents movement. They are normally used alongside other sensors to help improve the accuracy of the localisation algorithm.

2.4 Algorithms and Implementations

2.4.1 Algorithms

- EKF SLAM - FastSLAM - ORB-SLAM

2.4.2 Software

- GMapping - ROS

2.4.3 Challenges

- Feature extraction in dynamic env - Scalability - Computational efficiency

2.5 Real-world Applications and Case Studies

Real world applications: - Autonomous vehicles - Drones - Vacuum cleaners - Search and rescue - indoor, outdoor, underwater and airbourne

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

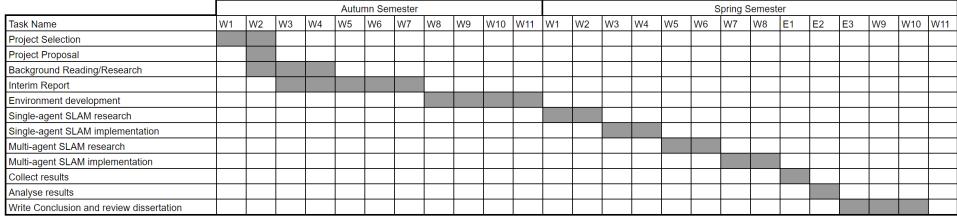


Figure 8: Gantt chart showing the project plan

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 8 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 well-being 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 proposed by Gao et al. [13].

Seed segment detection works by observing a set of points from a single sweep. The algorithm starts by fitting a line through the given points. Then, in order for a seed segment to be further considered, it must satisfy the following two conditions:

- The distance between the point and the line must be less than a given threshold.

- The distance between the point and it's predicted position must be less than a given threshold.

Seed segment detection uses orthogonal line fitting to propose a feature through a set of points, as it is more effective than using traditional methods, such as standard least square fitting; this is due to the nature of least square fitting which only takes into account the vertical distances of each point.

After, the algorithm applies region growing, which helps create line segments; which will then become our features. The region growing works by examining neighbouring points and adding them to the line segment if they satisfy the same conditions. This process is repeated until no more points can be added to the line segment.

6.1.2 Identifying Landmarks

6.1.3 Data Association

6.1.4 Pose Graph

6.1.5 Graph Optimisation

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, LI-DAR 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.

7.1.10 Meeting 10 - 15/03/2024

This meeting was a clear turning point in the project. As progress hadn't proceeded as expected, we discussed the scope of the project and how it could be adjusted to ensure that I could complete it on time. We agreed that I should focus on the single-agent components of SLAM, as they are the most important parts of my project. We also discussed how I could approach the final report - including changes that would need to be made to adhere to the new project scope. Finally, we discussed in further detail how I could gather data for my analysis and how I could present it.

7.2 Project Proposal

Swarm Robotics: Exploration and Mapping in Simulated testing Environments

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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				

8 References

References

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