Characterisation of a Nuclear Cave Environment Utilising an Autonomous Swarm of Heterogeneous Robots

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Abstract

As nuclear facilities come to the end of their operational lifetime, safe decommissioning becomes a more prevalent issue. In many such facilities there exist 'nuclear caves'. These caves constitute areas that may have been entered infrequently, or even not at all, since the construction of the facility. Due to this, the topography and nature of the contents of these nuclear caves may be unknown in a number of critical aspects, such as the location of dangerous substances or significant physical blockages to movement around the cave. In order to aid safe decommissioning, autonomous robotic systems capable of characterising nuclear cave environments are desired. The research put forward in this thesis seeks to answer the question: is it possible to utilise a heterogeneous swarm of autonomous robots for the remote characterisation of a nuclear cave environment? This is achieved through examination of the three key components comprising a heterogeneous swarm: sensing, locomotion and control. It will be shown that a heterogeneous swarm is not only capable of performing this task, it is preferable to a homogeneous swarm. This is due to the increased sensory and locomotive capabilities, coupled with more efficient explorational prowess when compared to a homogeneous swarm.

Dedication and acknowledgements

I would like to thank all of my friends at the Bristol Robotics Laboratory for their support and companionhip throughout my studies; Anouk van Maris, Ben Ward-Cherrier, Luc Wijnen, Luke Cramphorn, Chanelle Lee and many more. In addition Edward Hares, who always took a sports break with me when it was needed and proved a fantastic housemate!

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Finally, I would like to thank Ellie Tonsbeek whose love and support has got me through the final year of the PhD with a smile on my face.

Author's declaration

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

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Chapter 1

Introduction

This research is motivated by the National Nuclear Laboratory's ongoing desire to utilise autonomous robotics to aid in nuclear decommissioning, specifically for characterisation of nuclear cave environments. A nuclear cave is an area within a nuclear facility through which much of the key pipework and pressure vessels are routed, as can be seen in figure 1.1. After its construction the cave is sealed, in order to protect plant workers from the harmful radiation contained within. The operational lifetime of a nuclear facility can be up to fifty years, during this time the state of a nuclear cave may deteriorate. In addition, plans for the cave that were created on construction may not be accurate. The concatenation of these factors means that there is no clear idea of the exact structure and contents of a nuclear cave when it comes to decommissioning.

Due to the harmful radiation and lack of information about the interior of a nuclear cave, it is deemed unsafe for plant workers to generate surveys. Thus, it is strongly preferable to implement a robotic system for this task. At the early stage of decommissioning being considered during cave characterisation, access to the cave is granted only through the drilling of up to 15cm diameter holes, this is to enable maintenance of the negative pressure inside the cave which prevents irradiated gas escaping. This limits the size of robotic agents. As the cave presents complex terrain, a varying locomotive approach is appropriate. Additionally, the need to gather varying data including temperature, humidity, radiation and geometric data amongst others, necessitates a wide array of sensing capabilities. The combination of size limitations and varied sensing and locomotive modalities lends itself to the decentralised control of a team of heterogeneous robots.

The aim of this research is to answer the question: is it possible to utilise a heterogeneous swarm of autonomous robots to remotely characterise a nuclear cave environment? To answer this question the three key components of the swarm are analysed, these are: sensing, locomotion

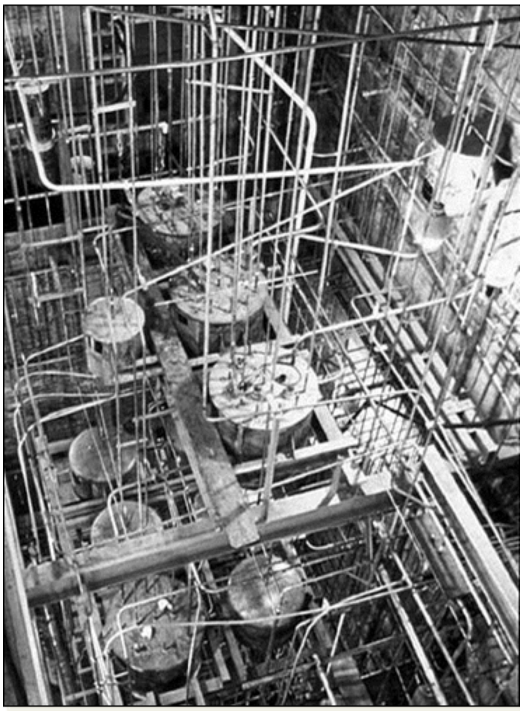


Figure 1.1: A picture of a nuclear cave environment, taken before it was sealed.

and control. Using these three elements a swarm can perceive, move within and make decisions whilst exploring and mapping its environment.

To achieve this goal, a combination of review, simulation and physical experimentation is employed. To examine the sensory capabilities of a heterogeneous swarm, the desired modalities are given by an industrial expert from the National Nuclear Laboratory. The sensors that are applicable are then reviewed and suggestions put forward for the best choice in each case. The sensing modalities are: distance, radiation, pressure, humidity, image capturing, temperature, chemical and tactile perception.

The investigation into locomotion involves a combination of experimentation, design and review. First, the locomotion strategies that are feasible within a nuclear cave will be explored through review. The most promising ground locomotion strategies will then be compared through experimentation. Then the novel design of a supplementary locomotion method, in the form of a detachable grappling hook, will be put forward. This will allow a full examination into the capabilities of a swarm that utilises heterogeneous locomotion.

The final element that will be examined is robot control. This research puts forward the 'Reactive Virtual Forces' method for exploration and mapping of a nuclear cave environment. This utilises virtual analogues of the fundamental forces of nature to guide a swarm in exploration of an unknown environment. This control architecture will be examined in conventional simulation and embodied simulation. It will be shown to be capable of producing simultaneous localisation and mapping in conjunction with an extended Kalman filter.

This work seeks to contribute to knowledge in numerous areas. The overall contribution of the thesis is in consolidating knowledge surrounding, and examining the requirements for, the characterization of a nuclear cave environment using a heterogeneous swarm; an application domain that has not been investigated previously. As has been described this is achieved through the examination of the three key areas that comprise a heterogeneous swarm: sensing, locomotion and control. The contributions in these areas are as follows:

- **Sensing** – this thesis contributes to knowledge through the review of the sensing modalities that are required for a nuclear cave, assessing their suitability for transport by a heterogeneous swarm of robots. Here, novelty lies in the review criteria and the amalgamation of knowledge pertaining to sensing with a swarm in nuclear environments.

- **Locomotion –** this thesis' contribution is through the assessment of the locomotion strategies suitable for use by a heterogeneous swarm in traversing a nuclear cave, through review and experimentation. Additionally, it contributes with the novel design of a detachable grappling hook that could allow ground robots to move to the higher reaches of the nuclear cave [27].

- **Control –** this thesis contributes with the design of the 'Reactive Virtual Forces' framework for exploration and mapping [28]. Within this framework novelty lies in the sole use of potential fields for mapping and organization, without the use of a shared map, along with the examination of performance for both a heterogeneous and homogeneous swarm. Additionally, it contributes with the use of the 'Reactive Virtual Forces' framework for simultaneous localization and mapping (SLAM); previously SLAM has not been achieved with virtual fields. Finally, the thesis contributes with the design of an exploration performance scale that can be used to assess the quality of exploration strategies and it is applied to the 'Reactive Virtual Forces' framework to explore its capabilities.

Overall, this research will show that not only is it possible to utilise a heterogeneous swarm for the characterisation of a nuclear cave environment, it is preferable to a homogeneous swarm. It will be shown that the diverse sensory and locomotive capabilities of a heterogeneous swarm are beneficial for exploration within the cave. In addition, the 'Reactive Virtual Forces' framework will be shown to operate more efficiently on a heterogeneous swarm when compared to a homogeneous swarm.

This thesis will be structured as follows: chapter two presents a review of the relevant literature; an evaluation of the sensing modalities applicable to a nuclear cave will be detailed in chapter three; the possible locomotion strategies will be investigated in chapter four; the control of a heterogeneous team will be explored in chapters five and six; and finally, chapter seven will explore future work and draw conclusions from the work.

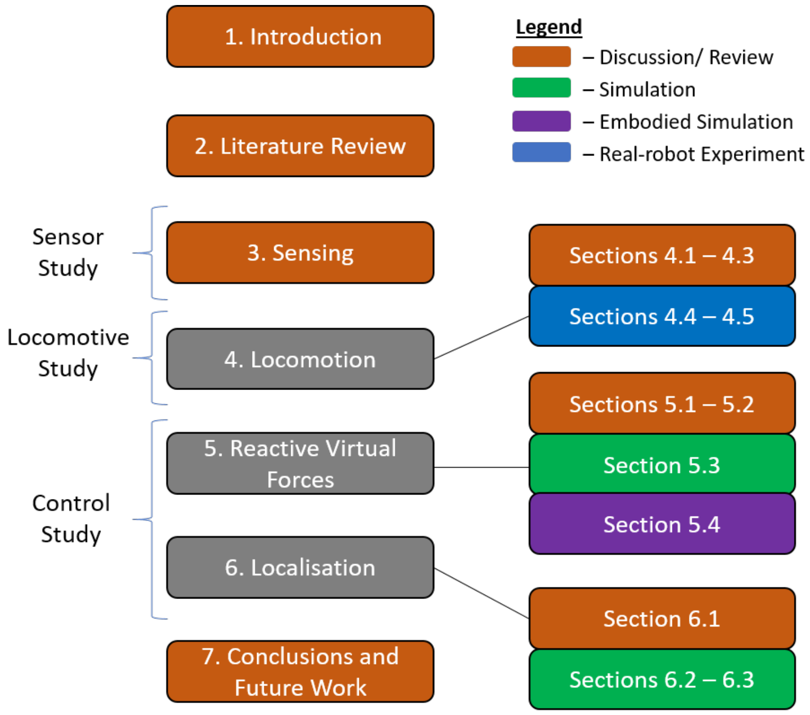


Figure 1.2: Shows the structure of the thesis, highlighting where experimental work was conducted.

In order to identify the areas of the thesis that represent experimental work, and contributions to knowledge, figure 1.2 is provided. This shows the structure of the thesis with the experimental approach taken for each section. 'Simulation' refers to experiments that were entirely conducted in simulation. 'Embodied simulation' refers to experiments that were conducted on real robots that were imbued with some virtual properties to allow for heterogeneity to be instigated on homogeneous robots. 'Real-robot' experiments refer to experiments conducted without any simulated or virtual parameters.

This thesis contains work from two published papers, these will be referenced again at the beginning of their respective chapters but are included here for completeness:

- **Chapter 4 -** *"A novel design for a robot grappling hook for use in a nuclear cave environment"*, Published at Mechatronics 2016
- **Chapter 5 -** *"Reactive Virtual Forces for Heterogeneous and Homogeneous Swarm Exploration and Mapping"*, Published at TAROS 2017

CHAPTER 2

LITERATURE REVIEW

Decommissioning of nuclear facilities is a time consuming, dangerous and expensive task. The hazards to plant workers are many and can include: exposure to dangerous radiation, unpredictable environments and exhaustion. These dangers may be diminished through the use of autonomous robotic systems. In the specific case of exploration and mapping of a nuclear cave environment, the size restrictions, necessity for diverse sensory capabilities and requirement of varying locomotion strategies lends itself to the use of a heterogeneous swarm of autonomous robots.

The design of such a swarm involves the combination of multiple components: a comprehension of what robotic systems already exist in the nuclear industry; a deeper examination of swarm use in hazardous and nuclear environments; knowledge of the existing robotic platforms that could be used to examine swarm behaviour; an appreciation for the design of swarm behaviours; an awareness of what behaviours swarms are already capable of exhibiting; and an acquaintance with current mapping and exploration techniques. It is the aim of this review to provide an overview and analysis of these topics, and the applicability of existing work to exploration and mapping of a nuclear cave environment. The motive of this review was twofold: first to guide the research in this project, allowing knowledge of the field to be gained; second, to inform the nuclear industry of the current capabilities and potential applications of robotics for exploration and mapping of a nuclear cave environment. To serve both of these requirements, much detail has been included in the review.

There are multiple elements to be considered when examining the suitability of examples presented in the literature. Communication is difficult within a nuclear cave due to the poor line of sight and interference from radiation, in addition to thick concrete walls. A swarm therefore needs to be capable of performing the exploration and mapping task with little, or sparse communication.

In addition, it is preferable for the nuclear industry to train current plant workers to use any implemented robotic systems. So it is desirable for the solution to be easily implemented, and interpreted, by plant workers. Further, it is important that a swarm can effectively cover the area being mapped; this allows a complete understanding of the environment to be gleaned. To be implemented in the nuclear industry the robotic systems need to be economically viable and readily available, preferably off the shelf. Finally, as a heterogeneous swarm is likely to be utilised in a nuclear cave environment the performance of a system or control strategy in this context should be contemplated. Thus, the communication requirements, plant worker interpretation, coverage, cost and availability, and consonance with heterogeneity are the main factors to be considered when assessing the literature against the task of exploration and mapping of a nuclear cave environment.

Before beginning the review, a number of important background papers should be highlighted. The first of these is a recent paper by Brambilla et al. This review follows a similar structure to that adhered to within Brambilla et al's work, in addition the paper provides an up to date review of the abilities of swarms [26]. Barca and Sekercioglu corroborate many capabilities outlined by Brambilla et al., in addition to posing many of the problems still facing swarm systems [18]. For a definition of many of the terms used within swarm robotics readers should refer to Beni's paper on swarm intelligence and swarm robotics [22]. Another in depth review of the state of the art in swarm robotics, focussed on swarm behaviours, is put forward by Mohan and Ponnambalam [169]. A taxonomy for swarm robotics is introduced by Dudek et al. [74], in contrast a differing taxonomy is introduced by Iocchi et al., in addition Iocchi et al. compare the effects of reactivity and deliberation in swarm systems [114]. A review of physical robot implementations is given by Parker [187]. For an examination of research axes previously explored, along with suggested future directions the reader should refer to 'Cooperative Mobile Robotics: Antecedents and Directions' by Cao et al. [41]. An outline of the various learning methods used by swarms may be found in a paper by Panait and Luke [185]. Finally, an introduction to the idea of swarm engineering may be found in a paper by Winfield et al.[255].

The remainder of the literature review is organised as follows: section 2.1 provides background on the existing uses of robotic systems in nuclear decommissioning; section 2.2 describes swarms that are designed specifically for use in hazardous and nuclear environments; section 2.3 outlines physical robots used in swarm systems; section 2.4 analyses swarm design; section 2.5 provides an examination of the current behaviours of which swarms are capable; section 2.6 presents an overview of mapping and exploration capabilities of swarms; section 2.7 draws conclusions about the state of the art and the novelty of this project.

2.1 Current Robotic Systems Within Nuclear Decommissioning

The problem of nuclear decommissioning is becoming increasingly relevant as more nuclear facilities are coming to the end of their functional lives. In order to decommission a nuclear facility, details of its inner workings are required. Obtaining this information is difficult as many areas of the nuclear facility are not safe for humans to enter, due to the adverse effect on health. Hence, the nuclear industry hopes to implement robotic systems to aid in the ongoing process of decommissioning.

This section aims to describe some of the systems that have already been designed for use in the field of nuclear decommissioning. The selected examples are split into three distinct categories: maintenance and inspection; nuclear disposal; and nuclear disaster prevention/ response. This will provide a cross-section of the robotic platforms currently implemented for use in nuclear facilities.

2.1.1 Robots used for Maintenance and Inspection

The first of the three areas into which robotic systems in the nuclear industry fall is maintenance and inspection. These robots are used to detect faults and prevent failure while the plant is online, or to inspect hazardous areas whilst the decommissioning process is taking place.

One key challenge within the nuclear industry is to be able to inspect the walls of a reactor building, both whilst the plant is online and before decommissioning starts. The reactor is an area inaccessible to human workers due to the high levels of radiation; for the same reason's cameras will not survive. It was because of this that Robicen III was designed [210]. This robot is low weight (3kg) and capable of climbing the cylindrical walls of a reactor building. The robot uses four suction pads arranged on two gantries that can be raised, lowered and translated to produce motion; an image of the robot is shown in figure 2.1. This robot is able to detect cracks and radiation leaks within the reactor that would not previously have been detectable until they had become dangerous.

The inside of the reactor building is not the only area within a nuclear facility that requires innovative climbing robots, and many areas do not have the same smooth walls as a reactor. Rooms that contain large quantities of pipework and girders require a different locomotion strategy, such as that described by Wilson et al [207]. This paper describes a robot that can both travel through the inside of a pipe or tubular structure and climb its outside. In addition to tubular structures, the robot can climb girders using the addition of two legs. The robot consists of a modified Stewart-Gough platform with two connected rings that have grasping mechanisms on the outside and inside, with the potential for legs to be attached, as seen in figure 2.2. This design allows the robot to inspect the inside of the pipe for thinning due to corrosion, which could cause a breakage and hence radiation leak. The ability to scan the outside of the pipe enables the discovery of any leaks that have already formed; this is useful both for maintenance whilst

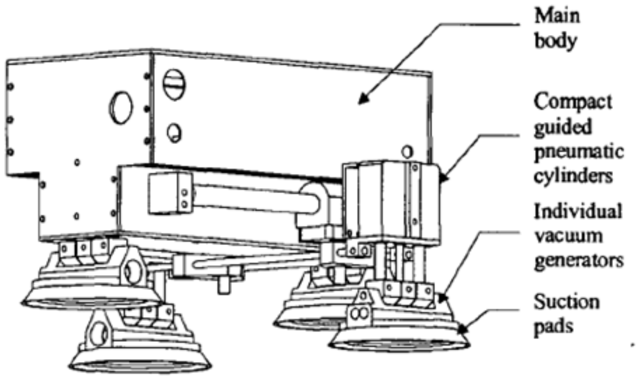


Figure 2.1: Shows the design of the Robicen III [210].

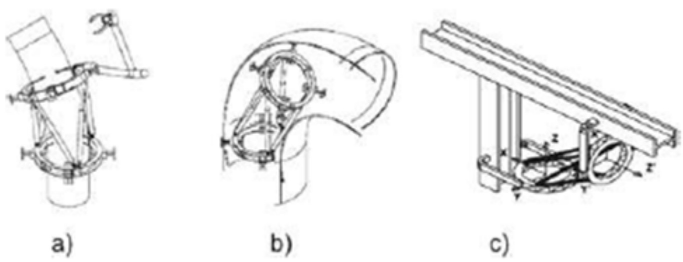


Figure 2.2: a) Shows the robot mode used to climb the outside of a pipe. b) Shows the mode used to climb through the inside of a pipe. c) Shows the additional of legs to enable the climbing of girders. [207]

the plant is online and characterisation of the environment during decommissioning. The final mode of the robot, allowing traversal of girders, enables the robot to climb within complicated structures which would help in the generation of 3D maps. The design of this robot requires teleoperation, which shields the user from radiation and enables a human worker to be included in the control loop and inspection process. This allows complex decisions to be made by an expert.

Another method that can be used for the inspection of hazardous areas is a robot that operates on fixed rails. This design is more useful if the rails are preinstalled, as the robot can then be used for online inspection and maintenance. This makes it a useful technology to be considered when constructing future nuclear facilities. One such railed robot is MonoCaRob [210]. This robot may be used for the remote inspection of drywell walls in a boiling water reactor. It is installed to travel along a copper rod that provides it with power, the design is shown in figure 2.3. When the robot is not in operation, it returns to a location shielded from radiation by lead plating. This protective shield enables a camera to be installed as it is only exposed to radiation in small doses. It is therefore possible to see areas of the plant that would normally be impossible to see during operation and decommissioning, a useful tool when analysing a plant.

As well as inspection, robots can also be used to perform maintenance tasks within nuclear

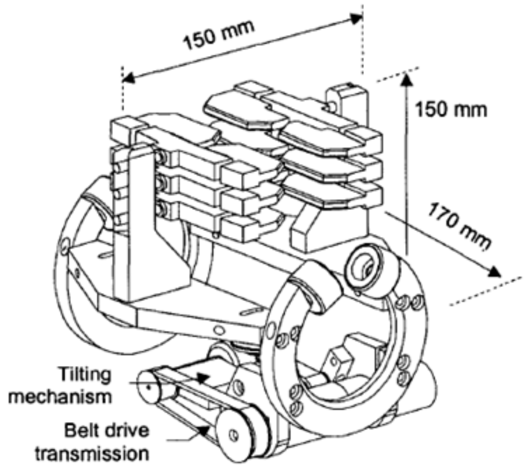


Figure 2.3: Shows the design of the MonoCaRob robot [210]

Figure 2.4: Shows a snake arm robot repairing a pipe at the Ringhals nuclear power plant [33].

facilities and decontamination during decommissioning. Two such robots are the snake-arm robot demonstrated by Buckingham and Graham [33] and the Robotic Contamination Cleaning System (RCCS) put forward by Kim et al. [127].

The snake-arm robot was designed to perform inspection and repair tasks in compact environments. Specifically, the robot was used to repair a pipe leak at Ringhals nuclear power plant; this is shown in figure 2.4. The snake-arm robot is flexible enough to operate in very tight environments where previously a large manipulator would not have fitted. This makes it an asset in the maintenance and decommissioning of a nuclear facility.

The RCCS was designed specifically to operate in the isolation room of the Korea atomic energy research institute. The RCCS is used to decontaminate debris that has been moved into the isolation room from the cell below. It is one of the few robotic systems in the nuclear industry that features an automatic mode, which may be overridden to allow manual control for delicate tasks. Due to the highly radioactive environment, the robot has a modular design so that if components fail, they are easily replaced. This is a very useful feature and could be incorporated into the design of future robots that are to be used in the hazardous nuclear environment.

In this subsection, current methods and research into the robotic systems for the inspection and maintenance of nuclear facilities have been explored. It has been demonstrated there are relatively few robots designed for nuclear inspection, and at present there is very little automation implemented within the systems. So far there have been no implementations of robots used to characterise unknown environments to aid in nuclear decommissioning. This motivates the design of a heterogeneous swarm of autonomous robots for use in decommissioning of a nuclear cave environment.

2.1.2 Robots used for Nuclear Disposal

The handling of spent fuel cells in the nuclear industry is a very delicate task. Facilities that require contact with fuel cells during the disposal process must have systems in place for remote operation. Systems installed in such environments must adhere to a number of constraints [62]:

- Capable of withstanding the maximum dose for 1 year (between 104 and 105Gy, this is the international unit of radiation dose, expressed in energy absorbed per unit mass of tissue)
- Decontamination capability using potentially aggressive products
- Operation at high temperature (508C, this is the typical temperature of the cooling gas in a reactor)
- Electromagnetic compatibility
- Volume and weight compatible with remote operations
- Compliance with safety and quality standards
- Diagnosis and maintainability constraints
- Compatibility with waste management
- Remote Maintenance

Most spent fuel cells are moved to reprocessing plants where they are left in large pools, in order to reduce their radiation levels. They must then be retrieved from these pools so they may be recycled. An early attempt to introduce a robotic system into this process was in the development of a pneumatic muscle actuator driven manipulator rig for nuclear waste retrieval operations [38]. In this article, it is explained that currently there are master slave manipulators that a worker may operate from the other side of a thick window. These manipulators are used to move waste out of the storage pools during the nuclear disposal process. To improve the quality

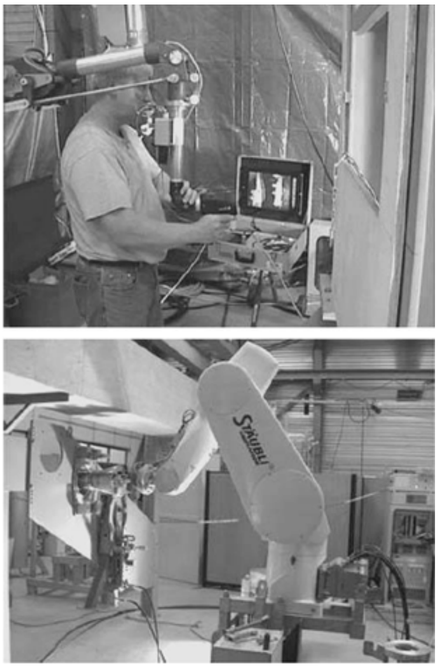


Figure 2.5: Shows a multi-axis robot performing the task of pipe cutting [12].

of this task, the use of a robotic system via teleoperation is suggested by Caldwell et al [38]. An arm is developed that is not dissimilar to the system already in place, however it is actuated so that a worker need not exert themselves during completion of the task. An interesting point is touched upon within the paper; the need for worker approval. It is claimed that previous attempts at introducing robotic systems have failed due to workers not being satisfied with the user interface. Thus, it is important to note that when designing a system's control architecture, the user interface should not differ too much from what is already in place. In this way, the transition to using robotic systems will not affect worker satisfaction.

The early attempt outlined above can be improved using force feedback technology. This aids in the disposal process because it allows more intricate tasks to be completed remotely. There has been work involved with creating a force feedback controlled, industrial robot [62]. This work outlines the force feedback teleoperation of an industrial robot in a nuclear spent fuel reprocessing plant, shown in figure 2.5. This robot was implemented in the 'La Hague' facility in France, where it was used to replace the dissolver wheel in the fuel reprocessing plant. This wheel is used to separate out the useful components of a spent nuclear fuel cell. This shows an industrial robotic system being implemented in the disposal process, making the task faster and considerably easier.

In addition to the need for force feedback control, there is also a need to improve the mean time before failure (MTBF) of custom robots used in the disposal process. A typical customised one-off solutions robot used in these tasks have a MTBF of 5-6 hours [212] [12]. Industrial robots have a much longer MTBF of around 70,000 hours. Therefore the use of industrial robots, that have been hardened for radiation, for nuclear disposal would be beneficial; such as that shown in figure 2.5.

Finally, the RoMaNS project (Robotic Manipulation for Nuclear Sort and Segregation) has recently focussed on the use of tele-operated robotic manipulators to sort spent nuclear waste [2] [158] [1]. This project was funded by the European commission, with a project scenario utilising a human worker to control a teleoperated manipulator to sort and segregate waste.

This section has shown the systems that have been implemented within the process of nuclear disposal. Most of these systems are in place or planned for nuclear fuel reprocessing plants. There are currently no swarm behaviours utilised for nuclear disposal. This is largely due to the fact that mobile robots are not always necessary when disposing of spent nuclear fuel, as the process often occurs in a static environment; however, there are a great many more tasks to be carried out in these environments that do require mobile robots, such as characterisation of a nuclear cave environment.

2.1.3 Robots used for Nuclear Disaster

The final category of robots used in nuclear environments are those implemented for nuclear disaster prevention and response. Thankfully, there have been very few nuclear disasters. The most notable of these are the Chernobyl accident of 1986, and the Fukushima Daiichi disaster of 2011. It is difficult to get hold of information about robots used in the Chernobyl accident, but it has been indicated that they failed due to the high-level radiation exposure [178]. The reaction to the disaster at the Fukoshima Daiichi plant is more publicly documented, and this review aims to give an account of this.

When the accident occurred at Fukushima Daiichi, the Japanese government were not prepared to cope with it. There existed search and rescue robots known as Quince robots, shown in figure 2.6. These robots, though adept at traversing complex environments, were not designed to operate in high radioactivity. It was urgent to test whether the robots would be suitable for use in the destroyed reactors at Fukushima Daiichi. In order to determine if this was the case, five criteria were designed, which could be applied to other nuclear disaster situations [178]:

1. Mobility – it is important that the robot is able to move around in the potential rubble strewn environment following a nuclear disaster

2. Radiation hardness – it is important that the robot be able to survive highly radioactive environments

3. Communication – it is important that the robot be able to communicate, either by cable or by WiFi

Figure 2.6: Shows the quince robots used for search and rescue in Japan [178].

4. Sensors – it is important that the robot be able to attain satisfactory measurements to characterise the environment
5. Hardware Reliability – once the robot has been exposed to the nuclear environment, it will not be possible to manually repair it

It was found that the current disaster response robots fulfilled most of these criteria. However, it was necessary to add sensors and use a combination of wired and wireless communication within the thick walls of the damaged reactor.

The robots used in the Fukushima Daiichi disaster show that there is still a long way to go in search and rescue robotics. Six test missions were implemented, of which two had to be abandoned; a third took far longer than expected because of a shutdown of the robot's motors, caused by the high temperature. Additionally, the need for an easy post-mission recovery method for the robots was exemplified by the fact that a robot remains trapped within the facility at Fukushima Daiichi to this day.

The robots outlined above fall into the category of emergency response. Though these are unfortunately necessary, there is another class of robot that could be utilised in the future: disaster prevention robots. These are essentially maintenance robots, but with a higher radiation tolerance and a more diverse range of sensors, which may be used to find unexpected problems within a nuclear facility. One such disaster prevention robot is the SWAN robot [105], shown in figure 2.7. This robot is compactly designed to allow it to turn in narrow corridors and has eight interchangeable work tools that may be used to perform different tasks, such as door opening and the checking of a tandem plug. The tools are carried on the robot's frame and can be changed remotely during a mission in order to best complete a task. The robot has been used in a mock up environment in which it was required to first open a door and then check a tandem plug. This shows that it is possible to use robots to prevent possible disasters at nuclear facilities by sending them into areas that would otherwise be inaccessible.

Overall, the current technologies used in nuclear disaster response have been outlined through the example of the Fukushima Daiichi accident. However, the failures at Fukushima indicate

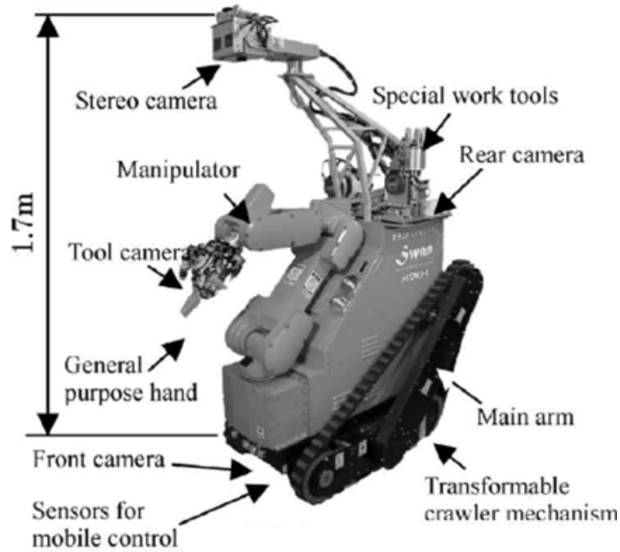


Figure 2.7: Shows the SWAN robot used for nuclear disaster prevention [105].

research is still needed in search and rescue in a nuclear environment. In addition, a design for a disaster prevention robot has been examined. It is clear that robots are a vital source of aid during nuclear disaster, but that more development is needed if they are to be made reliable.

2.2 Swarms in Hazardous Environments

Swarm systems are a rapidly expanding research area within the larger field of robotics. Such systems are comprised of many robots working together. These robots are often simple in design with the hope that their collective behaviour will cause the performance of the system to vastly out perform an individual robot [122]. Swarm systems often derive their inspiration from nature, drawing on the behaviour displayed by insects in a hive, birds in flock or fish in a school. Outside of academic research, there exist few examples of swarm robotics to aid in the nuclear decommissioning process, or for hazardous environments in general. This section aims to highlight the research that has focused on the use of swarms in both nuclear and extreme environments.

2.2.1 Extreme Environments

Much work in extreme environments focuses on mapping and exploration, this is to increase the operator's understanding of a hazardous environment before accessing it, thus improving safety. Bidding seems to be a popular method for completion of this task [234] [215]. Bidding involves robots competing for a task by providing the lowest 'bid', analysed under a particular metric, for example time to task completion. For the task of exploration and mapping the bid is won by the robot who can provide the shortest distance to a goal. Robots are required to communicate with each other or a central controller in order to win bids, this might be difficult within a nuclear cave environment. Despite this, bidding could be employed with a heterogeneous swarm, as individual robot capabilities may be considered during the bidding process. However, the research conducted in this thesis does not focus on bidding as it was desirable to implement a controller that does not require a centralised agent, to increase robustness and reduce the need for continuous communication.

Another task that swarms are utilised for is marking of hazardous areas. This could be relevant to the nuclear cave for the identification of chemical spills or leaks. This has been examined in work by Hardin et al., where robots are used to mark hazards on a grey scale map, and then form a perimeter around them. Agents continuously map the boundary and its change if the spill continues to spread [98]. Virtual potential fields have been used for the same task of surrounding a spill with robots [32] [31]. In these examples homogeneous swarms are used to find hazardous spills. The result is a perimeter around a spill. This provides useful and easily interpreted information for a plant worker. In addition, robots need only communicate over the size of the spill, which is more likely possible within a nuclear cave. The use of potential fields is interesting for this task, as will be seen later in this review, this is a versatile method that can be applied to many behaviours.

Automation is an important aspect in the implementation of a swarm system in nuclear cave environments as it allows plant workers to be trained only to deploy the swarm and analyse its results. Swarm use in space exploration exemplifies this. Although space does not seem directly applicable to nuclear caves, it shares similar requirements; robots are required to perform an exploration task with limited, or no interaction with humans. Truszkowski et al. describe the design and requirements of such a system [239].

Overall the use of swarms in hazardous environments seems to be underdeveloped. Furthermore, most research focuses on the use of homogeneous agents. This indicates that the design of a heterogeneous swarm for use in a nuclear cave environment is a novel undertaking.

2.2.2 Nuclear Environments

As this project focuses on the characterisation of a nuclear environment, it is important to review what progress has been made in multi-robot systems design for operation in this domain. It will become apparent that there is little literature in this field and hence a great potential for new research, justifying the need for this project.

One of the earliest attempts at implementing a swarm is the Mobile Automated Characterization System (MACS) [3]. This team features a pair of robots that carry dosimeters, with the aim of measuring the radiation levels around a nuclear facility to aid with decommissioning. Currently this work is a tedious and repetitive job carried out by human workers. The pair of robots aims to alleviate this tedium. The MACS robot is a large robot capable of moving through an environment swiftly and taking readings. It carries with it a Reduced Access Characterization

Subsystem (RACS) robot that is deployed when the MACS cannot reach an area. Together these robots have been used to take successful measurements around a nuclear facility at a similar rate to human workers. Though this is only a small ‘swarm’ the robots are heterogeneous. They are capable of performing different sensory tasks, and of locomoting to more diverse areas than a homogeneous pair, giving a better coverage. The system is automated and as such plant workers need not be trained in the operation of agents. This system shows that heterogeneity can be a benefit in tasks that where coverage is important, and further motivates the implementation of a heterogeneous swarm in a nuclear cave environment.

Another application within the nuclear sector is the characterisation of nuclear spills. A solution to this is to use glow worm inspired taxis [120]. This involves agents ’glowing’ more brightly when they are near a peak in radiation, and hence having other agents move towards them to better map the source. If instead the radiation is airbourne, then an area may be split into grids and a group of robots may use gradient measurements to locate the source [57]. Using luminescence for communication could reduce the need for robots to maintain connectivity. However, for robots to observe ‘glowing’ they need line of sight, which may be difficult within a nuclear cave. This solution would lend itself to a heterogeneous swarm. The algorithms discussed allow for spill mapping, which may aid in the characterisation of a nuclear cave environment. Despite this, glow worm inspired algorithms do not allow for efficient geometric mapping.

A final example of the use of swarm robotics in the nuclear industry is in the maintenance and monitoring of nuclear storage pools [179]. The monitoring of these pools is the closest analogy to this project. This is because it requires that a swarm of robots be sent into an unknown under water landscape, with debris and unknown topography, in order to map it. It is suggested that one possible solution to this task is to render an occupancy grid [77]. The task of localising whilst mapping is distributed between ’explorer’ robots and ’localiser’ robots. The explorers’ aim is to build the map, whilst the localisers maintain a line of sight connection to both the explorers and the nodes located around the rim of the pool. Using these localiser robots, the explorers are then capable of both finding their own position and mapping. Though this is not directly applicable to the nuclear cave, as nodes cannot be easily placed around it, the idea of using some robots to localise others whilst exploring is tenable. This shows that an occupancy grid provides useful and easily interpreted information to plant workers. It is for this reason, among others that will be discussed later in the review, that an occupancy grid was used for mapping in the work presented in this thesis.

Overall it is clear that there has been little study, and even less implementation, of swarm robots in the nuclear sector. This then shows that there is great scope for investigation into the use of a swarm in a nuclear environment. More to the point; to the best of the author’s knowledge there have been no studies involving the use of a swarm in a nuclear cave environment, hence making the application domain novel.

2.3 Physical Robots Currently used in Swarm Study

In this section the aim is to highlight the key physical robot implementations that exist in the literature. This is both to show which robots were considered for this project and to present to industrial readers other robots that are readily available for purchase and implementation. The section is split into two sub-sections: homogeneous and heterogeneous. These are the two ways the physical swarm composition is defined. Homogeneous robot swarms are those in which all the robots are physically identical. Heterogeneous swarms are those in which the physical design of the constituent agents differs.

Both homogeneous and heterogeneous swarms have their advantages and disadvantages. From the perspective of the three key traits of a swarm: robustness, flexibility and scalability, it can be concluded that a homogeneous system is both more scalable and more robust. This is because any agent can replace any other agent and, when enlarging group size, it is cheaper to produce more of the same robot. However, heterogeneous systems are more flexible due to the potential for utilising different sensors, and locomotive methods. This makes them more suited to unknown or unpredictable environments. In addition, if the number of robots used is much more than the different physical designs, then a heterogeneous swarm may be made both more robust and more scalable.

From a control point of view a homogeneous swarm may be more attractive as each robot can implement the same controller. Though as will be seen in the literature it is not uncommon to have a homogeneous swarm become heterogeneous through election of leaders. Heterogeneous control is slightly more complex as a result of the different abilities of each robot, often requiring a controller for each physical type of robot with an overall task allocation scheme.

Due to the increased flexibility, allowing for more consistent use in unknown environments, the work reported on in this thesis utilises heterogeneous robots. This is because different areas of the cave may require different locomotive strategies and sensors, all of which cannot be fit into one design. In addition, as will become apparent, there are few real-world implementations of heterogeneous swarms. Thus, the choice of using a heterogeneous swarm in the mapping of a nuclear cave is both prudent and novel.

As will be described later in this thesis, the 'reactive virtual forces' framework is used for control of the swarm. This provides a framework that can be used with homogeneous and heterogeneous swarms whilst undertaking the exploration and mapping task. In addition, E-Pucks were used to conduct the embodied simulation experiments [171]. This provided a homogeneous group of robots that were imbued with virtual heterogeneity through the use of a VICON tracking system.

Figure 2.8: The swarm-bot robot, used for homogeneous experimentation [67].

2.3.1 Homogeneous

As mentioned previously, homogeneous swarms are the most prevalent in the literature. This is due to the fact it is cheaper to design and build one type of robot, rather than multiple different ones. In addition, homogeneous swarms are more robust to failure, albeit at the sacrifice of some flexibility. This section will look at some of the physical implementations of homogeneous swarms that have been explored in the literature.

The first and most abundant robot used in the literature is the Swarm-Bot, shown in figure 2.8 [172] [67] [66]. This has been used for multiple studies that will be described in this review. The Swarm-Bot is comprised of many smaller s-bots that are capable of self-assembly. Each individual s-bot is made mobile using 'treels', a system that combines the rough terrain ability of tracks with the on-the-spot turning of wheels. The sensors available on the s-bot platform include infrared proximity sensors, light and humidity sensors, and accelerometer and incremental encoders for each degree of freedom. In addition, for communication they have an omni-directional camera, a colour LED, a colour detector and a sound emitter and receiver. Finally, the s-bots designers also made a Swarm-Bot simulator, which allows for testing in simulation with the ability to then download the same code to the real robots. This coupled with the attractive self-assembly capabilities of the robot lead to its widespread use in research.

The E-Puck robot is designed for use in education and for examination of a variety of behaviours, an image of this robot is shown in figure 2.9 [171]. E-Puck locomotion is achieved using a

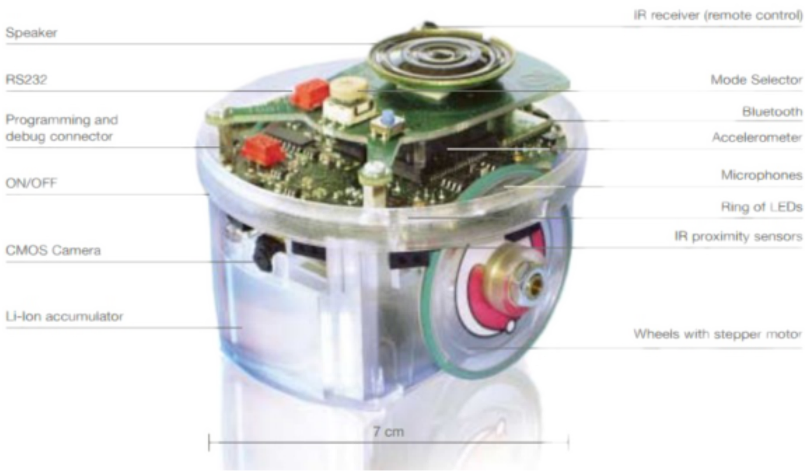


Figure 2.9: Shows the E-Puck robot for experimentation in this project [172].

differential twin-wheel drive. Eight infrared proximity sensors place around the robot's perimeter allow for obstacle avoidance and distance measurement. In addition, the robot is equipped with microphones, speakers, Bluetooth, accelerometer and VGA camera for the investigation of various behaviours. This is a readily available robot that can be bought in bulk at a reasonable cost of 250 euros [171]. As the E-Puck was already available in our laboratory, it made sense to use it for experimentation. The drawback is that the robots are homogeneous, thus virtual heterogeneity was imbued through the use of a VICON tracking system. The details of this virtual heterogeneity will be discussed in chapter five.

The ability to reconfigure seems to be a popular utility in the design of homogeneous robots. Three examples of such are M-Tran, Sambot and Polybot shown in figures 2.10, 2.11 and 2.12 respectively [177] [245] [266].

M-Tran stands for modular transformer, as can be seen in figure 2.10 the modules are made from two semi-cylindrical boxes and a link that joins them. This, coupled with permanent magnet connectors, allows the robot to reconfigure between different pre-determined patterns. In contrast both Sambot and Polybot use a mechanical connection to create larger structures. However, of the three robots, only Sambot is capable of movement at the individual module level, the others must connect to form locomotive structures such as caterpillars or legged robots. These robots could be used within a cave to form structures to overcome objects, or to gain better vantage points for the mapping effort. However, as these are largely custom built, they are not readily available for use for testing or within a nuclear cave.

It is rare that swarms of more than twenty are examined with physical robots. This is often due to the cost of manufacturing hundreds or thousands of robots to form a swarm. One solution to this issue is put forward in the form of the Kilobot robot [203]. This is a small robot that costs only 14 dollars (USD) to build. The behaviours are simple, but useful for swarm research, these behaviours include: forward and rotary motion using three vibrating legs; communication with

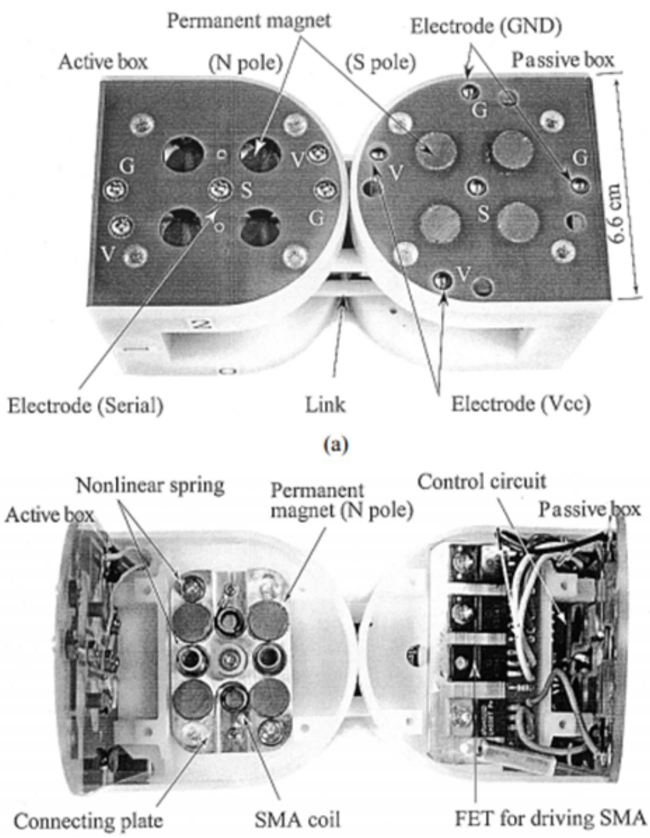


Figure 2.10: Shows the individual module that is the constituent of M-Tran [177].

nearest neighbour; ambient light measurements; and internal state display for debugging. In addition, for ease of scalability the robots can charge on a conductive table through their legs; be turned on and off in unison using an overhead infrared emitter; and be programmed by the same overhead infrared emitter. Overall then the Kilobot provides a helpful tool for future large-scale swarm developments. These robots are readily available and low-cost, and thus could be utilised for examining homogeneous behaviours of robots for use in the nuclear industry.

The final robot to be mentioned is the Jasmine robot, which has been used to imitate the behaviour of honey bees [123]. This robot is capable of communication over six channels. Movement is made possible using a differential wheel drive, fitted with an odometer. The Jasmine robot is small, only 26x26x20mm, but is capable of missions 1-2 hours in duration. Overall due to its small size the Jasmine robot makes an excellent platform for the examination of swarm behaviours.

Overall it is clear that there has been much work in the design of individual robots that can be used to form a homogeneous swarm. Though the aim of these robots is for use in a homogeneous swarm, some could be combined to form a heterogeneous swarm. It is important to note that the

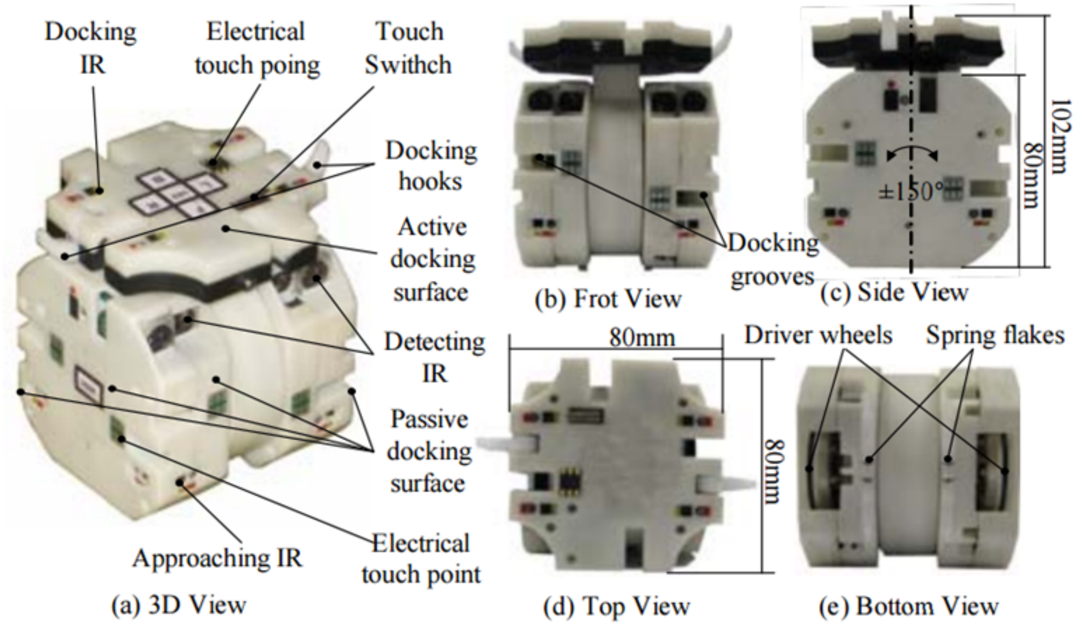


Figure 2.11: Shows the individual modules that comprise Sambot [245].

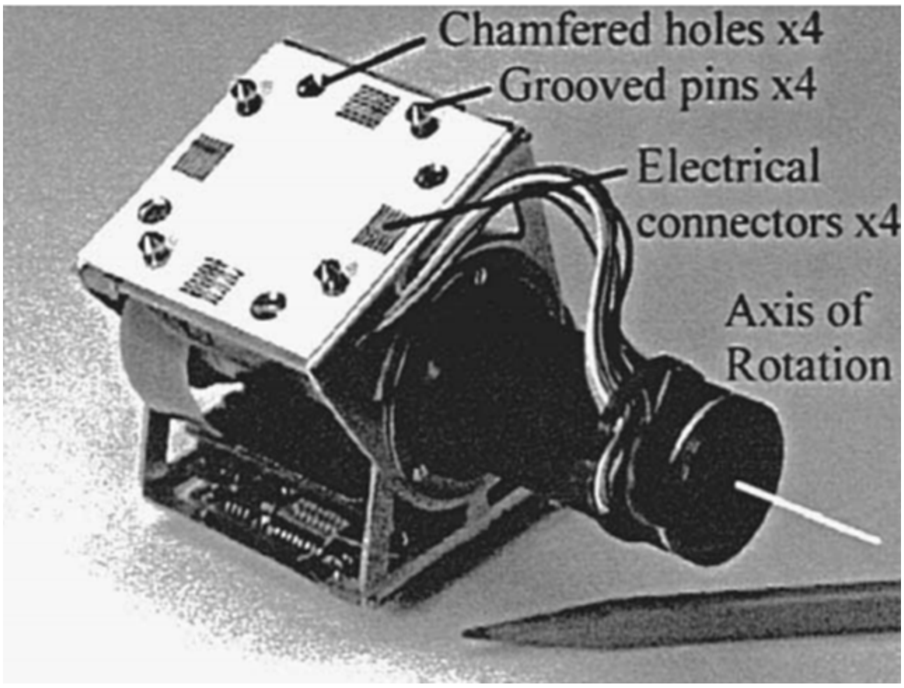


Figure 2.12: Shows the individual modules of the Polybot robot [266].

design of individuals comprising part of a swarm tends to be rather simplistic. This is because the robots are easier to control in this way and it is hoped that through emergent behaviour, the capabilities of the individual will be surpassed by that of the group. The choice to use the E-Puck for examining control in a nuclear cave environment was two-fold: there were multiple E-Puck robots available for use and they could be imbued with virtual heterogeneity with an already installed VICON tracking system.

2.3.2 Heterogeneous

The aim of this project is to create a heterogeneous swarm for use in the characterisation of a nuclear cave environment. This is because a heterogeneous swarm can be made more flexible due to the differing abilities of the robots; flexibility is a useful trait in unknown environments. The downside of heterogeneity when compared to homogeneity comes in the need for differing control, and the reduced robustness due to less agents being able to replace one another. This section will look at some of the physical implementations of heterogeneous swarms that have been explored in the literature.

One of the best known examples of a heterogeneous swarm is the Swarmanoid project [65]. This project is an extension of the swarm-bot project mentioned earlier. It incorporates an updated s-bot, in the form of the footbot. In addition to this there is also the Eyebot, a flying robot capable of adhering to the ceiling; and Handbot, a robot with a magnetic grapple and pair of grippers capable of climbing. The Handbot is not a mobile robot, but instead must be carried by Footbots. As an example of the capabilities of the swarm the task of collecting a book from a shelf in an unknown room was given. To do this, first the Eyebots found a route to the shelf, and adhered to the ceiling to mark the way. The Footbots then followed this route, carrying a Handbot. On arrival the Handbot released its grapple and climbed the shelf with its grippers. Finally, the Handbot grasped the book, descended and was carried back to the drop off point by Footbots. This gives an excellent example of the power of a heterogeneous swarm. There have been multiple other studies using the swarmanoid robots for example using Eyebots to emulate pheromone trails left by ants [69], or investigating recruitment using Footbots and Eyebots [191]. Thus, Swarmanoid gives an excellent jumping off point for researchers to examine the capabilities of heterogeneous swarms.

Another driving force behind swarm development is the Defense Advanced Research Projects Agency (DARPA). DARPA provides challenges to research teams, usually involving search and rescue. In addition, DARPA has specified some challenges for heterogeneous swarms. One example of a research development from a DARPA challenge is the development of a 'playbook' style of control for a heterogeneous swarm [217]. In this example a 'playbook', akin to that used in sports, is used to simplify a GUI for users. The robots know their roles in a play, and hence a play is selected and used for urban search and rescue. The robots used in this example are two Pioneers AT's, an RWI B21 and an RWI B24.

A further example from the DARPA challenges is the use of heterogeneous robots for mapping, exploration deployment and detection [108]. In this study robots are divided into simple robots and highly capable robots, based on their sensory capability and cost. There are many simple robots used, but few highly skilled agents. In this study the simple robot is chosen to be the AMIGOBOT and the Pioneer 3-DX is used as the highly capable agent. The highly skilled agent is used as a leader for the simple robots and guides them to position in order to create a chain of robots capable of detecting intruders. It is clear then that the challenges, and prize money, provided by DARPA aids the development of heterogeneous robotic systems. Both DARPA examples show that it is possible to enable a group of individually available robots to form a heterogeneous swarm, despite this not being their primary design.

It is not only homogeneous swarms that have been used for self-assembly, heterogeneous swarms have also been used to create reconfigurable systems. One such example is the dynamically reconfigurable robotic system (DRRS) [86]. This was an early attempt at reconfigurable systems (1988) and involved the use of three different cells. These were:

1. Joint/ mobile cell - rotating, sliding or motors

2. Branching cell - space filling cell, for example creates the part between two joint cells on a robot arm

3. End effector - this could be several items, for example a gripper

These heterogeneous cells could then combine to create different structures and may be transported to where they are needed by a mobile cell. Thus, giving a good example of a heterogeneous reconfigurable system. As with homogeneous reconfigurable systems, they could provide useful tools in a nuclear environment to aid in overcoming unforeseen obstacles and form structures larger than the available entry hole.

The final example of heterogeneous robots is the use of a mother/ daughter system. This can be demonstrated using a large mothership that is efficient over long distances and carries a smaller, more manoeuvrable daughtership [79]. In this example the mothership is useful for carrying a low flightime daughter ship to a site for urban search and rescue. This is an interesting concept for maximising power usage of a swarm. If robots within a nuclear cave could carry other robots to where their sensory capabilities are needed, then the operational life of the swarm may be extended.

Overall it has been shown that there is little work in the design of robots for heterogeneous swarms, with the exception of Swarmoid and DRRS, most researchers opt to use readily available robots to comprise a heterogeneous swarm. This has the benefit of availability, however it leads to robots not being specialised at working together for the task, which might limit their performance. It has also been shown that funded competitive events, such as DARPA, are excellent motivators for innovation in swarm robotics.

2.3.3 Implementation Considerations for Heterogeneous Swarms

An important consideration when designing and implementing a robotic swarm is how communication will be handled. This is especially true when that swarm is heterogeneous. In this case the robots must at minimum have the same communication device and be capable of recognizing one another's presence [65]. This is difficult as robots may need to take into account different design specifications, for example it is important for a flying robot that its devices are light and require less power. Conversely, a larger, more accurate sensor that draws more power might be better suited to a ground robot. One method to overcome such communicational concerns is to utilize stigmergy [248]. This allows robots to communicate through manipulation of their environment, rather than through direct communication. However, this still requires that robots are able to interpret environmental cues in the same manner; for example, if a robot leaves a visual clue for another robot, it is still a requirement that both robots possess some form of image processing.

The different methods utilized for communication in nature are discussed by Jung and Zelinsky [119]. In this work it is made clear that not only are the same physical requirements needed in order to send messages, but also to interpret them. If a ground robot is exploring a nuclear cave and receives information about the position of a flying robot, it might not be able to understand the meaning. This is because ground robots operate with three degrees of freedom, whereas flying robots operate in six. Thus it is necessary to account for this in the design phase so that robots are able to interpret the meaning of additional information such as this. Additionally, when communicating geometric positions, the robots should consider whether the information is directly related to their own position; the easiest way to overcome this is to have robots operate in the same global coordinate frame [241].

To overcome issues of interpretation and communication, it is possible to utilize the Robot Operating System (ROS) [195]. This software provides a middleware which allows data to be communicated as the same type. This allows a standardization of communication, between different implementations of hardware. For example, a point cloud could be generated by several different sensors and communicated between robots irrespective of hardware. In addition to communicative limitations, the physical implementation of a heterogeneous swarm can be challenging. For example, if heterogeneous robots are required to self-assemble then they are required to have the same docking station and method for coordinating docking [95]. Furthermore, different robots within a heterogeneous swarm each have their own specialized functionality. These considerations must be taken into account when designing self-organising behaviours; it has been shown that heterogeneous agents can cause interference with one another if not well coordinated [14].

Overall, it seems that the benefits provided by a heterogeneous swarm come at the cost of complexity. For the capabilities of a heterogeneous swarms to be fully realized, it is necessary to carefully consider the swarm's interaction in the design phase of the swarm. It is likely that there must be some level of homogeneity between robots, whether this be in a cooperative mechanic for self-assembly, or in a common sensor to allow stigmergic communication.

2.4 Swarm Design

Designing swarm behaviour is difficult as each member must be programmed at an individual level, with the hope of attaining a group behaviour. There are two approaches to behaviour design: behaviour-based design, involving manual adjustments to individual behaviour; and automatic design, which uses learning to optimise parameters. Once a behaviour is designed, it must be piloted. This requires a microscopic or macroscopic model so that the evolution of the behaviour may be examined.

When designing the 'reactive virtual forces' method, presented in chapter five, for use in the nuclear cave environment, a behaviour-based design strategy was implemented. This was complemented by a MATLAB simulation which was design to rapidly prototype the behaviour. This simulation is an example of testing that lies between macroscopic and microscopic work; it uses some simplifying assumptions and differential equations for update, whilst giving a visual representation of the simulation and modelling of individual agents.

In this section, first the design of swarm behaviour shall be examined, followed by an exploration of the current techniques that exist for modelling swarms.

2.4.1 Swarm Behaviour Design

Swarm behaviour design is the process of generating the correct rules at the individual level that create an appropriate emergent behaviour. This is one of the largest challenges in swarm robotics and currently there exist two forms of solution: behaviour-based design and automatic design. These two methods are discussed in this section.

2.4.1.1 Behaviour-Based Design

Behaviour-based design involves manually adjusting individual parameters to attain the desired behaviour. This is most commonly used when there are few parameters that need to be optimised. In addition, this method of design is usually undertaken when the task that the swarm will perform is well known.

The most prevalent method for behaviour-based design is the probabilistic finite state machine (PFSM). There are many examples of robots using this type of control throughout the review and may most densely be found in the Swarm Behaviours section [170] [134] [96] [166] [222]. PFSM's rely on a few states that the designer chooses. These states are transitioned between based on some probability, also defined by the designer. As many different states are possible, PFSM have received a lot of attention. This method allows for the user to change the behaviour through two methods: changing the states and changing the transition rules between states.

Another method used for behaviour design is virtual physics. As with PFSMs these are covered in the swarm behaviours section, with particular use in pattern formation and collective transport [16][125][28][223][15]. In general, virtual physics implements a potential field that is affected by obstacles, other robots and goals. These influences are then summed to create an overall force on a robot, and this force is used to calculate a robot velocity. This is the method undertaken in the design of the 'reactive virtual forces' method discussed in chapter five.

The final method used in behaviour-based design is the protoswarm language [9] [107]. Protoswarm is a language that has been specifically designed to allow the simplified programming of behaviours in swarms. The long-term goal of this is that a user may be able to compose a new behaviour from a library of different 'blocks' that have behaviours defined in them, for example a 'random walk' block. This is achieved by abstracting the network of robots to be a space filling medium, named the 'amorphous medium'. Density is then added to account for the movement of robots. This allows for the design of behaviours without too much computational overhead.

Overall it seems that behaviour-based design is the natural method of creating swarm behaviours, relying on the intuition and experience of the designer. As such design is usually limited to the task at hand, behaviour-based design tends to be less flexible than the automatic alternative. As the desired behaviour for use in a nuclear cave environment was known to be mapping, a behaviour-based approach was chosen to be the method for behaviour design in this project. A final note is that using behaviour-based design can be very time consuming, due to the trial and error nature of the programming and hence expedited simulations are useful.

2.4.1.2 Automatic Design

Automatic design involves the use of learning to find optimised parameters and create a behaviour. In general, this can lead to solutions that may be too complex for a human designer to achieve.

One of the most prevalent solutions to the problem of automatic design is the use of artificial evolution, or AE, which is also referred to as evolutionary computation. This process is used to tune many parameters, whose optimum value is unknown. One application of AE imitates evolution, through the introduction of mutations to some percentage of the bits. This is can be applied to a neural network where there are a set of sensor neurons, motor neurons and hidden neurons, encoding the various capabilities of the robot. Each of these neurons has a weight, and these weights are tuned during evolution leading to emergent behaviours. The best behaviours are then chosen from each generation and mutations are introduced. This process continues for some finite period leading to a convergence on certain behaviour. Many examples are given in the swarm behaviours section, and so no explicit example are given here [238] [225] [17] [224] [237].

Another method, less explored in this review, is reinforcement learning. Reinforcement learning is defined as "the learning of a mapping from situations to actions so as to maximize a scalar reward or reinforcement signal" [233]. The basic principle is that the swarm performs actions, beneficial actions are rewarded, and detrimental actions are punished. Under this regime the robots learn which behaviours are most effective for the general benefit of the swarm. An example of the use of reinforcement learning can be found in the learning of the transition conditions for a PFSM in the task of robot foraging [159]. Reinforcement learning has also been implemented as an imitation of an actor and a critic, which evaluates the performance of the actor [188].

Overall, automatic design seems to be a useful process for systems with many parameters. Its use can lead to interesting behaviours that could not be designed by an individual. In addition, as the learning process can be implemented for different tasks without need for reprogramming, this can offer a more flexible solution than behaviour-based design.

2.4.2 Modelling

Modelling is used for the analysis of swarms, so that an engineer may observe whether a desired property of the collective behaviour holds or not. Swarms can be modelled in two ways: the individual (or microscopic) level, models the characteristics of individuals and their interactions; the collective (or macroscopic) level, models the characteristics of an entire swarm. First microscopic models shall be examined, this will be followed by an outline of the macroscopic techniques that exist.

2.4.2.1 Microscopic Models

Microscopic models are those that focus on the detailed simulation of the individual and its interaction with other individuals or the environment. This is usually implemented in the form of classical simulators such as WeBots, V-REP and player/stage [168] [202] [242]. Such simulators produce accurate results, and many physical interactions may be simulated. However, for research into larger swarms microscopic models become less useful. This is due to the vast increase in computational overhead found when more robots are introduced.

Another approach, though less used than simulators in microscopic modelling, is to use probabilistic techniques [156]. This reduces the activity of robots to a sequence of probabilistic events, allowing faster run time and handling of larger swarm sizes.

Overall microscopic models are usually used for examination of smaller swarm sizes. Despite this drawback microscopic models are capable of being very accurate. In addition, it is often possible to directly transfer the control code used in simulation to a real robot, allowing direct transfer of the tested behaviours.

2.4.2.2 Macroscopic Models

Macroscopic models focus on modelling the behaviour of the entire swarm. This allows many agents to be simulated without the increase in computational overhead associated with microscopic models. However, the results of the analysis tend to be somewhat less accurate than those achieved through microscopic modelling, this is due to assumptions that are made during the simulation process. Due to the speed of this method of modelling, the end result of the behaviour can be more rapidly reached.

In general, macroscopic modelling is achieved by use of the rate equation or probabilistic modelling [26]. For an in depth review of probabilistic methods the interested reader should refer to work by Lerman et al. [141]. The probabilistic tool is useful due to its ability to analyse which parameters (such as swarm size, density etc.) affect the outcome of a behaviour most [157]. The rate equation provides a useful tool in its rigorous mathematical grounding.

Overall macroscopic models use a lot of approximations which allows large groups of robots to be modelled simultaneously. However, if these assumptions are not correct or cause a divergence from real events then the simulation can become inaccurate.

2.5 Current Swarm Behaviours and their Application to a Nuclear Cave

Swarms are currently capable of a multitude of behavioural paradigms. The control algorithm investigated in this project is the ‘Reactive Virtual Forces’ framework [28]. This involves treating a robot as a particle under the influence of virtual analogues of the fundamental forces of nature, to allow for the mapping and exploration of an unknown environment. This method is akin to virtual potential fields, which have been used to instigate many behaviours including: pattern formation, spatial distribution and path planning. This section aims to examine the behaviours that swarms, both homogeneous and heterogeneous, are currently capable of. The goal is to highlight what possible traits might be useful for mapping in a nuclear cave and show the utility of reactive virtual forces for exploration and mapping.

The behaviours, and therefore this section, are split into: spatially organising behaviours, navigation behaviours, collective decision making and a special section on potential fields. This follows a similar classification used by Brambilla et al. [26]. Within each section, sub-sections will describe specific behaviours and give examples of their implementation. Potential fields are described among the first three sections, but they are emphasised in their own section due to their similarity to the ‘virtual reactive forces’ framework used in this project.

2.5.1 Spatially Organising Behaviours

Spatially organising behaviours are those that let a swarm choreograph themselves in 3D space. Such behaviours could be useful for mapping, for example to move into a grid formation so that coverage may be maximised. There is an abundance of research into spatially organising behaviours in the swarm robotics community. To navigate this work, this section is divided into the following parts: aggregation, box pushing, chain formation, object clustering and assembly, pattern formation and self-assembly/ morphogenesis.

2.5.1.1 Aggregation

Aggregation involves the gathering of a group of robots around an area or object. This behaviour can be observed in nature in the gathering of insects around a food source, bees around a hive or fish around a mating area. Most examples in the literature seem to follow two paradigms: probabilistic finite state machines (PSFMs) or artificial evolution (AE). In the simplest form AE is used to select the parameters of a neural network, and PSFMs are used to locomote and decide whether to maintain proximity with other robots. This section will thus first examine use of PSFMs, then explore AE for use in aggregation. Aggregation could prove a useful tool in the exploration of a nuclear cave as robots could gather in areas that require more detailed inspection.

The PFSM combines several simple behaviours with probabilistic transitions between. Such a controller can be used to control both homogeneous and heterogeneous swarms, making it versatile; though heterogeneous swarms may require different PFSMs for different robots. One example of a PFSM being used for aggregation may be found in the paper by Soysal et al. [222]. In this work four simple behaviours are used: avoid obstacle, approach (the direction of the loudest sound), repel (drive away from the loudest sound) and wait. As each robot is emitting noise, this PFSM is used to attract the robots to one another. When in the group the robots wait for a random amount of time before switching to repel. Using this behaviour, the robots form dynamic clusters eventually forming one large cluster, as this gives the loudest noise. This could be applied to a nuclear cave characterisation task by using robots to call one another to areas that their sensors are not capable of examining. In this way, a swarm comprised of heterogeneous agents could seek to recruit help from members with differing sensory capabilities. However, due to the cluttered nature of the nuclear cave the directionality of the sounds may be lost.

A further example of a PSFM is in the creation of convoys using simple chorusing [166]. This paper seeks to imitate the behaviour that causes crickets chirping to become synchronous. Robots in a group that is of the desired size enter a primed state. After a short delay a signal is emitted and at the start of this signal robots move towards their next goal. Any other robots in the vicinity that are also in a primed state detect the signal and join in moving, thus creating a group. As this can happen multiple times many groups of robots can leave a larger group leading to a convoying behaviour. Such behaviour could be utilised in a nuclear cave to determine when a larger group examining an area should splinter into smaller exploratory groups. As with the previous example, the use of sound to communicate may lose directionality and thus may not be directly applicable.

As mentioned, artificial evolution is used to evolve the parameters for a neural network, often when the desired parameter values are unknown. This can lead to behaviours that could not have been predicted, or designed, by a human user. This has been used for evolving aggregation behaviour in Swarm-Bot for self-assembly [238]. The goal was to have the robots move close enough to one another to form physical links. The behaviours that evolved were using sound emittance. In one scenario, the static scenario, the robots attract other robots then remain still, this leads to many smaller clusters being formed. In the second scenario, the dynamic scenario, the robots move over time like a flock of birds, leading to a larger cluster size. This shows that it is indeed possible to design aggregation through AE.

Overall, it has been shown that aggregation is a well studied and useful behaviour. Both PFSMs and AE have been employed to implement such behaviour, with PFSMs being the more studied solution. Aggregation could be useful in a nuclear cave environment to allow robots to gather around areas of interest, such as a chemical spills or dangerous areas that should be avoided during decommissioning.

2.5.1.2 Box Pushing

Box pushing is the general term for utilising robots to push objects. In most swarm research the difficulty of this task in swarm robotics is using multiple agents to move a single object. Box pushing presents an interesting task to study as it requires that robots cooperate, avoid obstacles, collectively move towards a goal and maintain contact with an object. Within a nuclear cave such behaviour could be used to move debris and obstacles from the path of the swarm, or towards a disposal point. Though this is beyond the scope of this project, it remains an interesting behaviour to examine.

Box pushing in swarm robotics is often based on the collective taxis of insects for example, the ant. When an ant can't move an object, it requests aid by depositing chemicals. It then moves itself around the object until the desired trajectory is achieved. In the paper by Kube and Bonabeau this behaviour is imitated by a group of robots [135]. Using a PFSM the robots find the box, which is illuminated, then move around it cooperatively until a desired trajectory is achieved. This directly corresponds with the behaviour of the ant and again shows how swarm robotics may be influenced by nature.

It is important to note that when attempting to push a box, communication is important. This is because it allows robots to inform other agents of their trajectory and goal, so that a consensus may be reached on how and where to push the box. Communication during the act of box pushing is examined by Mataric et al. [160]. In this paper two six legged robots are used to push either end of a long box. It is found that when a single robot is compared to two robots with and without communication, the two robots able to communicate perform by far the best in terms of accuracy and speed.

It has been shown box pushing is an interesting research task, and solutions exist for its accomplishment. In this project such behaviour might be useful in order to move debris aside within the cave, or to push faulty robots and waste to a collection area. This is a behaviour that could be interesting to examine in greater detail in future work.

2.5.1.3 Chain Formation

Chain formation involves a swarm of robots connecting themselves between two points. This can then be used as a path for other robots or surveillance. Such methods are used by ants when foraging, though these tend to be dynamic chains rather than static. In a later section pattern formation shall be discussed; it should be noted that chain formation is a derivation of pattern formation, but due to its prevalence in the literature it has been afforded its own section. Within a nuclear cave, robots could form chains in order to maintain connectivity for communication. This would allow for data to be sent between robots and back out of the cave. In addition, a chain of robots could be put into standby mode and later reactivated to perform routine inspection.

One popular method to achieve chain formation is the use of virtual physics. This method uses virtual forces to calculate a vector based on attracting and repelling forces, such as those experienced by electrostatically charged particles. As an example, such forces could be designed so that robots are attracted towards a goal or repulsed from an obstacle. In the case of chain formation forces pull robots towards the two goals and other robots, up until a critical point at which they become repulsive to keep an ordered distance between agents. An example of such a method in action may be found in a paper by Maxim et al, in which robots are used to form a chain in an indoor building, with a linking robot maintaining communication range [162]. This exemplifies one use for virtual forces and shows that they can be used with relatively few rules in order to design a complex behaviour. As attractive and repulsive forces are a familiar concept, this could aid in plant worker acceptance of the system.

Another method used is the PFSM. This is utilised in Nouyan et al.'s paper on teamwork in robot colonies [181]. This seeks to imitate behaviour found in ants where individuals are not recognised. The task was to find prey items and return them to a nest. This was achieved with the behaviours: random walk, move around encountered structure (chain or nest), remain in chain, recruit (other robots to aid moving prey), plan route (back to nest based on positions of robots in the chain) and deposit prey. This was tested in group sizes of up to twelve robots and found to work satisfactorily. A similar method could be imagined for exploration, if instead of prey the robot was looking for unexplored areas and returning to base to communicate findings.

A final method used in chain formation is AE. An example is the work put forward by Sperati et al. [225]. In this work simulated E-puck robots [171] are used to form a chain between two targets. The inputs to the neural network are sensors (IR, ground, vision), with 3 hidden neurons and 4 output neurons (2 for angular wheel speeds, and 2 for blue and red LEDs). Having evolved these parameters, the best solution was found to be: use the blue light to signal direction whilst performing a random search; then when another agent's blue light is detected, the red light is switched on briefly. This then leads to two dynamic chains of robots continuously passing between the two targets. This is an interesting example as it shows the use of the E-Puck for studying swarm behaviour, which is additional motivation for their use in this project.

Chain formation is clearly a well-studied topic, with multiple solutions. In a nuclear cave such behaviour could be utilised to maintain a connection to a wireless device at the entry point to the cave, or potentially as an exploratory technique. The literature shows use of potential fields and of E-Puck robots for experimentation, both of which are methods adopted in this project.

2.5.1.4 Object Clustering and Assembly

Object clustering and assembly is in principle similar to box pushing, but usually requires that multiple objects be moved to a goal or various specified areas. More specifically,clustering is bringing the objects close to one another; assembly is the creation of physical links between the moved objects. In order to avoid interference both tasks are usually tackled sequentially. In addition, most solutions involve a PFSM as there are clear states such as: search, avoid, move object towards goal and rest. Robot foraging is essentially object clustering and can be used as a benchmarking exercise due to its requirements of harvesting, homing while transporting and depositing followed by a return to searching or rest [254]. This behaviour could be utilised in a nuclear cave to assemble bodies that would not fit through the 15cm diameter entry hole. For example, robots could attempt to construct a manipulator or monitoring device.

One of the first examinations of such behaviour was in the movement of furniture using a team of robots [204]. This is an interesting task as it requires that the robots rotate the furniture to its most opportune orientation to, for example, fit through a door. It was found that multiple robots were favourable due to their ability to rotate the furniture on the spot, and that communication between the robots was key to successful results.

Communication between robots is clearly important for joint tasks such as object clustering and assembly. However, this communication does not necessarily have to be direct. Werfel et al. examined the use of stigmergic communication in the blocks being assembled [248]. This involved a comparison between communicating blocks, writable blocks, and inert blocks. The communicating blocks each carry a map of the occupancy grid and can communicate with robots about the position that they need to be placed in, however this is not realistic as it requires that blocks being assembled have in built processors. Writable blocks had RFID tags which could be written to by robots in order to imbue them with knowledge of the occupancy grid; this is truer to life as many shipping containers have RFID tags. Finally, the inert blocks had no form of interaction, other than physical, with the robots. As to be expected, it was found that the robots performed best with the use of communicating blocks, when tasked with building an 'H' formation. This study shows an interesting reflection on the power of stigmergic communication. It is possible that stigmergic communication could aid in circumventing the communicative limitations within a nuclear cave. If combined with wireless communication, it could provide an interesting paradigm for the transfer of information between robots.

A final interesting study in the area of object clustering and assembly is an examination of whether specialisation aids in the completion of a task [14]. This paper compares the use of homogeneous and heterogeneous swarms through the task of moving two different types of block to a goal. The examination compares homogeneous robots (able to move any block), to specialisation by colour (two types of robot each able to move one colour), to territorial (robots drop the blocks near home and a home robot moves them to base). It was found that the homogeneous robots performed best, this was because the specialised robots caused interference. It is interesting to note though that in a real-world scenario it might not be possible to design all robots to move all objects, thus instigating the need for specialisation. This work shows that heterogeneous agents may work together to perform a collective task, which is the aim of this project.

Overall, as with box pushing, object clustering and assembly could be useful for the movement of debris or faulty robots to a collection area. It could also be used for the construction of larger bodies within a nuclear cave. The literature reviewed has shown that it is possible to operate under communication restrictions, and that heterogeneous swarms may work collectively to perform a task. Both are important factors in the exploration and mapping of a nuclear cave environment.

2.5.1.5 Pattern Formation

The aim of pattern formation is to distribute robots in an ordered and repetitive manner, whilst maintaining the distance between them. A useful background paper for the interested reader, has been published by Bahceci et al., in particular this paper highlights the difference between centralised and decentralised control for pattern formation [11]. Pattern formation is relevant to a characterisation of a nuclear cave as it may be used to distribute a sensor network for on going monitoring of the environment and for coverage maximisation

The most common method undertaken for pattern formation is the use of social potentials. As mentioned in earlier sections such potentials involve the use of virtual physics to calculate forces acting on a robot, which is then translated into a motion vector. Some studies, such as that by Kim et al., require only the agent's own position and the position of the nearest neighbour to calculate the forces and hence velocities [125]. In addition, it is possible to add other physical traits, such as electron spin, in order to improve the number and quality of patterns produced [223]. Overall, potential fields are simple and easy to implement, and due to their basis in physics there are multiple in-depth studies into the forces and interactions. The ability to use simple rules, grounded in physics and nature, to manipulate swarm behaviour is an attractive property. This is great motivation for the use of the 'reactive virtual forces' framework later implemented for controlling a swarm in the mapping of a nuclear cave.

Another interesting method for pattern formation has its basis in the covalent bonding of molecules [15]. This seeks to emulate the behaviour of atoms within a crystalline structure. Such behaviour is achieved through the assignment of 'attachment sites' on the faces of the agents in use. Changing the distribution and number of these attachment sites thus allows different shapes to be produced. This is similar to the use of potential fields but provides fewer attractive regions, thus imposing more control over the swarm behaviour.

The literature in pattern formation is dominated by potential field approaches. Potential fields offer a simple, yet powerful solution to the pattern formation problem. As will be seen in chapter five, they may also be harnessed for the exploration and mapping of a nuclear cave environment.

2.5.1.6 Self-assembly and Morphogenesis

Self-assembly involves the connection of various agents to form a larger entity. However, morphogenesis has been defined as "the process that leads a swarm of robots to self-assemble" [26]. In addition, morphogenesis often has its basis in biology and may include self-repair, self-reconfiguration and self-organisation [118]. Thus, this section will first focus on self-assembly, then on morphogenesis. For a historic account of research in self-assembly the interested reader should refer to the investigation made by Gross et al. [94]. As with object clustering and assembly, self-assembly and morphogenesis could allow larger structure to be formed within a nuclear cave. These could allow for manipulation tasks and for monitoring structures.

Self-assembling systems usually use PFSMs as their underlying control architecture. This is because the task can be broken down into obvious states, such as searching for others or connecting. One key example is the swarm bots project, which focusses on a team of s-bots that come together and link. They use a gripper in order to engage in collective transport [67].

A useful capability of self-assembling robots is to form different types of manipulator and link. One robot that has this ability is Polybot [266]. This robot is composed of segments and nodes that can join together to form different shapes. Polybot has achieved multiple different forms of locomotion e.g. rolling, caterpillar and four legged.

The ways in which the robots assemble is different. A common method is to preassign robots a position in the structure, however this is not all that flexible. A more malleable method is to organically 'grow' a structure, an example of this is given in Christensen et al.'s study [50]. This gives robots the roles of seeds and lets the desired pattern grow around them. An important distinction between aggregation and self-assembly is the formation of a physical link, and in general this requires a docking procedure. Usually this is a mechanical hook such as in CEBOT, Sambot and Polybot [87] [245] [266]. However, one alternative is the use of magnetic links, such as those used in the M-Tran system [177]. Within a nuclear cave both pre-determined and organically grown structures have their place. A pre-determined structure affords plant workers greater control over what tasks robots perform while inside the nuclear cave. Allowing the structures to grow organically gives more flexibility and therefore the ability to overcome unforeseen obstacles.

Morphogenetic systems often employ morphogen gradients to move robots to appropriate positions. These are gradients that grow from one point to anther and guide cells (in biology) to where they need to go. This can be implemented by having a robot at the correct site broadcast a value of zero, neighbouring robots then increase this value by one and broadcast. Subsequent broadcasts increase the value by one, thus giving a gradient to the robot who initiated the transmission, presumed to be at the goal. This is useful to determine where robots need to be and is adaptable to multiple goals. Such a gradient is implemented in work by Castano et al. the gradient is used to simulate the location of the barycentre of a group and to form circle and ring patterns [154]. A physical implementation of a morphogenetic robot is found in the CONRO system [44]. This exhibits the self-reconfiguration capabilities associated with a morphogenetic robot system. CONRO uses homogeneous parts to form structures, for example a snake and a hexopod. Its reconfiguration ability was proven by turning a snake into a rolling wheel configuration. This shows that swarms may be used to create different locomotive capabilities that may be able to overcome the difficult terrain present within a nuclear cave.

Self-assembly and morphogenesis are unlikely to be used directly in this project, since these systems are themselves difficult to design and do not present a robust solution to exploration of a nuclear cave. However, self-assembling robots could be used to form bridges for other robots over the obstacles that are present within the cave. Overall there is a profusion of self-assembly and morphogenetic literature, with the former focusing on the use of PFSM, and the latter on morphogen gradients.

2.5.2 Navigational Behaviours

Navigational behaviours are those that aid in the exploration and relative motion of robotic swarms. This is important for the project as the robots will have to coordinate their motion within the cave in order to efficiently explore it. The section is split into three main subject areas: collective exploration, coordinated motion and collective transport. It should be noted that some methods for collecting transport have already been discussed in the previous section, in the form of box pushing and object clustering and assembly.

2.5.2.1 Collective Exploration

Collective exploration is achieved through the combination of area coverage and swarm guided navigation. Area coverage attempts to deploy robots in an environment in order to create a grid of communicating robots. Swarm guided navigation is the use of this grid to guide other robots through the environment. In order to obtain the grid, social potentials are usually employed, with PFSMs used to engage swarm navigation. Such behaviour could be employed in a nuclear cave environment in order to achieve efficient coverage.

One method of exploring an environment is employing a static sensor network. Such a network involves having robots spread themselves through the environment in order to maximise coverage. In addition, the robots may be used to localise each other within the grid, thus allowing accurate mapping. As mentioned above such a network may be achieved through use of potential fields, as examined by Howard et al. [107]. In this study, potential fields are used to distribute a sensor network with the aim of maximising area coverage and minimising time until static equilibrium is reached. Though a static network proves to be a useful tool for exploration and monitoring, it can often require that an environment is known a priori, or that mapping first be completed in order to best distribute the network. In the case of a nuclear cave environment, neither of these is true. Therefore, potential fields provide a useful distribution method, but a dynamic exploration strategy is preferable, this motivates the use of 'reactive virtual forces'.

When a network has been established, it can be used to guide other robots through the environment. This can be achieved through the imitation of ant chemical trails, using virtual pheromones. This technique has been exploited by Di Caro et al., by using virtual ants to find the shortest distance to a goal [63]. In this paper a virtual ant is broadcast and used to find the shortest distance to a goal between nodes (robots). Once this has been achieved the route can be navigated by the other robot in one of two ways. Firstly, the navigating agent can move between robots in the grid, or the other robots can use their IR sensors to plan a straight-line route for the navigating robot. Both methods prove to work; however, the former is dependent on the grid remaining stationary and the latter does not necessarily avoid all obstacles.

A final important aspect of collective exploration is the maintenance of swarm energy levels. If a swarm is deployed in an environment, it may have a finite level of energy, or a charging station where it may acquire additional battery life. Thus, it is important that the swarm monitor and maintain this energy level and explore in the most efficient manner possible [228]. This is particularly important in the nuclear cave example, as it is not ideal for the robots to lose energy mid-mission; this would cause more waste in the cave that would become irradiated and require disposal.

Overall it is clear that collective exploration is an important research domain in swarm robotics. Exploration strategies, combined with spatially organising pattern formation, will be important for distribution and efficient coverage for agents in the nuclear cave environment. The potential fields approach used to distribute sensor networks forms a basis for the use of the 'reactive virtual forces' framework in this project.

2.5.2.2 Coordinated Motion

Coordinated motion, also known as flocking, is the process of robots moving around in formation together. It can help both with moving around with fewer collisions and with improved sensing capabilities. Such behaviours are influenced by nature, usually drawing inspiration from the flocking of birds, or the schooling behaviour of fish. This is important for robotic exploration as it involves coordinating movement so as to improve efficiency and decrease number of collisions.

Social potentials based on virtual physics are a promising method for achieving coordinated motion. This is because they allow the same controller for all robots, homogeneous or heterogeneous, and are relatively simple to implement. In the context of coordinated motion, the utility of combining several different potential functions becomes apparent; this allows an attractive force towards a goal whilst at the same time maintaining formation. An example of this is in the traversal of an obstacle field by a group of robots [16]. This makes use of an attractive force towards attachment sites on each robot and using this the group is able to safely move across an obstacle field collision free. This shows the use of potential fields in moving towards a goal, in chapter five of this thesis that ability will be used to move the robot towards unexplored regions of an occupancy grid in the 'reactive virtual forces' framework.

Another method for coordinated motion is the use of AE. This allows the emergence of behaviours without the need for painstaking design. A good example is found in the taxis of a group of robots towards a light source [17]. This requires robots to move towards the light source, when this source is reached it is switched off and an alternate source is turned on. Using AE for the solution of this task led to three distinctive behaviours: flock, amoeba and rose. Flock gave rise to robots forming a compact group and moving in a straight line to a target; amoeba had robots form a group and move towards a target by varying their relative position; and finally rose led to agents forming compact groups and rotating on themselves.

A further example of the use of AE in coordinated motion is in the exploration of an environment and the formation of a path between two target areas [224]. The emergent behaviour in this scenario has been discussed in an earlier section but led to the formation of two dynamic chains between the target points.

The final method to be discussed is the formation of dynamic networks [52]. This approach considers the fact that communication range is usually limited. Thus, robots form ad hoc groups when entering communication range of one another. When forming these groups information is shared and motion plans are generated, taking into account the relative motion of other members of the subgroup. The robots vote on the best collision free path given the information provided in their subgroup and hence execute this plan. This has been tested both in simulation and on a group of five micro autonomous rovers, leading to successful results for collision free path planning.

Overall it is clear coordinated motion is an integral part of swarm research. It allows for multiple robots to inhabit a joint area without the danger of interference and has a plethora of solutions applicable for the task. It will be particularly important in a nuclear cave, as robots must share information regarding hazards and move relative to each other to avoid them. As in other examples virtual physics has arisen as a potential solution. This versatile method will later lend itself to the implementation of the 'virtual reactive forces' framework.

2.5.2.3 Collective Transport

Collective transport involves the use of a group of robots to move an object. It has been afforded its own section for the sake of completeness, but due to the overlap with both box pushing and object clustering/ assembly, this section shall be brief. Particular focus shall be given to the less covered topics of deciding goal direction and negotiating obstacles as a group. These behaviours are important when traversing a hazardous environment, like a nuclear cave, as some directions may cause harm to the swarm and so a safe consensus needs to be reached.

When transporting an object, a group direction must be negotiated. This necessitates the group to have knowledge of both the goal, and the trajectory of other robots, which requires communication between agents. In addition, robots must update their decision on the group trajectory during motion. This has been achieved through finding the orientation of neighbours using LEDs and vision cameras, then updating based on the collective average trajectory [39]. A visual communication method may allow better negotiation in a nuclear cave, as wireless communication can often be inhibited.

Another task during collective transport is obstacle avoidance. This requires that the robot's manoeuvre both themselves and the object being transported around some obstacle. In essence this is another group trajectory decision, but more specified to a regular event. One solution involves the propagation of a socially preferred direction [81]. This method has robots propagate a preferred direction if they have no knowledge of an obstacle. If instead they know of an obstacle, they broadcast a direction that avoids it. Such a method allows a group of robots to avoid an obstacle even if only one robot perceives it.

Overall collective transport is important to this project for the same reason as box pushing and object clustering/ assembly: it allows robots to move debris and faulty robots, whilst avoiding collision.

2.5.3 Collective Decision Making

Collective decision making is essentially the convergence of a group on a single choice, for example that a certain agent should move to a certain position or area. This is important for use in a nuclear cave as it will enable reduced interference and maximum efficiency for mapping. This section is split into three topic areas: consensus achievement, task allocation and collective fault detection.

2.5.3.1 Consensus Achievement

Consensus achievement is the task of reaching a single decision from several alternatives. This can be difficult since the best choice may change over time or may not be obvious to the robots with their limited sensing. Consensus achievement can be approached in two different ways. First, it can be achieved using direct communication, with each robot being capable of communicating its preferred choice, or some related information. Second is via indirect communication, where robots communicate based on some indirect cue for example population density. Consensus achievement could be useful in a heterogeneous swarm as it may help agents decide which individual is best equipped for a certain task. In the case of exploration of a nuclear cave, this could involve deciding which robot has the locomotive capabilities to reach certain areas.

Consensus achievement can be found in nature, for example in the collective decision to forage for food. This then assigns the questions of who will fill which role, and what is the shortest path? One method to communicate this information is through trophallaxis. In nature this is the transfer of fluids from mouth to mouth, or mouth to anus. In robotics this is akin to short range communication, and has been used to find the shortest path using a PFSM in work by Gutiérrez et al. [96].

Inspiration has also been derived from the democratic nature of government. This is easy to understand as it involves the swarm voting on decisions and the decision with the most votes becoming that which is followed. This has been examined with regards to hunting, and the decision between which of two moving prey to pursue [250].

As has often proved to be the case in swarm systems, AE proves a useful tool for collective decision making. In this case though AE may be used to ascertain the optimum time to switch between behaviours. This has been researched using s-bots, implementing AE to find the optimum time to switch between group and individual behaviour [237].

Overall, whenever working with a swarm there will be some element of consensus achievement, whether this be passive using inhibiting behaviours, or active, through the use of methods like voting. Usually consensus achievement requires that robots be in communication to make the best decision. This might not always be possible in a nuclear cave, and so the 'reactive virtual forces' framework proposed in this thesis does not directly utilise active consensus achievement.

2.5.3.2 Task Allocation

Task allocation is the process of distributing a swarm between numerous different responsibilities, in order to maximise the efficiency of the operation. The tasks to which robots are allocated are likely to change over time. Hence, dynamic task changing is useful and usually implemented with PSFMs. In general, this is particularly important for heterogeneous swarms where different robots are likely to have different capabilities and hence perform better at different tasks, for example characterising different areas within a nuclear cave environment.

As with multiple facets of swarm systems, biology offers some solutions to the challenge of task allocation. In general, social insects have several castes in order to improve efficiency. This is examined in work by Momen et al. [170]. In this work robots are divided into three castes:

- Larvae - this caste has two states with random transition: hungry or satisfied.
- Brood Carers - this caste takes food from the food dump to feed the larvae, and if the food falls below a threshold they aid in foraging.
- Foragers - this caste searches for food and drops it in a convenient location for the brood carers.

The use of these castes means that the task of feeding the larvae is completed more efficiently, and with less interference, than a homogeneous allocation of tasks. A similar method could be imagined for exploring a nuclear cave, where robots are assigned explorers and data hubs.

The explorers seek to attain new data, whilst the hubs maintain connectivity and transmit the acquired information out of the cave.

In addition to caste systems, social insects also react to stimuli that are related to the task that is to be completed; these stimuli usually have some threshold for activation. This behaviour has been ported to robotics in a study by Krieger et al. [134]. In this work a group of 12 robots was given the task of maintaining energy levels in a nest. Collecting food items increases energy in the nest, whereas foraging and moving food items decreased it. The threshold behaviour was implemented in a simple manner: when the nest energy fell to certain levels different robots would aid in foraging. It was found that the energy level was maintained by use of only this one simple activation method.

A further method for task allocation is based on the concept of bidding. In this framework robots bid on tasks based on their perceived ability to complete them. They are offered incentives in the form of virtual money, or other form of reward on completion of a task. The lowest bidder is generally awarded the task, akin to the lowest contractor being awarded a contract. An overview of these methods can be found in the survey put forward by Dias et al. [64]. A good example is the use of bidding to handle an emergency, where multiple alarms need to be switched off [161]. In this case the bids are based on the robot's distance to the alarm, the smallest distance gets awarded the task and hence the most efficient outcome prevails.

In contrast to the bidding method is the broadcast of eligibility [249]. In this paradigm instead of bidding, the eligibility of each robot is compared and the robot with the best eligibility for a task inhibits that behaviour in other robots. This allows for dynamic task assignment due to the predisposition for eligibility to change over time. In addition, this can easily be applied to a heterogeneous swarm, whose individual eligibility may greatly differ.

In general, there is no one defined way in which tasks are assigned in swarm robotics. Later in this work, the 'reactive virtual forces' framework will be shown to exhibit some task allocation abilities. Robots exchange the location of areas they are unable to reach in order to recruit other members as potential solutions.

2.5.3.3 Collective Fault Detection

Collective fault detection is the ability of a swarm to identify faulty agents within the swarms' rank. This is an important area of research as currently implemented robots are not fully reliable and hence prone to failure. In hazardous environments, such as a nuclear cave, this becomes even more pertinent.

Once again, examples have been drawn from biology to inspire swarm behaviour. Particularly in the synchronised flashes of fireflies. In fireflies this synchrony is achieved through a threshold that when reached, which causes them to flash. If nearby fireflies see this flash, then their activation threshold is increased by an amount, this eventually leads to synchrony. This can be utilised by robots to detect a faulty robot, as if a robot is not flashing in synchrony it can be assumed to be faulty [49].

A more commonly used method is the 'I am okay' signal [256]. This method relies on the periodic broadcast of a signal that informs the rest of the swarm that the broadcaster is functioning correctly. If this message is not received, then the robot is assumed to have malfunctioned. A downside of this technique is that if only the communication systems fail, the robot may still be able to perform some functions but is assumed to be entirely broken.

The utility of fault detection in a nuclear cave environment is readily apparent. Due to the hazardous nature of nuclear environments it is likely that the on-board electronics may fail. In order to continue operating at maximum efficiency this fault must then be detected by the rest of the swarm, and the failed robots' tasks redistributed. Though fault detection is beyond the scope of this project, it is still an interesting and relevant area of study.

2.5.4 Potential Fields

In chapter five 'Reactive virtual forces' will be put forward as a solution to exploration and mapping using a heterogeneous swarm, within a nuclear cave environment. This involves treating robots as particles under the influence of virtual analogues of the fundamental forces of nature. This method is akin to the use of virtual potential fields already present in the literature. Potential fields provide an easily implemented method of designing complex swarm behaviours. As will be shown in this section, there has been little work on potential fields for heterogeneous swarms or in their use for exploration. So far, this review has touched on various uses for virtual potential fields including pattern formation, spatial distribution, and path planning. In this section a history of potential fields research is given, this will show the current state of the art and highlight the novelty of the 'reactive virtual forces' implementation.

The first use of potential fields in robotics was by Khatib [124]. In this implementation 'artificial potential fields' were employed to allow manipulators to conduct obstacle avoidance. The artificial potential fields used were not grounded in physics, but instead involved attractive and repulsive forces dictated by functions designed by Khatib. This early work shows the utility of virtual potentials for obstacles avoidance, an important factor within the exploration of a nuclear cave.

The term 'social potentials' was coined in 1999, by Reif et al., so called because the forces between robots can be seen to represent their social relations [199]. In this work inverse square laws were utilised as potential fields, to guide social behaviour in a group of robots. The paper examines in simulation the use of these potentials for robot clustering, moving as a group, guarding/ escorting behaviour and for demining. The work focusses on a large homogeneous group of robots. This shows that virtual forces may be used for manipulating robot positions relative to one another. There is no focus on exploration of unknown environments, or the use of heterogeneous agents in this work.

Coverage is an important part of mapping; robots must be distributed over an area to maximise sensory data gathered. This problem was examined using potential fields in 2002 by Howard et al. [107]. The electrostatic force was used as a physical basis in simulations of a homogeneous swarm. This work shows that potential fields can be used to distribute robots in an environment to gather sensor data. Furthermore, it utilises the electrostatic force for distribution; in chapter five this same force will be utilised for obstacle avoidance.

'Physicomimetics' was introduced as a concept in 2004 by Spears et al. [223]. In this work pattern formation is motivated by physical forces, such as the Newtonian law for gravity. Hexagonal and a square lattices were generated through the leveraging of the physical properties of mass and spin. This work was later extended to allow a hexagonal homogeneous swarm formation to move towards a light source. Again, this work exemplifies another of the forces used in the reactive virtual forces framework; the gravitational force. In addition, this work provides motivation for using real physical forces, grounded in mathematics, to control robotic swarms.

Zhou et al. combined the physical traits of crystal lattices, with virtual potential fields to create formations of robots [274]. 'Attraction sites' are generated around a robot, such as those found about a carbon atom when forming a lattice structure. These attachment sites become potential wells that other robots are attracted to. If the number and distribution of the attachment sites are altered, different patterns may be generated. This variation shows that a designer may slightly modify the interaction between forces and in doing so change the behaviour of a group of robots. It is this quality of virtual forces that makes them so versatile.

In 2007 Barnes et al. used a group of unmanned ground vehicles to maintain a pattern under the influence of potential fields [19]. In this work, it was postulated that potential fields could be extended to heterogeneous groups of robots. This poses an interesting discussion, as the rules used to dictate the homogeneous swarm would not need to be altered for use with the heterogeneous swarm. Having rules remain the same for both homogeneous and heterogeneous swarm eliminates the difficulty in specialising a controller for each unique agent within a swarm. Thus, this motivates the use of a virtual forces controller.

Further work exploring heterogeneity was compiled by McCook and Esposito [163]. This work simulates a convoy of military vehicles being harassed by an attacker. Heterogeneity is introduced by defining some robots as 'defender units' and others as 'supply units'. Supply units feel a force that drives them away from the attacker, whereas defenders feel an attractive force to stop the supply units being harassed. Robots in this case have predetermined roles and hence they do not have the same controller. Despite this, this work shows an interesting use of heterogeneous agents working together towards a goal under the influence of virtual forces.

Work by Wiegand et al. examines how heterogeneous agents may be defined when utilising virtual forces [251]. It is stated that for heterogeneity to be included each particle being used must have its mass and coefficient of friction defined. Once these parameters are defined, an engineer must express any special relationships between agents. In doing so the appropriate behaviour with the potential fields is created. This is similar to the idea of utilising different virtual physical properties to leverage heterogeneity within the 'reactive virtual forces' framework, however in this case there is no need to define special relationships.

In 2016 counter rotating artificial potential fields were utilised to fully inspect obstacles with a pair of robots by McIntyre et al. [164]. Waypoints are used to instigate path planning, whilst attracting forces are used for goals and repulsing forces for obstacles. Potential forces are also used to maintain the separation between robots. As the distance between the robots is their only constraint, they behave as a fluid. When approaching an obstacle, the midpoint between the robots is determined, and the robots are assigned goals on different sides of the obstacle. This ensures that both sides of the obstacle are scanned. The work is tested in simulation, on a pair of homogeneous robots. The use of attractive and repulsive forces for mapping an object is similar to the 'reactive virtual forces' framework. However, the 'reactive virtual forces' framework uses physical forces for exploration of unknown environments, whereas the work put forward by McIntyre et al. uses predetermined waypoints in a known environment.

Finally, in 2018 Bridgwater et al. utilised 'reactive virtual forces' for the exploration and mapping of an unknown environment. This work examined the used of virtual forces, grounded in physics on both heterogeneous and homogeneous swarms. A geometric map was created using an occupancy grid. It was found that the heterogeneous swarm covered the environment more efficiently. Later in this thesis, the 'reactive virtual forces' framework will be shown to be an efficient solution to the exploration and mapping problem with a heterogeneous swarm in an unknown nuclear cave environment.

Overall, it is clear there has been prior investigation into the use of potential fields for the distribution of robots in an environment. Despite this, there has been little work examining potential fields for exploration. In addition, the use of heterogeneous swarms is still underdeveloped. To the best of the authors knowledge, there have been no studies using a heterogeneous swarm, under the influence of virtual reactive forces, for exploration and mapping. Thus, utilising the gravitational force, electrostatic force, and strong nuclear force in the same exploration control architecture appears to be novel, and their utility will be outlined in subsequent chapters.

2.6 Exploration and Mapping

Exploration and mapping of a nuclear cave environment using a heterogeneous robotic swarm is the goal of this project. Mapping forms a large area of research within swarm robotics. The aim is to use the sensing capabilities of the entire swarm in order to generate a single, consistent map. Due to the number of robots involved in the procedure, maps created by a swarm can be more accurate than those generated by a single robot. However, they usually involve the merging of maps from various agents, which can present a challenging problem. In general, the problem of mapping can be divided into three key tasks. These are localisation, exploration and mapping strategy. As such, the first three parts of this section will examine these topics.

In general, there exist two forms of solution to the mapping problem. The first class of solution assumes some form of localisation is already possible, such as GPS, and uses this to build a map. An excellent overview of work in this field is given in a review by Thrun et al. [235]. The second requires a robot to both build a map of its environment and localise itself in that map simultaneously, known as simultaneous localisation and mapping (SLAM). The final part of this section examines the SLAM problem.

2.6.1 Localisation

Localisation is an integral part of the mapping process, as without knowledge of your position it is difficult to build an accurate map. For the purposes of map building without SLAM it is usual to have an absolute positioning system, such as GPS or infrared cameras.

However, if the map is already partially known, there exist several techniques to localise a robot. One of the most well-known techniques is Monte Carlo localisation [61]. This effectively postulates a probability density in terms of particles across the map. It then compares the virtual sensor readings of each of these particles with that of the real robot. After this, the robot moves and the probability density is updated using odometry and sensor readings. This process is repeated until the particles converge on the most likely location of the robot. Though this method is well studied and provides accurate results, the nuclear cave environment is unknown and so this technique may not be implemented.

The Monte Carlo technique is usually used for the individual, but there has been work in using it with multiple robots in order to improve accuracy [73]. This utilises the fact that a group of robots can define a coordinate system with respect to one another, rather than using environmental features. The coordinate system then allows for a global map to be stored as a relationship between neighbouring robots. Such a system could prove interesting in a nuclear cave environment, as robots could use one another for localisation. Despite this, it would require robots maintain communication; within a nuclear cave this might be difficult.

A final method for localisation is the extended Kalman filter (EKF), which relies on the observation of landmarks combined with dead reckoning information. An example is given in work by Madhavan et al. [151]. The process of localisation in this case is that firstly a state prediction is made. This is followed by an observation validation where a compass or GPS reading is only accepted if it falls within the normalised residual validation gate. Finally, covariance and state updates are performed using the EKF update equation. This implementation of the EKF filter is interesting, however as GPS readings are not feasible within the nuclear cave it is not possible to implement it directly. It will be shown later that the EKF can be utilised for simultaneous localisation and mapping, with the update step relying on distance measurements. This is the method used for localisation in chapter six of this thesis.

Overall localisation is a well-studied, and largely solved, area of robotics. In general localisation is achieved through absolute positioning when maps are being generated, or if the map is already known then through techniques described above. The challenge of knowing neither the map nor the absolute position is that of SLAM and will be discussed later; this is the problem presented by exploration and mapping of a nuclear cave environment.

2.6.2 Exploration

The exploration phase of mapping is important, it is how the robots go about maximising coverage and moving through the environment in a coordinated and efficient fashion. Exploration strategies are largely Deliberative or reactive (i.e. plan decisions and paths for the future vs, reacting to obstacles and presence of other robots/ external stimuli as and when they appear), a comparison between these two techniques, and a hybrid employed for robot foraging, can be found in work by Carpin et al. [43]. The 'reactive virtual forces' framework outlined in chapter five of this thesis is, as the name suggests, reactive in nature. The nuclear cave environment is cluttered, making path planning difficult. Therefore, it seems prudent to utilise a reactive control method so that robots may avoid obstacles as they arise, whilst continuing the mapping effort.

If the environment is known then the map can be represented as a graph and the exploration problem becomes the travelling salesman problem of minimising the distance travelled between nodes [35]. However, in an unknown environment only a partial map may have been generated, in this situation it is useful to implement frontier cells [264]. The use of frontier cells requires that a map be divided into a grid. A frontier cell is then a cell that is known and is next to an unknown cell. The basic idea of using this for exploration is that a robot should move to such a cell in order to maximise its knowledge gain. This is often a trade-off between the utility of the cell, a heuristic measure of how much information will be gained from it, and the cost of the cell, which is usually the distance to it [36]. It is possible to utilise a bidding system to ascertain which member of a swarm will attain the most utility from a cell for the least cost [216]. This method allows for robots to continuously be moving to new, unexplored areas. The 'reactive virtual forces' framework utilises a force akin to the strong nuclear force to attract robots to the frontier cells of an occupancy grid [28], this method will be outlined in chapter five of this thesis, and provides a useful tool for the exploration and mapping of a nuclear cave environment.

Stachniss et al. also use the information gain of a robot in order to guide exploration [226]. In this work the entropy changes of the system, given a certain action, are calculated. The entropy change is calculated by integrating over the robot's world model, given all possible measurement sequences. Such modelling can become computationally complex due to the need for ray-casting.

Dudek et al. show that if a robot does not have a compass or method for determining its orientation, then the exploration problem is unsolvable [72]. It is discussed that mapping using dead reckoning alone is not sufficient, due to the accumulation in errors. The authors put forward the use of markers that may be placed and picked up by the robot in order to provide landmarks for mapping. This provides motivation for the use of landmarks in the exploration task, which will be used with the EKF filter in chapter six of this thesis, to aid in localisation and mapping of a nuclear cave environment.

So far, single robot exploration strategies have been examined; by and large it is possible implement such strategies using multiple communicating agents in order to increase efficiency. However, strategies have been designed and tested on swarms of robots, which will be discussed subsequently.

Marjovi et al. use multiple robots to map and explore an unknown environment, whilst minimising exploration time [155]. Agents aim to explore different areas of the map to identify fire sources. Potential fields are used to enable obstacle avoidance and to attract the robots to goals, such as the frontier of exploration. Khepera robots with known positions are used to test the algorithm. 'Reactive virtual forces' follows a similar paradigm to that discussed in work by Marjovi et al.: potential fields are used to attract the robot to exploration goals; and repel them away from obstacles. The differences are that the 'reactive virtual forces' framework is grounded in real physical forces and requires less communication overhead. In addition, simultaneous localisation and mapping is examined with the 'reactive virtual forces' framework, as shall be discussed in chapter six. Finally Marjovi et al. examine the use of their virtual fields on a group of homogeneous robots, whilst 'reactive virtual forces' are examined with homogeneous and heterogeneous robots. This work shows that it is possible to use potential fields for robotic exploration, providing motivation for 'reactive virtual forces' whilst leaving open research questions.

Couceiro et al. extend two instances of particle swarm optimisation, to allow for inclusion of obstacle avoidance [53]. The algorithms use social inclusion and exclusion to aid in a multi-robot exploration task. This is instigated through the deleting and spawning of particles within the swarm. The algorithm was tested in MATLAB on a simulated swarm. It was found that the use of inclusion and exclusion criteria increased the performance of the particle swarm exploration algorithm, whilst exploring an unknown environment. This work shows that MATLAB can be a powerful tool in assessing the quality of algorithms and provides motivation for its use in this project to test the 'reactive virtual forces' algorithm.

An alternative to frontier-based exploration is provided by Wurm et al [261]. In this work the exploration space is divided into sections, such as rooms, for individual robots in the team to explore. Segmentation is used in the hope of reducing the overall search time. Pioneer II robots are used to test the algorithm, under the assumption that the absolute position of robots is known. Map segmentation provides an interesting alternative to frontier-based exploration; however, it requires that a partial map of the environment is known a priori. This is not possible within a nuclear cave, as very little could be known before entry about the map, even as little as only knowing the perimeter of the room.

An interesting approach to multi-robot exploration is provided by Zlot et al. [275]. This work implements a market economy to allow robots to exchange services and maintain 'profitability' in the task of exploration. An operator executive is utilised to represent the desires of the user, which in turn pays revenue to individual robots for information about the environment. Through the sharing of price information, coordination is achieved. Pioneer robots are used to construct occupancy grids of the environment and it was found that allowing robots to negotiate, increased the exploration efficiency. Such a bidding system could be imagined for use with a heterogeneous swarm, to allow for indirect encoding of each members abilities. This would then prove an interesting method for use in a nuclear cave environment.

Finally, Burgard et al. investigate the coordination of multi-robot teams for exploration of an unknown environment, focussing on the selection of targets points for individual robots [36] [35]. Selection of these points considers the cost and utility of visitation. The work is first discussed under the assumption of global communication, followed by a discussion of extension to the limited communication situation. Deciding which members of the swarm should examine which areas is a useful tool to increase the efficiency of exploration. Though this is not directly examined in the 'reactive virtual forces' framework outlined in chapter five of this thesis, it is indirectly achieved through the entry points of robots.

Overall, exploration is a well-researched area within mobile and swarm robotics. This section has shown the use of potential fields, frontier cells and MATLAB simulation as tools to implement and investigate exploration in groups of robots. Novel areas for research, under-investigated in the literature include: the use of potential fields for heterogeneous robot exploration, the use of SLAM techniques in potential fields exploration, investigating the value of utilising multiple forces grounded in physics and the application to the exploration of a nuclear cave environment. Thus, the use of 'reactive virtual forces' in exploration of a nuclear cave environment shows itself to be a viable and novel source for investigation.

2.6.3 Mapping Strategy

Mapping is the process of attaining a representation of an unknown environment, usually this is topological. The most commonly employed method for this is the occupancy grid, pioneered by Alberto Elfes [77]. This method involves splitting the area that is to be mapped into a grid, with arbitrary sized grid squares. In each of these squares the probability of occupancy is stored, thus with reobservation the certainty of the map increases. With multiple robots it becomes more likely to re-observe the same area and hence a swarm can quickly produce an accurate map of an environment, providing they have some method for map merging [218]. The occupancy grid provides an easily interpreted representation of an environment, and for this reason is utilised later in chapter five in combination with the 'reactive virtual forces' framework for exploration.

Another representation of maps is in the use of landmarks. This representation usually lends itself to SLAM and involves points with an associated uncertainty that represent key features in an environment [85]. This provides the user with an idea of the uncertainty of each landmark but provides little or no information about the areas inbetween landmarks. As such this method is used in tandem with the occupancy grid in chapter six, to provide additional information and localisation capabilities to the ‘reactive virtual forces’ framework.

A final representation involves the storing of vertices and the links between them [136]. Such a map provides information about the location of landmarks and their position relative to one another, whilst leaving out geometric information in a global coordinate frame. This is useful for the exploration of an unknown environment where defining a global coordinate frame between multiple robots may be difficult. However, when mapping a nuclear cave environment to aid in its decommissioning, it is important to know the global position of items in the cave.

Regardless of representation, map merging is an important problem in swarm mapping research. This is due to the use of decentralised control, which usually leads to the creation of individual maps. In this situation, agents in the swarm must have some method of merging their maps so that a complete picture of the environment is available to each member. In general, this problem is easily solved if the starting positions of the robots are known, as a transform between each robots’ frame is readily available. However, if the starting position is unknown one method to achieve map merging is to use a particle filter so that each robot can localise itself in another robot’s map [132]. Overlaps are then searched for in terms of landmarks in the other robot’s map in order to align them.

Overall the problem of swarm mapping is relatively well studied, and other examples of its implementation may be found throughout the review. In this project, the choice of an occupancy grid for mapping with the ‘reactive virtual forces’ framework was twofold: first, it provides an easily interpreted map for a plant worker to use for nuclear decommissioning; second, it is easily implemented and provides the utility of frontier cells that can be used to define exploration goals.

2.6.4 Simultaneous Localisation and Mapping

Exploration and mapping are much more easily conducted when the position and orientation of a robot is known. Similarly, the task of determining the pose of a robot may be made more straightforward when the map is known. Simultaneous localisation and mapping (SLAM) is the process of estimating both the pose and the map concurrently. This is also a requirement for exploration and mapping in a nuclear cave environment. This section seeks to investigate the current state of the art of SLAM in robotics, and its possible implementation within a nuclear cave.

SLAM using a single robot has been well-studied, with most of the research utilising extended Kalman filters and expectation maximisation algorithms [112] [110] [111] [51]. SLAM in the multi-robot domain is less examined and the problem of matching landmarks from different angles across maps made by different agents is still being researched.

The extended Kalman filter (EKF) is used to simultaneously maintain an estimate of robot position and the position of landmarks in the map [85] [201]. In addition, an estimate of the uncertainty is also maintained through a covariance matrix. Whilst the robot moves through the environment two steps are iterated sequentially. First, a prediction step which involves a robotic agent estimating its position, and the position of landmarks, based on odometry data. Second an update step, which involves comparing the odometry data to the observations made by the robot. A weight is determined between the odometry and sensor measurements to decide which is more trusted. These are then combined to estimate the current position of the robot and landmarks in the map, along with their associated uncertainties. This method is used in chapter six to aid in localisation of the swarm whilst exploring and mapping a nuclear cave environment. A full description is reserved for this chapter.

SLAM using EKF maintains a full estimate of the uncertainty of the robot position and landmarks, this causes the size of the covariance matrix to grow proportionally to the number of observed landmarks. As a result, the computational complexity of the algorithm is high and can be slow. To remedy this FastSLAM was designed [174][173]. FastSLAM exploits the fact that knowledge of the robot's path makes the individual landmark measurements independent. It postulates many different particles sampled from the motion model of the robot, each with their own EKF. The importance of each particle is then weighted to test whether they should enter the final set. These particles are then used to estimate the robot path, with each containing an estimate of landmark position. Both fastSLAM and EKF SLAM solve the same problem, using the same motion and measurement models. In addition, both utilise an EKF approach with fastSLAM repeating this many times for each small particle and EKF SLAM applying it once. They differ in the storing of the state vector. EKF SLAM maintains a state vector with the pose of the robot and all landmark positions stored within it, which allows for a full covariance matrix storing the uncertainty over time. FastSLAM maintains a covariance matrix in each particle, giving only the current uncertainty. In general, FastSLAM proves to be a more computationally efficient solution to the mapping problem, however EKF SLAM remains more studied in the literature and allows for a full definition of uncertainty to be maintained. This full definition of uncertainty is an important consideration when mapping a nuclear cave environment, as it provides valuable information for decommissioning. Due to this, the EKF implementation was chosen to aid with localisation in chapter six.

A significant problem in SLAM is the correspondence problem; when a robot re-observes a landmark it has previously observed, it must decide that this is what has happened and that it is not a new object. Use of an EKF allows this to be done whilst simultaneously maintaining an estimate of uncertainty in the map. This challenge is increased when multiple robots are used to overlay the maps, landmarks that have been observed in each agent's map must be identified and matched. In fact, there are several new challenges introduced when engaging in multi-agent SLAM [83]:

1. Coordination of robots

2. Integration of information collected by different robots into a consistent map

3. Dealing with limited communication

The usual solution to this problem is the use of a gating mechanism [23] [201]. This involves comparing landmarks in each individual's map, or between update steps, to see whether they match. Often the Mahalanobis or Euclidean distance is used as a comparison metric [60]. If the distance is found to be below some threshold, then the two landmarks are assumed to be the same. In chapter six, this method will be utilised to allow for landmark correspondence to be tested.

A method that has previously been described for localisation, particle filters, has also been implemented in the SLAM case. This process is easier to solve if it is assumed that the starting position of the robots is known. For example, a Rao–Blackwellized particle filter "uses a particle filter to approximate the posterior probability distribution over possible maps and adds robot observations incrementally using a Bayesian update step" [106]. This allows robots who encounter each other to fuse sensor data and produce maps that utilise information from the encountered agent. In order to do this in an efficient manner, it is important that only data that has been gathered since the last encounter is fused [42]. This is achieved by use of a simple time stamp, meaning that all agents initiate a time counter at the start of the mapping process. The data that are fused are then assumed to be a virtual robot that moves backwards in time along the trajectory that the encountered agent followed.

There have been other examples of extending the distributed SLAM problem to teams with unknown relative starting positions. One such example uses extended information filters [236]. This process consists of three phases: a measurement update phase, where the measurements of the robots are updated; a motion update, which involves updating the position of the robot post movement; and finally sparsification, this leaves the covariance matrix more sparsely populated, and allows operation in real time due to reduced matrix operations being needed. After this process is complete a search for corresponding landmarks in different agents' maps is initialised. This involves looking for landmark pairs in different maps, through searching for triplets of three adjacent landmarks in a small radius.

Manifold representations have been used to store the map data and make the mapping process more efficient. The manifold representation keeps a graph stored with vertices and edges. The vertices contain sensor data and the edges contain pose differences and uncertainty information. This can be combined with grid-based methods, as graphs use less memory but grids contain better detail. An example of a team of robots doing this is in work by Pfingsthorn et al. [190]. In this study displacement is estimated using a laser range finder and scan matcher, this is to update the position at which the nodes (vertices) are located. This is then simply extended to the multi-robot case by having the parts of the map that are not yet included transferred to other robots. Scan matching is then performed to ensure that there are no overlaps.

Map merging is a large focus of the distributed SLAM problem. This is because robots can use single robot SLAM and cooperative exploration techniques to create a map if they are able to merge these maps. This problem is more easily solved if initial poses are known, as this allows a transformation to be generated from the start positions. When they are unknown the map merging is usually completed by rendezvous [274] [184]. This can either be planned or assumed, in that robots can plan to meet to exchange data or it can be assumed that during the mapping procedure they will encounter one another. When robots meet, they can estimate each other's relative poses and use these to attain a transform. This can then be used, along with landmark matching, to combine their two maps and improve the accuracy of overlapping areas.

Overall it can be seen that multi-robot SLAM can be made to be more accurate than single robot SLAM due to the reobservation of landmarks by multiple agents. There have been few implementations of SLAM in real world environments, and even fewer in hazardous or nuclear environments. Thus, the implementation of EKF SLAM for mapping and localisation whilst harnessing a 'reactive virtual forces' technique for exploration of a nuclear cave environment with a heterogeneous swarm appears to be novel.

2.7 Chapter Summary

Presently there exist few robotic systems in the nuclear industry. However, early nuclear sites are coming to the end of their operational life and so the need for such autonomous systems is increasing. The first section of this review examined the systems that have been utilised in nuclear facilities to date. This provides background on the state of such systems and shows the need for new innovative solutions to protect plant workers from dangerous working conditions; such as those found within a nuclear cave environment.

Swarm systems present a useful solution to traversing hazardous and nuclear environments. Such systems are robust due to multiple agents and can efficiently cover an environment due to their number. The second section of this review examined the current swarm solutions that are under study for use in both nuclear and hazardous environments. It was found that there are few implementations of heterogeneous swarms for use in such environments. Furthermore, there are few implementations of swarms in general within the nuclear industry. The presence of swarm robotics in hazardous environments motivates their utility, and the lack of heterogeneous or nuclear implementations provides a novel area of research. This shows that carrying out an investigation into the utilisation of a heterogeneous swarm of autonomous robots for exploration of a nuclear cave environment is both valid and novel.

Following the examination of swarm systems in hazardous and nuclear environments, physical robots used for swarm experimentation were discussed. The reason for this was twofold: it provides useful information for industrial readers who might be looking for off the shelf solutions to problems; and it demonstrates the motivation for using the E-Puck robot [171]. It was found that this robot has been used for other studies and is reasonably economic so that multiple robots may be implemented. The downside of using only the E-Puck is that it is homogeneous, however this problem was overcome by imbuing virtual heterogeneity with a VICON tracking system; this will be discussed in chapter five.

Having determined the physical robots that could be used for examining swarm behaviour in a nuclear cave environment, it seemed prudent to examine how such behaviours are designed. It was found that there are generally two methods for designing behaviour: behaviour-based design and automatic design. The first of these involves the user manually adjusting individual parameters in order to attain the desired behaviour. The second uses artificial evolution to tune parameters, resulting in behaviours a designer may not have considered. Behaviour-based design is more often used when the desired task is known, as such this is the method utilised in the design of the 'reactive virtual forces' framework in chapter five. In addition to detailing the behaviour design processes, the techniques used to analyse behaviours were reviewed. It was shown that macroscopic modelling, using simplifying assumptions, can be used to rapidly prototype algorithms and allow faster, but less accurate analysis. Conversely microscopic models, such as simulations, allow for a slower and more detailed analysis of behaviour. The MATLAB simulation, designed for analysis of the 'reactive virtual forces' framework, combines both methods; some simplifying assumptions are made to allow for faster runtime, whilst each robot and artefact in the environment are individually modelled.

Subsequently, existing swarm behaviours were analysed. These were split into three broad categories: spatially organising behaviours, navigational behaviours and collective decision making. It was shown that the use of virtual potentials is a prevalent mechanism in each of these areas, and as such was afforded its own section. This showed that virtual potential fields allow for simple interactions to be defined in terms of attractive and repulsive forces. These simple interactions can be manipulated and allow for complex swarm behaviours. Focus has been given to homogeneous swarms to enable pattern formation, spatial distribution, and obstacle avoidance. There is little work on environment exploration, especially with the use of a heterogeneous swarm. The 'reactive virtual forces' framework uses virtual analogues of the fundamental forces of nature, in combination with an occupancy grid, to guide heterogeneous robotic exploration. This has been shown to be a novel concept.

The final section of this review examined literature surrounding exploration and mapping. It was found that the extended Kalman filter (EKF) provides a well-researched method for state estimation and localisation; it was also shown that it lends itself to use with simultaneous localisation and mapping. Furthermore, the EKF method allows for an estimation of uncertainty to be maintained, which is an important factor within a nuclear cave environment. For these reasons, this method was selected for localisation in the 'reactive virtual forces' framework and will be outlined in chapter six. It was also shown that occupancy grids provide an easily interpreted mapping technique. Moreover, they allow for frontier-based exploration strategies. These strategies involve guiding robots to the frontier of exploration so that new areas of the map may be discovered. There have been few implementations of such strategies using virtual potentials, and none using physical forces with a heterogeneous swarm. Additionally, there have been no comparisons of the same control strategy between heterogeneous and homogeneous swarm. Thus, the implementation of the 'virtual reactive forces' framework on a heterogeneous swarm is an original concept; with the comparison between homogeneous and heterogeneous swarms in chapter five being novel research.

Overall it has been shown in this review that robotic systems to aid with decommissioning are desired in the nuclear industry. Heterogeneity has been seen to be an under-investigated concept in the field of exploration of nuclear environments. The use of virtual potentials for the control of swarm behaviour has been revealed as a versatile method. There has been little study on its application to exploration and mapping with a heterogeneous swarm. Thus, the use of a heterogeneous swarm of autonomous robots for exploration and mapping of a nuclear cave environment appears to be novel.

The rest of this thesis will first explore how heterogeneity can be achieved through sensing and locomotion. This is followed by a description of the 'reactive virtual forces' framework, which is designed for the control of such a swarm. The next chapter will examine the sensing modalities available to a heterogeneous swarm for exploration and mapping of a nuclear cave environment.

Chapter 3

Sensing

Sensors are prevalent in nature. Humans utilise multiple methods of sensing to perceive their environment, including: optical (vision), chemical (taste and olfaction), tactile (touch) and acoustic (hearing). Robots seek to imitate these sensing modalities in order to complete delicate tasks and also to achieve efficient locomotion in complex environments. There are a vast array of sensors available in the market today, the focus of this chapter is to provide an overview of sensors that might be used to characterise a nuclear cave environment. In particular, sensors will be assessed based on their suitability for transport by a small swarm of heterogeneous robots carrying out the task of exploration and mapping.

When deciding which sensing capabilities were desirable when exploring a nuclear cave environment, it seemed prudent to consult an expert from the National Nuclear Laboratory. This expert was Bob Bowen, an industrial supervisor on this project. It was decided that the following sensing capabilities would be desirable for the characterisation of a nuclear cave environment:

- Distance – To allow geometric maps to be generated, along with enabling obstacle avoidance for robots

- Radiation – To allow dangerous areas to be found before humans enter the environment

- Pressure – A negative pressure must be maintained within the cave to stop harmful gases escaping, monitoring pressure levels is desirable

- Humidity – A more humid environment allows for transfer of dangerous radiation more easily which may: affect working conditions when the cave is entered by plant workers; and effect the accuracy of other sensors

- Image Capturing – This is the most easily interpreted sensing method for plant workers as it allows visualisation
- Temperature – Some chemicals become more reactive at higher temperatures, also higher temperature areas may be indicative of radiation and therefore dangerous for plant workers
- Chemical – To detect dangerous chemical agents that may have leaked onto the floor
- Tactile Sensing – To determine if there may be surface defects on structures within the cave

Acquisition of the appropriate data to safely decommission the nuclear cave is the goal of a robotic swarm. This chapter will describe the sensors necessary for this task, in the order they are presented in the above list. The chapter will end with suggestions for which sensors might best be utilised for exploration and mapping of a nuclear cave environment.

3.1 Distance Sensing

To safely decommission a nuclear cave environment, it is necessary to attain a geometric map of its interior. This is so that before entering the cave, plant workers are equipped with a detailed knowledge of the whereabouts of obstacles and other hazards. Additionally, possessing a geometric map of the environment allows the decommissioning process itself to be safely planned before entering the cave.

To create a map of the environment, robots must be able to detect the position of obstacles relative to themselves; this is achieved through distance sensors. Using such sensors robots are able to populate maps, such as occupancy grids. In chapter five, robots will use distance measurements to determine the virtual forces acting on them and to generate an occupancy grid. In addition to allowing maps to be created, distance measurements also allow for robots to avoid collision with obstacles and other robots.

This section will explore three classifications of distance sensor: magnetic sensors, ultrasonic sensors and optical sensors. These sensors are chosen as they may be used to attain distance measurements without requiring contact. Proximity switch sensors also exist; these are threshold distance sensors that respond once the distance falls below a predetermined value and contact is imminent. Though they can measure short distances and allow obstacle avoidance, contact sensors are excluded from this section as they do not provide enough utility inside a nuclear cave environment. This is because, though they may be used for detection of obstacles, their effective range is small which does not allow efficient or detailed geometric mapping of the environment. For more details on contact sensors, the interested reader may refer to the handbook of modern sensors by Fraden [84].

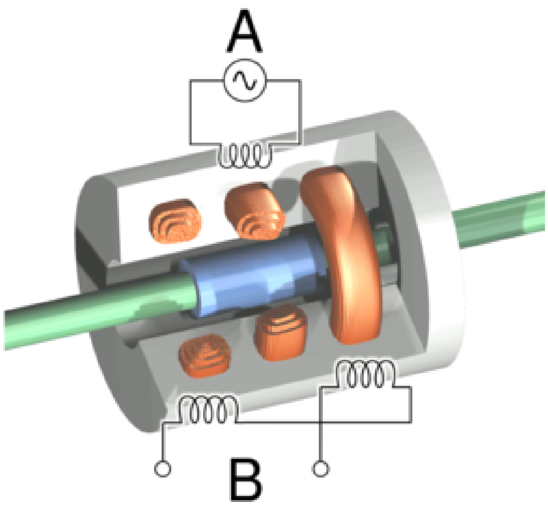


Figure 3.1: Shows the design of an LVDT sensor [252].

3.1.1 Magnetic Sensors

Magnetic sensors usually work on the principle of induction; a changing magnetic field induces a current or voltage which may be measured to ascertain distance. In general, if an object is not magnetic then the field may penetrate it and thus information may be gleaned about its interior. In a nuclear cave this might be useful for inspecting the surface of structures to detect whether they have corroded over time.

The first magnetic sensor to be examined is the linear variable differential transformer (LVDT). This sensor uses a primary coil, set between two secondary coils which produce a magnetic field, shown in figure 3.1. In the centre of these coils sits a ferromagnetic core. When the core is displaced the magnetic field between the coils is altered, this field change induces a voltage that is proportional to the displacement of the core. In turn, this voltage may be measured and the displacement determined. An LVDT is usually implemented in short range measurements and can often be used as a contact sensor. They have been implemented in robotic manipulators to accurately assess joint displacement to aid in force feedback control [34] [90]. Despite the accuracy of these sensors, their short range makes them unlikely to be helpful for geometric mapping of a nuclear cave environment. Though they are small enough to be carried by a small robot and hence could be used to take precise, short distance measurements if required.

Eddy current sensors take advantage of an electrical phenomenon discovered in 1851. This effect causes a current to be generated when a magnetic field is changed due to the relative motion of the source and a conductor; or when the intensity of a magnetic field is altered. It is thus possible to measure the change in current to calculate the distance between the emitting source and the surface being measured. Eddy current sensors have been used to inspect aircraft for cracks, corrosion and degradation [220]. Eddy sensors could be useful in a nuclear cave environment for the same task: inspecting the surface of objects within the nuclear cave to check for degradation that could have occurred over time. However, Eddy current sensors need an alternating current that requires a high power consumption to work effectively, which might not be possible for a small mobile robot to produce.

The final magnetic sensor to be discussed is also the most prevalent, the Hall effect sensor [84]. A Hall effect sensor utilises a thin strip of metal, with a direct current applied along it. When this strip is exposed to a magnetic field, the electrons are deflected towards one edge, creating a potential difference across it. This potential difference may then be measured and is dependent on the proximity of the strip to the magnetic field. The advantage of a Hall effect sensor over inductive sensors such as the LVDT or Eddy current sensors is that they can detect non-changing magnetic fields. If the magnetic field is known, then the distance from the Hall plate may be measured [198]. Often these sensors are employed for small distance measurements, such as to determine whether a printer is out of paper. In robotics, Hall sensors have been used for measuring the displacement of wheels to allow for odometry measurements, for example in the MICAbot [165]. An array of hall sensors has also been used to localise a magnetic robot for potential use in medical applications [221].

Overall magnetic sensors provide a useful tool for proximity detection. If there are few magnetic materials in the environment then they can provide low noise measurements in situations where other sensors, for example optical sensors, may not be suitable. It has also been shown that magnetic sensors may be used to inspect surface defects on structures; this could be valuable in understanding corrosion on objects within a nuclear cave. However, due to the small range of these sensors they are unlikely to be useful for the larger scale geometric mapping of a nuclear cave environment.

3.1.2 Ultrasonic Sensors

Ultrasonic waves are mechanical acoustic waves, present at a frequency far higher than that perceivable by humans. When these waves are incident on an object, some of the energy is reflected. The reflected energy can be measured and based on the time it takes to return to the sensor, the distance may be calculated. The advantage of ultrasonic sensors over optical sensors is that ultrasonic waves travel at the speed of sound rather than the speed of light, this makes the time taken for their reflection easier (and cheaper!) to detect.

Within robotics the low cost and availability of ultrasonic sensors has led to their widespread use for obstacle avoidance and mapping of environments [25] [56] [88]. Ultrasonic sensors have been designed to be small, with some only 45mm across. This means that they could easily be carried by a swarm of heterogeneous robots hoping to map a nuclear cave environment.

Despite the upside of availability and economic value, ultrasonic proximity sensors can be affected by noise interference and some will have a blind zone at close proximity. This could hinder robots trying to create a geometric map of their environment, as they could be forced into close proximity with other robots; for example, if there is small corridor between two areas that are being mapped. In addition, the surface angle and roughness of the target surface can affect the sensor. As the orientation and composition of objects within the nuclear cave is unknown, reflections may be weakened. Finally, the speed of sound can be affected by temperature and humidity which can impact the resolution and accuracy of the sensor. As different areas of the nuclear cave might vary in temperature due to the presence of radioactive elements, this could mean that the calibration of an ultrasonic sensor may have to be changed on the fly. This is difficult and could yield inaccurate results.

Overall, ultrasonic sensors are small and economic making them suitable for transport by a group of small autonomous robots tasked with mapping and exploring a nuclear cave environment. However, due to the adverse conditions with a nuclear cave, these sensors might not provide reliable measurements. As an accurate geometric map of the environment is integral to the decommissioning process, ultrasonic sensors may not prove to be the best choice for distance measurements within a nuclear cave environment.

3.1.3 Optical Sensors

Optical sensors utilise the travel time between emittance and reflection of electromagnetic waves to determine distance. They are usually comprised of three key components: a light source, a photo detector and a light guidance device (e.g. mirrors/ lenses/ optical fibres). Optical sensors are a popular method for measuring distance as there is little or no interference from magnetic or electrostatic fields.

One common optical sensor is the light detection and ranging device, or LiDAR. These sensors emit pulses of light and measure the reflected beam, often thousands of times per second. The fast refresh rate coupled with the small beam width, allows for accurate distance measurements. LiDAR's can be made to rotate three-hundred-and-sixty degrees in order to generate dense point cloud maps. These maps can then be used to construct an accurate representation of the environment being scanned, for example they have been used to map urban environments with the ability to detect small features up to one hundred metres away [211]. Due to their high precision, they have been used for multiple purposes in robotics: to aid in driverless car navigation and obstacle avoidance [258]; to correct GPS error and aid with localisation [269]; and to generate real time maps of environments [271]. LiDAR's are usually large devices that would be difficult for a small robot to carry into a nuclear cave environment. However, it has been shown that it is possible to miniaturise a LiDAR to be as small as 55x60x135mm across [130]. A LiDAR of this size would make a valuable asset in exploring and mapping a nuclear cave environment; as it could be carried by members of the swarm to generate dense point cloud maps that are accurate and easily interpreted, or used to reliably populate an occupancy grid.

Another optical distance sensor often utilised in mobile robots is the infrared sensor. This can be made cheaper and smaller than a LiDAR sensor, but due to the lower energy of the infrared beam, the range is shorter. Infrared sensors are often used as proximity sensors to enable obstacle avoidance, as is the case with the E-Puck robot [171]. As with the LiDAR sensor, it is possible to attain a three-hundred-and-sixty-degree view of surroundings, usually by placing sensors at reasonable intervals about the perimeter of a robot. Another method of attaining a three-hundred-and-sixty-degree view is to use two rotating sensors [138]. This has been shown to give an accuracy of 2.6cm over a range of 100cm. Small rotations of around thirty-seven degrees have also been explored to eliminate blind spots in the perception of mobile robots [186]. Though infrared sensors are cheaper and smaller than their laser counterparts, their accuracy and range are significantly reduced. In addition, they are significantly compromised in environments where there maybe light-reflecting particles in the air, such as water droplets (e.g. rain, fog) and smoke particles.

Overall, optical sensing seems to be the most likely candidate for distance sensing in a nuclear cave environment. This is because the range allows for geometric maps of the environment to be created. A small LiDAR sensor would give accurate measurements and allow the generation of dense point clouds that could be used to aid with nuclear decommissioning. Due to the high cost of LiDAR sensors, one solution could be using infrared sensors on all robots to allow obstacle avoidance and simple mapping, whilst equipping specialised agents with LiDARs. This would allow for accurate maps to be produced, while remaining economically viable.

3.2 Radiation Sensing

When characterising a nuclear environment one of the most important sensors to have is one capable of detecting the presence of radiation. It is useful to be able to detect the various sources of radiation; alpha, beta and gamma. In addition to this, useful functions include the ability to detect radiation level and energy, as well as resolve the direction of the radiation. Not all radiation sensors are able to fulfil these criteria. In this section the three most prevalent types of radiation sensor will be described, these are cloud and bubble chambers, ionizing detectors and scintillator detectors.

3.2.1 Cloud and Bubble Chambers

A cloud chamber is a gas filled device that can be used to detect ionizing radiation. This means that it is primarily used for beta and alpha particles, though it is possible to use it for gamma detection. The chamber contains a supersaturated mixture of alcohol and water. When an ionizing particle passes through this mixture it causes condensation, leaving a mist trail along the path of the particle. The size and shape of this trail can determine what type of radiation has passed through. If the particle is deflected using a magnetic field then the charge to mass ratio of the particle may be determined, allowing a more accurate characterisation of the radiation.

Currently gas detectors tend to be larger and used primarily in research areas to observe particle trajectory. Taking one into a nuclear cave on a mobile platform and attaining accurate results could be challenging. Despite this, there have been uses outside the laboratory. For example, a cloud chamber was attached to a weather balloon and used to observe cosmic ray electrons [76].

Bubble chambers are similar to cloud chambers, except that they are filled with liquid as opposed to gas. When ionizing radiation passes through such a chamber small bubbles are formed. As the size of the chamber increases the bubbles become larger and can be photographed and used to observe the trajectory of a radioactive particle. Bubble chambers are more sensitive to gamma radiation, for example liquid hydrogen has been used to detect gamma radiation as it boils in its presence [259].

Both detectors provide excellent directional resolution and allow observation of radioactive elements. However, it might be difficult to mount such detectors on mobile robots. In addition, the dark cave would not allow for photographs of the trajectory's to be taken without a light source. One potential solution could be using mobile robots to carry a chamber into the nuclear cave. This could then be illuminated and examined with a camera to determine which direction radiation is coming from. Following this, robots could move to these areas for further examination using other radiation sensing equipment, which will be discussed subsequently.

3.2.2 Ionizing Detectors

3.2.2.1 Ionizing Chamber

Ionizing chambers are the oldest and most widely used of the radiation sensors. The ionizing chamber relies on the photo electric effect. This effect removes electrons from one plate thus allowing them to drift, this in turn causes a current to flow between the two plates, which is proportional to the level of incident radiation. Thus, measuring the current gives an indication of the level of radiation present. This type of sensor requires a high voltage be maintained in order to prevent the electrons recombining with their parent atoms [240].

A robot carrying an ionization chamber has been implemented for scanning the nuclear medicine department of a hospital [213]. This shows that it is possible to mount an ionization chamber on a mobile robot. Such a method could be envisaged for examining the presence of radiation within a nuclear cave environment.

Overall these sensors provide a good uniform response to gamma radiation, accurate overall dose reading and sustained high radiation does not degrade the sensor. In addition, ionization chambers have been used previously for radiation scanning with mobile robots. However, they produce low electronic output so require a sophisticated electrometer and their operation and accuracy is affected by moisture, which could vary within a nuclear cave environment.

3.2.2.2 Proportional Chamber

This type of sensor is usually used for low energy x-rays and neutron detection. This is because it utilises the gas multiplication phenomena in order to produce stronger pulses than in a standard ionizing chamber. This phenomenon causes the release of electrons from atoms due to collision with the electrons released from the photoelectric effect. In order to produce high energy electrons, and allow this effect to take place, a high voltage must be maintained. This can be as high as 10^6V [84].

A patent for a mobile robot carrying a proportional detection chamber has been filed [70]. This patent details a robot carrying a proportional chamber for detecting radiation that can follow a predetermined path, whilst avoiding obstacles. This shows that a proportional chamber can be mounted on a mobile robot to allow scanning of radioactive areas. However, the size of the robot is not mentioned but due to the mention of 'hoses' and 'gas tanks' it is assumed to be large. This makes it likely that a proportional chamber could be too large to carry into a nuclear cave environment by a small mobile robot.

This chamber can easily measure the difference between gamma and alpha radiation, in addition to being able to detect the energy of the radiation (which is proportional to the intensity of the pulse). However, the anode wires in such a sensor can lose sensitivity over time and exposure to oxygen can degrade efficiency if it gets into the fill gas. Though the sensor has been shown to be transportable by a mobile robot, it is likely to be too cumbersome to be utilised by a small swarm of heterogeneous robots within a nuclear cave environment.

3.2.2.3 Geiger-Muller Counter

The output of a Geiger-Muller sensor does not depend on the energy of the radiation, but only on applied voltage. This means that such a detector is only capable of measuring the level of radiation, not the energy. Similarly to the poportional chamber, the Geiger-Muller counter produces avalanches of electrons, via the gas multiplication phenomena. However, now an additional element plays a part in the avalanche; the UV energy released by electrons returning to their initial energy state. This energy may in turn start another avalanche, because of this the anode of the counter will eventually become enveloped in electrons. When this happens the chain reaction of avalanches is terminated. The time it takes for this termination to occur can be used to determine the level of radiation [84].

These detectors are cheap and robust, with a large output signal. Also it has been shown that it is possible to make Geiger-Muller sensors between 0.8x0.8mm and 3x3mm, which could be carried by small mobile robots [58]. The obvious downside of these sensors is the inability to measure radiation energy, which could be an important metric when looking to safely dismantle a nuclear facility. As well as this, there is a tendency for the filler gas to degrade over time when exposed to sustained levels of high radiation. Geiger-Muller counters have been implemented with mobile robots to locate a radiation source [143]. This shows that they could be utilised in a nuclear cave environment by a small swarm of heterogeneous robots in order to determine the location of radiation sources to aid in nuclear decommissioning.

3.2.2.4 Semiconductor Detector

Semiconductor sensors provide the best resolution of modern radiation sensors. They work on the principle of electron-hole pairs, which act as information carriers. On average one electron-hole pair is created per incident photon. The electron is liberated from the valence band and promoted to the conducting band which instigates a current. This current is then proportional to the incident radiation. In order to generate a current, the photon must have enough energy to promote the electron across the band gap. This means that by tailoring the energy of the gap, through doping, the sensor can be tuned to particular wavelengths of radiation and can thus be selective. The gap may be made as small as 3eV, this is compared to the 30eV resolution of a cloud chamber [84].

A drawback of the semiconductor detector is that it can suffer from inaccurate results due to background radiation. A possible solution to this problem was put forward by Gary et al. [89]. This work suggests that instead of observing the changing charge caused by the radiation, the effect on spin could be measured. The electron spin is changed by the electromagnetic field of the radiation, and so absorbance of radiation is not required. This in turn reduces noise and allows the sensor to operate at higher temperatures.

Though the semiconductor sensor is easily manufactured, very small and can be integrated into a circuit, there are drawbacks. First, without an array of sensors, directional resolution is not possible. As well as this, the sensor can become damaged by continuous use. Additionally, the sensing of penetrating radiation is difficult since semiconductor detectors are often thin. Finally, semiconductor sensors require cooling in order to operate, often through liquid nitrogen [104]. Overall, it seems that semiconductor sensors provide the best resolution of the radiation sensors, but due to their cooling requirements it would be difficult to utilise these sensors on small mobile robots within a nuclear cave environment.

3.2.3 Scintillator Detectors

A scintillator detector relies on the ability of a material to convert radiation to light. Widely used materials for scintillator detectors include inorganic halide crystals, organic based liquids and plastics. These materials are used to build the photocathode, which releases electrons due to the photo-electric effect. However, a photocathode generally produces a small signal and so a photo multiplier is needed. Electrons released from the photocathode are accelerated by dynodes, which are maintained at increasing voltages. These dynodes release more electrons when impacted by the current electrons and hence increase the electrical signal. Finally, the electrons reach the anode at the opposite end and a detection signal is generated. The design of a scintillator detector

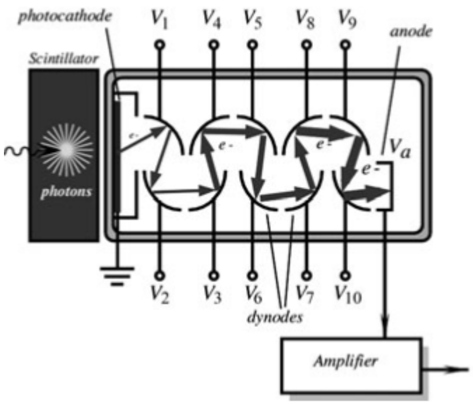


Figure 3.2: Shows a the design of a scintillator detector, with a photo multiplier [84].

Figure 3.3: Shows the design of a scintillator detector utilising a channel photo multiplier, and the relative size of such a detector [84].

can be seen in figure 3.2. A scintillator detector is capable of measuring both the intensity and the energy of incident radiation.

In order to avoid the complicated dynode structure of the photo multiplier in a standard scintillator, detectors using a channel photo multiplier have been designed. These can be made smaller than a standard detector, as can be seen in figure 3.3. Instead of using dynodes to release electrons, a channel of semi-conducting material is created. Each bend acts like a dynode, releasing electrons and accelerating them along the path [84].

There exists a design for a robot that utilises a scintillator detector in order to search surfaces for radiation sources [71]. This robot can use a scintillator detector attached to a rig to scan flat surfaces to measure radiation levels. In addition, the robot can generate real time maps of the radiation on the surfaces it has scanned. This lends itself to a nuclear cave environment, as robots could be used to scan surfaces and determine the location and quantity of radiation to aid in characterisation of the environment.

Overall scintillator detectors are useful as they are able to detect low radiation levels, due to photo-multiplication. In addition, they can be made to have relatively fast response times so long as fast transfer processes are utilised [140]. Like semiconductor detectors, scintillator detectors are solid state; this makes them easily carried by mobile robots. Though scintillator detectors provide less resolution than semi-conductor detectors, they do not require cooling. This, in addition to the fact they may be miniaturised, likely makes scintillator detectors the best choice for radiation sensing in a nuclear cave environment using a heterogeneous swarm of autonomous robots.

3.3 Pressure Detectors

Inside a nuclear cave it is important to maintain a negative pressure. This is to prevent irradiated air from escaping the cave. For this reason, it is important that the pressure within the cave is monitored. In addition, any local disturbances to the ambient pressure of the room could be indicative of leaks in the pipework. A typical pressure sensor is able to detect three types of pressure:

1. Absolute pressure - this is the pressure relative to a perfect vacuum
2. Differential pressure - this is a measure of the difference between two pressures
3. Gauge - this is a measure of pressure relative to the ambient pressure

Most pressure sensors utilise a membrane or thin plate of known area, on which the pressure is exerted. The deflection of such a plate can be measured in numerous ways and thus give an estimate of the pressure. This section will explore: piezoresistive sensors, capacitive sensors and variable reluctance pressure (VRP) sensors.

3.3.1 Mercury Sensors

Mercury pressure sensors were among the first pressure measuring devices to be conceived [84]. They operate on the communicating vessels principle. A U-shaped wire is immersed in mercury, as the pressure changes the level of the mercury rises or falls, this in turn changes the resistance of the wire. It is therefore possible to pass a current through the wire and measure either voltage or resistance in order to attain an estimate of pressure. An example of a mercury pressure sensor may be seen in figure 3.4.

A mercury detector is unlikely to be affected by increased radiation levels and thus would make a useful detector if it could be installed inside the nuclear cave. However, such a detector would not be applicable to a robot whilst mapping a cave environment; this is because a mercury pressure sensor requires precision levelling and is susceptible to shocks. Thus, a mobile robot would not make a good platform for the sensor to operate on.

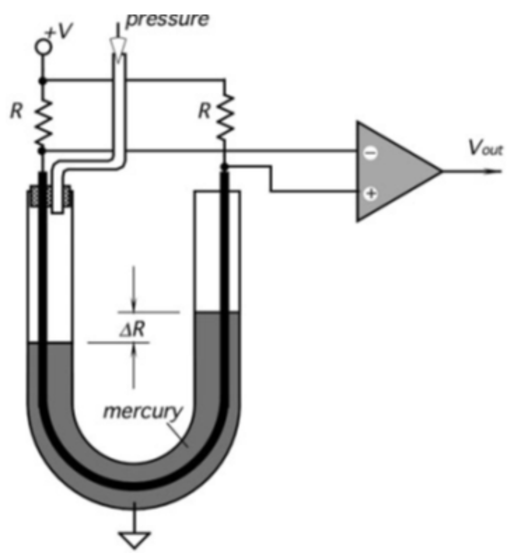


Figure 3.4: Shows the design of a mercury pressure sensor [84].

3.3.2 Piezoresistive Sensors

The design of a piezoresistive sensor relies upon the deflection of a thin plate or membrane, along with the fact that a piezoresistive material will change resistance based on applied stress. As the pressure changes the level of deflection changes. This is sensed at the edge of the membrane using a piezoresistive element. In modern sensors the membrane and piezoresistive element are manufactured using silicon, with impurities designed into latter to increase piezoresistive response. The change in resistance of the silicon is measured using a wheatstone bridge [84].

A piezoresistive pressure sensor has a number of attractive qualities for use in a nuclear cave; it may be designed to have a response time of milliseconds [219]; it may be created at a small size which has been used to control a robot in a high electromagnetic interference zone across a wide temperature range [230]; and finally, piezoresistance is unaffected by radiation [102]. The most significant disadvantage of the piezoresistive pressure sensor is that at the extremes of pressure, the membrane may tear, which renders the sensor useless. However, the pressure within the nuclear cave is not extreme enough to cause destruction of the sensor. Hence, due to the piezoresistive sensor's wide availability, size and ability to fit onto circuit boards it is likely the best choice of pressure sensor for a nuclear cave environment.

3.3.3 Capacitive Sensors

Capacitive pressure sensors, like piezoresistive sensors, measure the deflection of a silicon diaphragm in order to attain an estimate of pressure. The difference being that instead of measuring the deflection at the edges using a piezoresistive element, they instead measure the central deflection using a capacitor.

In the design of a capacitive pressure sensor, the diaphragm acts as one of the plates of a parallel plate capacitor. The deflection of this diaphragm under pressure changes the capacitance as much as 25% over the diaphragm's range of motion. This change of capacitance can then be measured and from it the pressure may be deduced. This offers a greater sensitivity to low pressures than piezoresistive sensors, as a higher output voltage is provided. This higher output offers not only improved sensitivity but also better temperature behaviour, stability and power consumption [193].

Currently capacitive sensors are used in aviation and automobile industries. However, these are usually large sensors, on the order of 15mm or more in diameter, and each must be individually made [209]. Despite the use by these large industries, there are few commercially available capacitive sensors.

The most significant downside for use of a capacitive pressure sensor in a nuclear environment is the fact that capacitance may be affected by radiation, depending on the choice of dielectric material [45]. It has been found that the capacitors dielectric can be degraded by ionizing radiation. This limits the range of available sensors, and hence makes a piezoresistive sensor a more versatile choice.

3.3.4 Variable Reluctance Pressure Sensors

A variable reluctance pressure (VRP) sensor is generally used when the pressure change is so low that the deflection of a diaphragm by piezoresistance or capacitance is undetectable [84]. Operation relies on the use of a magnetic sensor in place of a capacitor. When a diaphragm is deflected the shape of the airgap within the sensor is changed. As the magnetic core has a conductance one thousand times greater than the air gap, the change in conductance may be measured via the induced current. This gives excellent resolution.

This method is reliable and useful for the measurement of low pressure. However, it is also more complex than both capacitive and piezoresistive sensors, making these sensors more expensive. As the level of pressure resolution afforded by a VRP sensor is not necessary in a nuclear cave, the added complexity and cost renders a VRP pressure sensor a less desirable choice for operation within a nuclear cave.

3.4 Humidity Sensors

Humidity is an important factor for operating certain equipment, for instance, high impedance electronic circuits, electrostatic sensitive components and high voltage devices. Higher humidity can lead to erroneous measurements of radioactivity but can be calibrated for if relative humidity is known [142]. In addition, higher humidity can lead to uncomfortable working conditions for plant workers, if the humidity is known then conditions can be accounted for when planning decommissioning. It is therefore important for a robot operating in a nuclear cave environment to be able to take measurements of humidity, and thus a humidity sensor is required. There are three important quantities to be considered when measuring humidity:

1. Relative Humidity – ratio of actual vapour pressure of the air at a temperature to the saturation vapour pressure at same temperature

2. Absolute Humidity – mass of water vapour per unit mass of dry gas

3. Dew point – where relative humidity is 100%

In order to measure humidity some reference humidity is needed; this is usually either dry air (with 0% humidity) or saturated steam (with 100% humidity). An alternative reference is a saturated salt solution; however this requires strong temperature uniformity inside the sealed box where the reference humidity is being generated which can be challenging.

This section will investigate: capacitive sensors, conductive sensors and optical hygrometers.

3.4.1 Capacitive Sensors

A capacitive sensor takes advantage of the fact that the permittivity of the dielectric is affected by the humidity, which in turn affects the capacitance. The easiest method for this is to use an air-filled capacitor whose permittivity changes according to humidity by equation 3.1 [84].

$$\kappa = 1 + \frac{211}{T}(P + \frac{48P_s}{T}H)10^{-6} \tag{3.1}$$

Where T is temperature in Kelvin, P is pressure of moist air in mmHg, P_s is pressure of saturated water-vapour at temperature T in mmHg and H is relative humidity as a percentage.

It is possible to improve the sensitivity of a capacitive sensor by using a dielectric whose permittivity is affected by humidity more than air. When designing the sensor, it is important that a zero potential be maintained across the sensor, otherwise permanent damage to the sensor could occur.

Capacitive sensors can have fast response times of around one second, this is achieved using multiple columns of sensing material. It has been proven that the response time of such a detector is dependent on the number and radius of these columns [121].

It has been shown that it is possible to insert such a capacitive sensor onto an RFID tag that can then be used to monitor items whilst they are being shipped in large shipping containers [183]. This could be useful if such a sensor were installed in the nuclear cave for monitoring. Additionally, a small capacitive sensor is capable of being fitted into an electronic circuit and thus could be carried by a team of mobile robots. This would allow reconnaissance of the humidity around the cave. However, as with other capacitive sensors, the negative effect on some dielectrics caused by radiation could mean that this is not an ideal choice of humidity sensor for use in a nuclear cave environment. Despite this, given the correct choice of dielectric, this is likely the most suitable sensor to be taken into a nuclear cave environment; due to the fast response time, size and integration with electronic circuits.

3.4.2 Conductive Sensors

There are two distinct types of conductive sensor, these are electrical and thermal conductivity sensors. Electrical conductivity sensors rely on the fact that the resistances of many non-metal conductors depend on their water content. Usually this means that a moisture sensing material has low resistivity that then changes significantly under varying humidity. This change can be between $10M\Omega$ and 100Ω over a range from 0-90% humidity. This then means that the resistance of the material can be measured using a wheatstone bridge and from this the humidity may be inferred [47].

Thermal conductivity sensors use the thermal conductivity of gas to measure humidity. The measurement is achieved using a thermistor which measures the difference in conductivity of dry air and the humid air being analysed. The output signal of this style of sensor gradually increases as the humidity increases. However, measurements using a thermal conductivity sensor must be made in still air to prevent erroneous results caused by convection currents which may not be possible within a nuclear cave environment.

3.4.3 Optical Hygrometer

Optical hygrometers are the most expensive choice of humidity sensor, but they can overcome issues that other hygrometers suffer from, for example temperature dependence. An optical hygrometer uses a mirror that is precisely maintained at a given temperature. This temperature is gradually changed until dew starts to form on the surface of the mirror, this is the dew point. When this dew forms, the temperature change is halted and instead the temperature is maintained at the dew point. At the dew point the reflective properties of the mirror are altered and may be detected by a suitable photodetector. From the dew point both absolute and relative humidity may be calculated. This method of sensing can be very accurate and resolve humidities to approximately 0.03% accuracy.

Such humidity sensors have been employed on environmental monitoring missions, and to increase the longevity have been designed to use infrared light rather than the visible spectrum [247]. An optical humidity sensor would provide accurate measurements within a nuclear cave, however the mirror needs to be constantly wiped in order to take multiple readings in changing humidities. In addition, the size of an optical humidity sensor is not suitable for use on a mobile robot in a nuclear cave environment, due to the motion of the swarm disturbing the air.

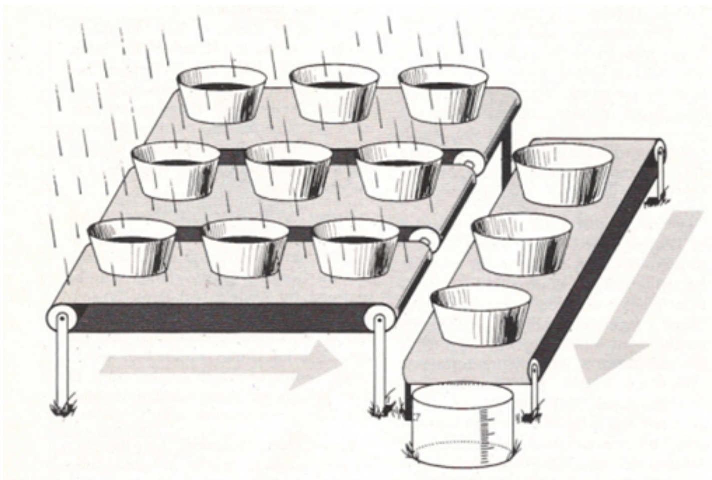


Figure 3.5: Shows how a CCD device operates with a simple analogy, where the water collected represents incident light and the buckets represent pixels [116].

3.5 Image Sensors

Visual information pertaining to a nuclear cave environment is likely the most easily interpreted by plant workers. This data would allow for decommissioning to be planned with as much information as possible. It should be noted that there is no light in a nuclear cave environment; this section is considered relevant because it is likely a mobile robot will take its own lighting equipment into the cave, to aid with mapping and to attain images of the cave.

There are currently two types of image sensor, these are the charged coupled devices (CCD) and the complementary metal oxide semiconductors (CMOS), which are both types of camera. In a CCD every pixel has its charge transferred through a small number of output nodes, which is then converted to a voltage and sent as an analogue signal off-chip. Following this the analogue signal is then digitized by an A/D converter. This style of sensor allows every pixel to be dedicated to capturing light, which gives better uniformity and hence quality. In addition, these sensors are cheaper and less complex than their CMOS counterparts. When operating, pixels collect electrons from the photoelectric effect. At the end of the frame each pixel contains electrons proportional to light that was incident upon it. The pixels are then 'clocked' which means they move to one of the bottom corners column by row, to give the output signal, this is illustrated in figure 3.5 [116].

CMOS devices work on a different principle, each pixel has its own charge to voltage conversion. In order to do this there is often an amplifier and noise correction device included in the circuit. A CMOS device has less uniformity than a CCD device, and this can offer lower image quality if not corrected for. However, for basic operation a CMOS device requires less off-chip circuitry. It also eliminates the process of clocking, instead each pixel is read on an x-y axis.

Cameras are highly sensitive to radiation and picture degradation can occur even when the radiation dose is moderate [214]. This means that it is necessary to either shield the camera or utilise one that is radiation hardened [152]. Such cameras have been used in combination with mobile robots to explore multiple nuclear environments [30] [268] [263].

Overall, a radiation hardened camera coupled with a light source could provide valuable information about the state of a nuclear cave environment. However, due to the size and cost of a radiation hardened camera, it is likely that a small cheap camera is the best solution to image sensing in a nuclear cave. Such a camera could be carried by mobile agents in a heterogeneous swarm, and be used to gather information and navigate within the nuclear cave, then disposed of after the imaging task is complete.

3.6 Temperature Sensors

To aid in the decommissioning of a nuclear cave it is important to know if there is a safe temperature for humans to enter. In addition, small temperature spikes within the cave may show damage, or decay of pipework and pressure vessels. For these reasons, it is useful to have a temperature sensor on a mobile robot capable of traversing the cave.

A measure of temperature relies on the transfer of a small portion of energy from the body being examined to the sensor. This means that any measurement of temperature will have error as the presence of the sensor alters the temperature of the body. When measuring temperature there are two methods: equilibrium and predictive. An equilibrium measurement requires that the sensing element and the surroundings no longer have a thermal gradient, at this point the sensors temperature measurement is considered to match that of the body being examined hence a measurement is recorded. Predictive sensing uses a computer element to predict the temperature based on the rate of change of temperature of the sensing element. Both these types of sensor require that the sensor be decoupled from its surroundings as much as possible in order to give accurate results.

It is important to note that there are typically two temperature measurements that are possible. The first of these is a measure of absolute temperature, which is the temperature measured relative to some absolute point on the temperature scale. The second is relative, which measures the difference in temperature between two objects, with one being the 'reference'.

This section will detail: thermoresistive sensors, thermoelectric contact sensors, acoustic sensor and piezoelectric temperature sensors.

3.6.1 Thermoresistive Sensors

The electrical resistance of various metals is dependent upon temperature. This is the basic principle that all thermoresistive sensors exploit. Most thermoresistive temperature sensors are used to measure absolute temperature. They have the advantages of simple interface circuits, good sensitivity and long-term stability.

Thermistors are used to measure absolute temperature. This type of sensor can usually be divided into two types: positive temperature coefficient (PTC) and negative temperature coefficient (NTC). Generally only NTC thermistors are useful for precision temperature measurements.

The resistance of an NTC thermistor decreases with an increase in temperature, however this increase is highly non-linear. This non-linearity results in errors of plus or minus 10%. However it is possible to calibrate such a thermistor by placing it in a heat bath of known temperature and measuring the resistance. After calibration the temperature can be determined by equation 3.2 [84]:

$$T = \left(\frac{1}{T_0} + \frac{ln(\frac{S}{S_0})}{B_m}\right)^{-1} \tag{3.2}$$

Where T_0 and S_0 are point on the calibration curve, S is the measured resistance and B_m is the materials characteristic temperature.

Thermistors have frequently been utilised in robotics for temperature measurement. One such example is in the following of temperature trails laid by a mobile robot carrying a halogen light [206]. This shows that a thermistor can be integrated into a mobile robot and be used to carry out detailed inspection.

Overall, thermistors provide an easily integrated and commercially available solution to temperature sensing for mobile robots. Due to this, and their low cost, they are likely the best choice for temperature sensing within a nuclear cave environment.

3.6.2 Thermoelectric Contact Sensors

Thermoelectric contact sensors, often referred to as thermocouples, utilise at least two dissimilar conductors joined to form a junction; in order to make a practical sensor at least two of these junctions are required. A thermocouple is used to measure relative temperature as one junction acts as a reference for the other.

Currently thermocouples account for 37% of the market of temperature sensors and are very reliable with only 0.4 faults per year. Additionally, it is possible to have a thermocouple self-validate, allowing the sensor to detect when it has malfunctioned or even lost contact with a surface [265].

Thermocouples have been installed by climbing robots to conduct ongoing inspection in nuclear power facilities [149] [148]. This work utilises a multi-legged vehicle with suction grippers to adhere to the steel surface of the reactor pressure vessel allowing installation of thermocouples in areas that are not possible to reach using fixed based manipulators.

Thermocouples have the advantages of being readily passive and available sensors. The former meaning that a thermocouple generates its own voltage and thus does not need any excitation current in order to operate. The most significant drawback is that such a detector requires direct contact with the body whose temperature it is taking, which is not always possible when traveling in a nuclear cave environment.

3.6.3 Acoustic Temperature Sensors

A the extremes of temperature, such as those found inside nuclear reactors, measurement of temperature becomes difficult. Acoustic temperature measurement devices have been shown to work at 1000 degrees Celsius with plus or minus 5 degrees accuracy [139].

Acoustic devices operate based on the relation between the temperature of an object and the speed at which sound propagates through that object. In general, two piezoelectric plates are used, one as a transmitter and the other as a receiver. The transmitter passes an acoustic signal through a hermetically sealed gas chamber which is at temperature equilibrium with the body being measured. When the transmitter emits its signal a clock is started, this clock is then stopped once the receiver picks up the signal. The propagation time is then used to estimate the speed of the wave and hence the temperature of the gas.

An acoustic sensor has been shown to work at high temperatures expected in a nuclear reactor; a nuclear cave has a temperature much lower than a nuclear reactor and a significantly lower level of radiation. It is not therefore anticipated it would be necessary to use an acoustic temperature sensor inside a nuclear cave.

3.6.4 Piezoelectric Temperature Sensors

In general, the piezoelectric effect is a temperature dependent phenomenon. If a quartz crystal is excited to vibrate by an electrical circuit, then it is possible to measure its oscillating frequency. This frequency is dependent on the temperature of its surroundings. If the crystal is brought to equilibrium with the surroundings a measurement of its oscillating frequency can be used to attain a measure of temperature.

The downside of such a sensor is that its response time is long. This is largely due to the difficulties associated with thermally coupling the crystal with the body whose temperature is being measured. The long response time makes this sensor acceptable for measuring the temperature of the cave in general, but poor for areas where the temperature may have spiked. This is because it is not practical for a mobile survey robot to spend long periods of time stationary in order to attain temperature measurements, as they have limited battery life and are required to map other areas.

3.7 Chemical Sensors

Chemical sensors are important as, within a nuclear cave, it is necessary to determine areas that may have increased toxicity or contain dangerous substances that need to be identified for disposal. This requires a mobile robot to have a chemical sensor on board or to be able to take samples and transport them outside the cave. Transporting chemicals outside the cave would allow a more in-depth investigation into the structure of the compound, but in situ measurements allow more rapid mapping of dangerous areas and reduced complexity.

In general, systems that are miniaturised, for example for use on a small mobile robot, have issues with sensitivity, stability and reproducibility. When looking at chemical sensors it is important to realise there are two important characteristics: selectivity and sensitivity. Selectivity describes the degree to which a sensor will respond to only the target species. Sensitivity measures the minimal concentration, or change in concentration, that may be repeatably and reliably sensed.

A further factor to consider is that many chemical sensors can only be used for a few measurements. This is because the sensor can be easily damaged by the target chemical and this renders the sensor inert.

This section will assess: chemiresistors, chemFET sensors and electrical and electrochemical transducers.

3.7.1 Chemiresistors

Chemiresistors are polymer films that are capable of adsorbing chemical species onto their surface causing them to swell. This swelling increases their resistance as a physical response to the presence of a chemical species. This means that it is possible to design a polymer film to adsorb a particular chemical, giving it good selectivity [84].

It is possible to have a chemiresistor that is capable of response times as low as one second, however a more average response time is around 10 seconds. This is a reasonable response time for a mobile robot in a cave environment, as it would allow measurements to be taken often.

Chemiresistors have been used to create electronic noses that are capable of artificial olfaction [24] [232]. An electronic nose has been implemented on a mobile robot in order to identify objects based on their olfactory properties [147]. This could be utilised by a heterogeneous swarm in a nuclear cave to locate chemical spills and identify the contents.

3.7.2 ChemFET

ChemFET is a chemical field effect transistor, which utilises a gas-selective coating or series of coatings between its transistor gate and the analyte. The device is given a control input which modifies conduction in relation to select chemical species. This detector can detect multiple chemicals. When used for the detection of hydrogen or organic material the sensor will not oxidise and over time will produce more stable results [4].

It is also possible to build an array of chemFET/ resistive sensors that can measure various properties of gas and liquid, using the same sensing material for both; as the FET sensor is embedded within the resistive sensors [54]. This would be useful in a nuclear cave where it is not certain either what properties of a chemical are required to be known, or which chemicals may need detecting.

3.7.3 Electrical and Electrochemical Transducers

There are several different kinds of electrical and electrochemical transducer. However, they all rely on a direct measurement of the electrical properties of the target analyte or the effect of the analyte on the electrical properties of another material. Due to the simple design of most electrical and electrochemical transducers, it is possible to use them in a harsh environment, such as a nuclear cave. The various types of transducers are as follows:

- **Metal-oxide Semiconductor Devices (MOS) -** detects a change in concentration of a reactive species which translates as a change in resistance. They are usually constructed of a semiconducting sensitive layer, an electrical connection to measure resistance of that layer and a heater to control the temperature of the device.

- **Electrochemical Sensors -** one electrode is left in the presence of the reaction, while another is isolated. The separation of these electrodes allows either a current to flow, a potential difference to form, or a change in resistance to take place between the two electrodes.

- **Potentiometric Sensors -** utilise the effect of the concentration of a target species on the equilibrium of redox reactions occurring at the electrode-electrolyte interface, in an electrochemical cell. Such reactions may encourage the development of a potential difference. This potential may then be measured in order to determine the concentration of the target species.

- **Conductometric Sensors -** measures the change in conductivity of electrolyte in an electrochemical cell, brought about by a change in concentration of a target species.

- **Optical Transducer -** measures the interactions between various forms of light or electromagnetic radiation and a target chemical species by detecting the modulation of some property of the radiation. These modulations include intensity, polarization and velocity in a medium.

Of all the chemical sensors, tranducers are the least expensive and most commercially available. Most electrical and electrochemical transducers are better suited to lab measurements than in situ measurements in a nuclear cave, as they are difficult to transport. This would mean that a mobile robot within a cave would need some form of sample extraction in order to use such a sensor; as is discussed for application in the oil industry by Heyer [101]. If a robot were capable of taking samples, this method would give the most accurate results for chemical sensing.

3.8 Tactile Sensing

Tactile sensing is a useful modality inside a nuclear cave. This is because there is little light and so surface profiles are hard to generate using standard imaging; tactile sensors are capable of performing this task regardless of lighting. In addition, tactile sensors could be useful as contact sensors for collision avoidance for a mobile robot.

This section will examine: piezoelectric sensors, capacitive touch sensors, whiskers and optical sensors.

3.8.1 Piezoelectric Sensors

Piezoelectric sensors utilise three films laminated together; the top and bottom film are both piezoelectric with the middle film being used for acoustic coupling. The softness of this middle film determines the sensitivity of the device and the operating range. An AC voltage drives the bottom film. This voltage causes mechanical vibration which is mirrored in the upper film and when force is applied, the vibration changes. This change is read by a demodulator and appears as an output variable voltage. Such a sensor is capable of responding to deformities as small as 50μm in size.

Piezoelectric sensors have been utilised in robotics on end effectors to determine the shape and size of objects [133]. In addition, they have been designed to be used as robotic prosthetic fingers [59]. The ability to sense small deformities would allow for use in a nuclear cave to examine the surface structure of elements within.

3.8.2 Capacitative Touch Sensors

A capacitive touch sensor relies on the applied force changing the distance between the plates of a parallel plate capacitor or varying the surface area of a coaxial capacitor. In general, two conductive plates are separated by an elastomer dielectric, which is best designed to have a high permittivity. When contact is made this dielectric is compressed and the plates of the capacitor are brought closer together, changing the capacitance. This capacitance change is then measured and translated to a resultant force.

As with piezoelectric sensors, capacitive sensors have been used to replicated human touch characteristics in robotics [176] [153] [40]. Though the ability to sense the surface and material has been examined, there seems to be little work examining the use of capacitive sensors on mobile robots. This could mean that attaining a surface profile is difficult to achieve outside of arm-like manipulators.

3.8.3 Whiskers

As a nuclear cave contains no natural light, whiskers could prove useful for mapping and object characterisation. In nature, whiskers are used frequently to determine distance, shape and orientation of objects. For example, the sensitivity of a rat's whisker may be compared to that of a primate's finger [150].

In general whiskers can be used to gather three-dimensional information about an object. This includes the generation of surface profiles. Most artificial whiskers rely on the bending of the whisker being registered by a piezoelectric element [205]. It is also important to have the tip of the whisker be the sole point of contact with the object in order to reduce error, hence it is useful to have the whiskers pre-bent.

Whiskers have already been implemented in mapping algorithms [270]. In this work mapping was achieved through tactile whiskers. The robot could either be used in a learning mode in which follows a preplanned path which is update once obstacles are encountered; or mapping mode, where the robot moves systematically though an environment to create a map that is later used for path planning. This task is similar to generating a map in an unknown nuclear environment. It seems that whiskers are likely the best solution to tactile sensing within a nuclear cave. This is due to their ability to generate surface profiles and maps, without the need for complex manipulator rigs.

3.8.4 Optical Sensors

Optical sensors operate by using state-of-the-art vision sensors to examine the change in light intensity or refractive index attributed to mechanical contact, pressure, or directional movement. The requirement for light emitters and detectors generally adds bulk to the design of such sensors, which can be viewed as a drawback. Despite this, optical sensors provide high spatial resolution, simple wiring and robustness to electrical interference [180].

Optical sensors have been used for a variety of task including dextrous object manipulation [20], contact sensing [262] [109] and measurement of normal forces [100].

Another method for optical tactile sensing, using only a vision camera is provided by the TacTip sensor [244] [257]. The TacTip uses a camera to view the movement and interaction of many 'papillae' pins. From the motion of these pins the sensor can resolve pressure force, shear force, edge detection and shape detection. It may be possible to mount such a sensor on a mobile robot and use it to move perpendicular to a surface in order to examine its structure.

Overall, optical tactile sensors can provide detailed analysis of surface structure and applied force. It could be possible to mount a sensor on a mobile robot tasked with exploration and mapping of a nuclear cave environment.

3.9 Chapter Summary

The aim of this chapter was to provide an overview of sensors that might be used to characterise a nuclear cave environment; in particular sensors were assessed based on their suitability for transport by a small swarm of heterogeneous robots carrying out the task of exploration and mapping. The sensory requirements were defined by an industrial expert. Having reviewed each area, the following devices are suggested for their respective sensing modality:

- **Distance:** *LIDAR sensor* – this sensor can generate dense point cloud maps that can be used to visualise and navigate a nuclear cave environment
- **Radiation:** *Scintillator detector* – this sensor has already been used by robots to scan for radiation and can generate real time maps
- **Pressure:** *Piezoresistive sensor* – this sensor is easily integrated into circuitry, unaffected by radiation and effective across a wide temperature range
- **Humidity:** *Capacitive sensor* – this sensor can be made to have fast response times and has been miniaturised to fit onto RFID tags for monitoring humidity in shipping containers
- **Image Capturing:** *Cheap camera that is disposable* – such a camera, coupled with a light source, should be capable of relaying images of the nuclear cave to aid with decommissioning and is cheap and small enough to be taken into the nuclear cave and later disposed of
- **Temperature:** *Thermistor* – this sensor has shown to be used by robots for following temperature trails, and is capable of accurately measuring temperature within a nuclear cave
- **Chemical:** *Electrical Transducers* – chemical sensing seems to be the most difficult to achieve remotely, it is suggested that robots be used to attain samples that may be examined in laboratory conditions by electrical transduction, or more complex spectroscopy
- **Tactile Sensing:** *Whiskers* – these sensors have been used to generate surface profiles and maps of low light environments, lending themselves well to the nuclear cave environment

Overall it has been shown in this chapter that there exist multiple sensing devices that are capable of characterising a nuclear cave environment; suggestions have been given for the most applicable of these devices. Due to the size of the entry hole of the nuclear cave environment, it is likely that these sensors would need to be distributed among a swarm of heterogeneous robots.

Sensing is one of three key elements that a heterogeneous swarm must possess in order to characterise a nuclear cave environment; the remaining two are locomotion and control. Combining these three fundamentals, a heterogeneous swarm is able to perceive, plan and move within its environment. The next chapter will examine the potential locomotion strategies available to a heterogeneous swarm. Chapters five and six will examine the control of a heterogeneous swarm.

Chapter 4

Locomotion Strategy

Locomotion is a diverse and interesting topic of study. Without it, robots would not be capable of movement and would only be able to monitor their immediate surroundings. The aim of this thesis is to highlight the three key areas that must be combined to create a mobile robotic swarm capable of carrying out exploration and mapping in a nuclear cave environment. These three areas are: sensing, locomotion and control. This chapter will focus on locomotion.

For mobile robots seeking to traverse complex environments, the selection of an appropriate locomotion strategy is important. This is especially true when designing a heterogeneous swarm for exploration of an unknown nuclear cave environment; as when designing the swarm, it is possible to implement multiple locomotion strategies, spread amongst the swarm, to overcome the challenges presented within a nuclear cave. In order to optimally design the locomotion profile of such a swarm, it is first important to fully understand the strategies available within a nuclear cave. The focus of this chapter is to provide an analysis of the various locomotive strategies that are offered to robots within a nuclear cave environment and present the novel design of a supplementary modality, in the form a detachable grappling hook [27].

This chapter will begin with a review of the various locomotion strategies that exist in mobile robotics and discuss their application to the exploration of a nuclear cave environment. The locomotion strategies are split into four distinct categories which will be examined in turn: ground locomotion strategies; wall-climbing robots; flying robots and supplementary modalities. Experiments conducted to compare the most promising ground locomotion strategies will then be outlined. Finally, the design of a novel detachable grappling hook will be presented [27].

Figure 4.1: Shows a small whegged robot, capable of surmounting obstacles greater than the wheg diameter [137].

4.1 Ground Locomotion Strategies

A nuclear cave environment presents many challenges to robots seeking to traverse its floor. For example, there are slumps and channels on the floor of the cave; debris from previous excursions into the cave; an unknown floor geometry; leakages caused from damaged pipe work and inclined floors. This means that in order to navigate the floor of a nuclear cave, a heterogeneous swarm is preferable as it can provide varying locomotive capabilities to overcome a range of obstacles.

This section aims to outline the various ground locomotion strategies that are applicable to a nuclear cave environment. In chapters five and six, a control architecture designed for exploration of the floor of the nuclear cave will be presented.

This section will explore: wheeled robots, legged robots, spherical robots, tracked robots and metachronal motion.

4.1.1 Wheeled Robots

Wheels have been used for centuries to make vehicles mobile. There are now many examples of wheels used in mobile robots. This is because wheels are simple to implement and relative to the speed of travel, they are very efficient [113]. In addition, wheeled robots are considered easy to control, especially when implementing a differential drive.

The ability to exchange wheels is of great benefit, as it allows different environments to be tackled by the same robot. One such wheel is the so called wheel-leg or 'wheg', an example of which is shown in work by Morrey et al. [175]. These three spoked wheels, shown in figure 4.1, allows a robot to traverse obstacles of greater height than a conventional wheel. Thus permitting a small robot to overcome the debris found in a nuclear cave.

Overall, wheeled locomotion provides a well-studied, simple to implement, energy efficient solution for mobile robots. One downside of wheeled or whegged robots is that in order to surmount larger obstacles, a larger wheel or wheg is needed. Due to the size restriction imposed by the available access hole in a nuclear cave, the diameter of the wheels or whegs is limited; this innovates supplementary solutions to locomotion in order to increase obstacle clearance capabilities, which will be discussed later in this chapter.

4.1.2 Legged Robots

Legs are found frequently in nature, due to their adaptability over rough terrain and ability to overcome obstacles. It is natural then that legs would be studied as a locomotion strategy for robots. However, legs require complex actuation to operate, and intelligent path planning in order to place the feet.

Path planning is important to realise the advantages of legged locomotion, in order to place the feet in positions other locomotion strategies might not be able to achieve [48]. However, a large quantity of sensors are required in order to make the decision where best to place a foot. This is exemplified by BigDog, which has over fifty sensors in order to comprehend its environment [197].

Stability is important when establishing a legged locomotion strategy. Stability falls into two categories: dynamic stability and static stability [113]. A statically stable robot typically moves slower and can stop at any moment during operation, whereas a dynamically stable robot may move faster but if it is halted at the wrong time it will fall. Stability can be improved by increasing the number of legs the robot walks upon. A common highly stable leg configuration is the 6-legged hexapod [99].

Legged locomotion is well suited to the obstacles that are encountered during operation within a nuclear cave. However, difficulty would arise when trying to miniaturize the actuation and control systems, to fit through the 6 inch (15cm) diameter entry hole.

4.1.3 Spherical Robots

Spherical robots provide a number of locomotive benefits [55]:

- Incapable of landing the wrong way up
- Holonomic
- Can be designed to be robust against falling
- Can be made small

However, these benefits come at the cost of weaknesses in obstacle clearance and controllability on inclines.

Spherical robots may be built in several different ways, the most common of which are pendulum and wheeled designs. Pendulum designs require that the centre of mass be displaced

Figure 4.2: Shows the process by which a spherical, or circular, robot may deform to generate jumping motion [231].

to move the robot [117]. In contrast, wheeled spherical robots utilise wheels within the robot in order to drive the motion [97].

It is possible to give spherical robots the ability to overcome larger obstacles by deforming their shape rapidly to allow jumping in the air. In work by Sugiyama, a robot is described that can elastically deform its shape memory alloy shell and release the stored energy in order to jump, as shown in figure 4.2 [231]. This then removes one of the most significant hindrances to spherical locomotion: obstacle clearance.

Spherical robots provide good mobility within a nuclear cave due to their holonomic nature, and rapid shape deformation can obviate the disadvantage of poor obstacle clearance. In addition, their ability to fall from height without damage or fear of inversion makes them easy to deploy from the entry holes in a nuclear cave.

4.1.4 Tracked Robots

Tracks feature several connected plates actuated by the movement of two or more wheels, enabling movement over rough terrain. Tracks provide high turning mobility, through driving two tracks in opposite directions, as well as increased traction. The disadvantages of tracks are lower top speeds, greater mechanical complexity and the fact that loss of a single-track pad can cause the vehicle to become immobilized.

The ability of tracks to overcome obstacles can be increased through the use of semi-autonomous flippers [182]. This involves the use of flippers to maintain a pose relative to the ground so that the robot is able to remain stable whilst overcoming an obstacle. Alternatively more complex climbing tasks may be achieved through the implementation of multiple tracks [243]. These multiple tracks are individually actuated and used to climb a flight of stairs.

It is clear that tracked robots could be useful in a nuclear cave environment. This is due to their adaptability to rough terrain and ability to maintain a high level of traction, which aids with the surmounting of obstacles and the inclined floor found within the cave. However, assuming the centre of mass is designed to be central to the robot, tracks may only surmount channels that are half the length of their tracks or less. If a gap is larger than this then the robot will fall into it.

Figure 4.3: Shows the OmniTread robot utilising its serpentine design to overcome debris [6].

4.1.5 Metachronal Motion

Metachronal motion refers to a wave like motion used to propel a robot. There are two types of metachronal robots, the first is serpentine robots. These are robots that are made in segments but that employ a secondary method of locomotion to produce movement. The second is snake like, these robots use only ground contact and metachronal motion to move.

Metachronal robots can move in tight spaces due to their inherent flexibility brought about by their segmentation. In addition to this, it is possible to make a metachronal robot long, but with small diameter. This would enable such a robot to have multiple sensors for exploration of unknown environments, like a nuclear cave.

A large disadvantage of metachronal robots is that in order to make best use of their segmented structure, the links between segments should be actuated. The best power to weight ratio that is available is provided by pneumatic actuators [91]. These require a compressed air supply and are complex in design.

Most metachronal robots appear to be serpentine, as this is more energy efficient. One such robot is the Omnitread robot, shown in figure 4.3 [6]. This utilises tracks on all sides of the robot to propel it forwards, whilst actuated joints allow for the robot to move over larger obstacles. The stiffness of these joints is controlled using a 'proportional position and stiffness control', which minimizes the quantity of compressed air used.

Another example, from the same developers, is the omnipede robot [144]. This is also a serpentine robot that uses legs as its primary source of locomotion.

It seems metachronal robots could work well in the nuclear cave environment. This is because they can climb obstacles and fit through small spaces, such as the entry hole. However, the benefits that metachronal motion may provide do not appear to outweigh the complexity required in their design. In addition, leakages on the floor of the cave might cause issues if the robot is not water tight.

4.2 Climbing Robots

Climbing robots provide a stable exploratory platform for gathering data within a nuclear cave environment. The walls of a nuclear cave may show signs of degradation and decay, in addition to the multiple pipes and pressure vessels present in the cave. Climbing robots are capable of examining these areas, as well as using the various structures within a nuclear cave to gain a better view of the landscape as a whole.

This section aims to outline the various climbing locomotion strategies that are applicable to a nuclear cave environment. This section will explore: biomimetic climbing, electrostatic adhesion, electromagnetic climbing, climbing by suction and climbing with gripping equipment.

4.2.1 Biomimetic Climbing

Robots that use biomimetic methods to climb walls generally try to imitate the practices found in nature. Most robotic examples recreate the climbing mechanisms of geckos, along with some insects and spiders.

Geckos adhere to surfaces by exploiting the Van der Waals force, utilising small hairs to increase surface contact. This allows them to climb on almost any surface. There have been attempts to replicate this climbing method [167] [129]. However, the complex structure of the gecko foot is difficult to replicate.

Spines are used by some spiders and insects. This method of wall climbing relies on exploiting small surface defects as points that may be hooked onto with small spines. Spiny bot is inspired by this method and uses multiple spines to climb vertical walls [128].

Overall the gecko-like robots could prove useful within a nuclear cave. This is because they can climb on multiple surfaces, without causing damage, and hence surpass the obstacles protruding from the walls. However, they can usually carry only a small payload which decreases their sensing capabilities. Spines could make for a promising locomotion strategy but can be limited by surface roughness, therefore making them less desirable for climbing the metallic structures within a nuclear cave.

4.2.2 Electrostatic Adhesion

Electrostatic adhesion relies on exploiting the Van der Waals force, like the gecko's foot. However, in this case it is achieved through the process of electrostatic induction.

This process requires a very low power output to generate the adhesion. An example of this is the electrostatic clamp, which is able to stay adhered to a surface for up to a year [192]. This technology can be utilised to make a mobile robot. If the electro-adhesive material is made into a pair of tracks then a robot will be able to move around on a wall [46]. The benefit of this method is that a robot may be able to adhere to any surface, even in the presence of dust. The downside of this method of locomotion is that most existing robots are proof of concept rather than fully usable prototypes.

Electrostatic adhesion could be useful in a nuclear cave, as it is possible to adhere to most surfaces. However, the need to keep a low profile to prevent falling off the wall means that the robot needs to be concomitantly wide. This would limit the turning radius, which would make it very difficult to move in the obstacle-ridden environment. In addition, the high voltages needed to adhere to surfaces could prove dangerous to other electronic equipment present in the cave, or on board the mobile robot.

4.2.3 Electromagnetic Climbing

This method makes use of the electromagnetic force imposed between ferromagnetic materials and a magnet to adhere to surfaces. This generates a very efficient method of adhesion as, if permanent magnets are used, then no power is needed to adhere to a wall or ceiling.

Robots using magnetic adhesion have previously been used for inspection tasks in delicate environments [82] . This is because they are reliable and relatively fast when coupled with wheels or tracks.

The other option is to use electromagnets that are capable of supporting large payloads [93]. This is usually coupled with legged locomotion as electromagnets may be turned off each time the robot takes a step.

Unfortunately, within the nuclear cave there is a paucity of ferromagnetic surfaces and so electromagnetic adhesion is less useful. However, it may be useful for other complex environments, or even other nuclear environments.

4.2.4 Climbing by Suction

Suction is the most common form of adhesion for wall climbing robots. The problem with suction is that if a small gap is created in the seal then the entire suction cup loses adhesion. This risk is somewhat negated by the use of multiple legs, and has already been implemented in nuclear inspection [30].

The problem with using legs is that they are slow and cumbersome. An elegant solution to this problem is the Alicia 3 robot [145]. This uses a suction plate and tracks to adhere to the surface but remain highly mobile. This is an example of active suction, if instead the tracks are fitted with passive suction pads then the robot becomes more energy efficient [126].

Sliding suction cups and Vortex Regenerative Air Movement (VRAM) systems appear to be the most mobile implementations of vacuum adhesion. They both allow for the robot to remain highly mobile, whilst adhering to the surface with a suction cup that maintains negative pressure [194].

Overall suction is a reliable and well tested way of adhering to walls in cave. The downside is the amount of power it draws to maintain a negative pressure, and the fact that imperfections in the wall could cause failure in the seal. If the robot were to lose suction during a mission in the nuclear cave, then it may become irretrievable. This would then cause the robot to become nuclear waste that requires disposal.

4.2.5 Gripping Equipment

This method of locomotion relies on grasping equipment deployed to grip pipework and other protrusions in the environment. This seems a prudent choice for locomotion inside the cave, due to the complex network of pipes that could be used to navigate. However, complex path planning and actuation is required to utilise pipe climbing.

Gripping equipment has been implemented on the ROMA robot [13], which is able to move through networks of scaffolding, similarly the Shady3D robot [267] is able to climb trusses on steel structures. Another possibility for a robot is to move around the outside of pipework. This has been achieved using a modified Stuart-Gough platform, though a method for autonomously attaching to the pipes has not been explored [5].

In general, the difficulty of miniaturizing the gripping equipment so that it may be deployed into the nuclear cave, prevents this method of locomotion being optimal.

4.3 Flying Robots

Flying robots allow for exploration and mapping in three dimensions. Within a nuclear cave environment, this would allow for the data from upper regions of the cave to be gathered. However, it also presents a challenging arena for airborne robots to locomote within: there is the complex network of pipes, the geometry of which is likely to be unknown; large pressure vessels; support structures for both pressure vessels and pipework, and an initial negative pressure.

This section aims to outline the various flying locomotion strategies that are potentially applicable to a nuclear cave environment. This section will describe: lighter than air vehicles (LTAV); fixed wing robots; ornithopters; and finally, rotorcraft.

4.3.1 Lighter Than Air Vehicles

Lighter than air vehicles (LTAVs) rely on the use of gas bags filled with lighter-than-air gas in order to carry their weight, with a secondary propulsion mechanism to generate motion. LTAVs are very efficient compared to other flying methods as they do not require energy to stay in the air. As well as being energy efficient LTAVs also have the advantage of not significantly disturbing the environment they are operating in, coupled with the ability to remain stationary in the air for data collection. These qualities are exemplified by environmental monitoring missions [78]. In addition, the negative pressure found within the nuclear cave could be used to 'suck' the LTAVs into the cave, thus giving an efficient deployment method.

The largest downside of LTAVs is their size. If an inert gas such as helium is used then, in order to lift a 200g payload a 1.3m diameter balloon is needed [146]. This size is not feasible inside a nuclear cave as it would create a turning radius greater than the space between many adjacent pipes. Another disadvantage of LTAVs is that they have high inertia while moving, and hence are difficult to control [103].

Overall LTAVs would make a very useful scanning tool in a nuclear cave if they could be made small enough, but with current choice of inert lighter than air gas this is not possible.

4.3.2 Fixed Wing Robots

Fixed wing aircraft use aerofoils to generate lift, however this requires continuous airflow over the wings. On first glance fixed wing aircraft do not seem appropriate for nuclear cave environments. However, the energy efficient flight duration that fixed wings can provide is very useful for longer mapping missions.

Despite larger wingspans providing greater efficiency, some small, fixed wing UAVs have been designed (wingspans of 32 inches) [196]. This would still be difficult to maneuver through the cave. If the fixed wing aircraft could be made to hover, then it could move through small gaps carefully in addition to taking more detailed sensor readings. Controlled hovering of a fixed wing aircraft is possible, provided the thrust to weight ratio of the propellers and aircraft is greater than one [92].

Overall in a nuclear cave environment it is probable that a fixed wing aircraft would collide with the complex pipework. This is unless the aircraft is made to hover, in which case the energy efficient benefits of a fixed wing aircraft are not being fully utilised.

4.3.3 Ornithopters

Ornithopters are vehicles able to stay airborne through the ‘flapping’ of their wings, for example birds and some insects. Flight is achieved by continuously changing the angle of attack of the wing through flight to achieve maximum lift. This change of angle can be achieved actively, as it is in birds, or passively, as it is in most insects.

An advantage of ornithopters is that they are capable of vertical take-off and landing (VTOL). This could be utilised in the cave by having a ground vehicle equipped with wings. This would allow efficient exploration of the ground, coupled with the ability to be able to fly to overcome larger obstacles and gain a bird’s eye view.

A further advantage of the ornithopter is that it can be miniaturized [260]. A 13 gram ornithopter, shown in figure 4.4, has been designed with propellers to control heading and a gyroscope to estimate attitude [10]. These implements are used to track an infrared beacon. This shows that an ornithopter may be made small enough to enter and operate within a nuclear cave.

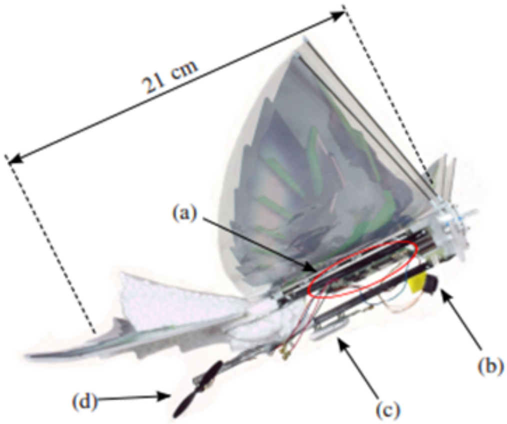


Figure 4.4: Shows the 13 gram ornithopter with (a) Control electronics, (b) a visual sensor, (c) a battery, and (d) a propeller [10].

As well as use for flying it has been found that wings may be used to assist running [189]. In this work a robot is presented that uses wings to double the maximum running speed previously achieved by a legged robot and triple the incline it was able to climb.

Despite their advantages, ornithopters have a messy flight path. This is problematic in a nuclear cave both because it makes sensor readings poor and because the erratic nature of the flight could cause collision. Thus ornithopters are unlikely to be an optimal solution to flight in a nuclear cave.

4.3.4 Rotorcraft

Rotorcraft rotate their aerofoil in order to generate lift. Advantages of rotor craft include VTOL, their ability to hover and their ability to fly slowly. However, this comes at the cost of design complexity when compared to other aircraft. In addition, VTOL aircraft suffer from reduced endurance as they are unable to glide and thus save energy like fixed wing aircraft.

The rotor craft most likely to be useful for nuclear cave exploration is the quadcopter. This is because it is stable, well researched and easily controlled. Most quadcopters feature an IMU to estimate pose, and when this is coupled with distance sensors a high level of obstacle avoidance is achievable [208].

However, if a quadcopter is not able to avoid a collision it is likely that it will fall out of the air, thus a rotorcraft that is robust against collisions becomes useful within the complex nuclear cave environment. The GimBall, is able to fly through a forest with only a heading and survive many collisions without failure [29]. This is achieved using a light weight outer shell that absorbs energy from collisions, shown in figure 4.5.

Rotorcraft appear to be the best airborne locomotion strategy for traversing a nuclear cave. This is because they are stable, controllable and available. In addition, there exist solutions

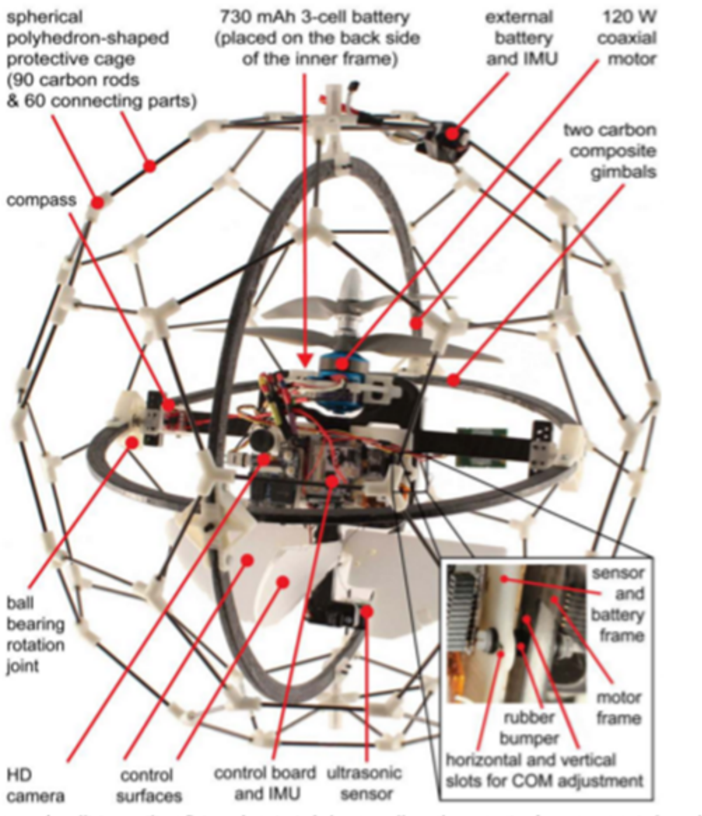


Figure 4.5: Shows the GimBall, a rotor craft able to fly through complex environments and survive multiple collisions [29].

robust against collision. These properties allow them to both gain accurate sensor readings and navigate through the complex network of pipes.

4.4 Supplementary Modalities

The size grain hypothesis says that as an object becomes smaller it becomes harder to overcome obstacles. Thus, supplementary locomotion modalities can be used in order to surmount these obstacles. These locomotion strategies are ‘supplementary’ as on their own they are unlikely to be viable, but are capable of increasing the performance and capability of existing locomotion strategies.

This section aims to outline two such supplementary modalities: first, hopping robots will be described; second, grappling robots will be examined. Later it will be shown that grappling presents a useful method of locomotion within a nuclear cave, due to large number of potential grappling targets. This will include the presentation of the design for a novel detachable grappling hook [27].

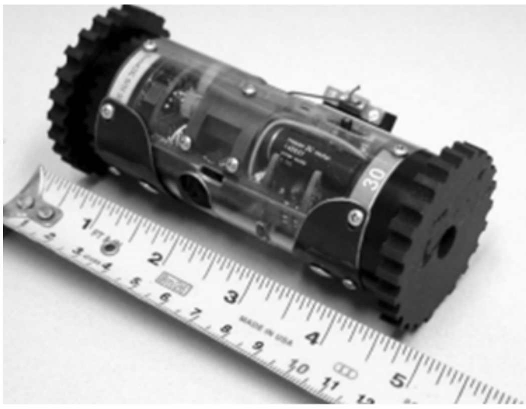


Figure 4.6: Shows the scout robot, a small robot capable of jumping 35cm into the air using a bent spring [229].

4.4.1 Hopping

There are various strategies employed to generate a hopping motion: a coiled spring, a bent spring, the use of momentum or an elastomer design [7].

A common obstacle encountered in manmade structures is the staircase. This presents an almost insurmountable challenge to, for example, a small wheeled robot. However, if hopping is introduced this task can be achieved. The scout robot, shown in figure 4.6, is one such example [229]. Using a bent spring that is retracted using a winch the scout can hop up to 35cm into the air and scale a staircase one step at a time. The scout robot is only 12cm long, and so can jump almost three times its own length. This method could be utilised to overcome large debris piles in a nuclear cave, or to cross wide channels.

Jumping mini whegs provide another example of small robots surmounting obstacles larger than themselves [137]. These robots employ whegs to move around the uneven test surface and climb smaller obstacles. When a larger hurdle is encountered a spring powered hopping mechanism is employed.

The difficulty with hopping robots is that once the robot has left the ground, they are hard to control. This can lead to an inversion on landing, or a misjudged landing position. One way to counteract this is using a dynamic tail [272]. This can produce a counter torque in order to keep the robot heading constant in the air, similar to the method employed by lizards.

Overall hopping makes for a useful supplementary locomotion strategy within a nuclear cave due to the increased obstacle clearance, allowing the robots to overcome the channels, sumps and debris present on the floor of the cave. The main drawback is that if the motion is uncontrolled, it can lead to the robot becoming immobile. Additionally, the nuclear industry needs to satisfy very precise regulations. Therefore often an uncontrolled robot, which therefore is unreliable in terms of repeatability and prediction, won't be considered.

4.4.2 Grappling

If a ground robot is able to grapple and raise itself into the air, then it is both able to overcome obstacles and get an aerial view of its surroundings. This is useful in a nuclear cave as it will allow a robot to attain more information about its environment and remove the 2D restriction imposed by the use of ground locomotion.

To date, few grappling robots exist. One example is the HandBot from the Swarmanoid project [65]. This utilises a magnetic grappling hook that supports the robot's weight whilst its arms are used for more precise climbing tasks. The difficulty with this method is that there are few ferromagnetic surfaces within a nuclear cave.

The scout robot, mentioned earlier, can receive a grappling hook mounting [68]. This enables the scout robot to climb over debris whilst moving through fallen buildings.

Asano et al. explore three interesting designs for detachable grappling hooks [8]. The first of these designs features a gripper at the end of a line, which must collide in a specific orientation to successfully grapple. The second design features a clamp. This can latch onto cyclindrical pipework and is the design most akin to that presented at the end of this chapter, however it was found that the design was too heavy to be launched reliably. The final design presented by Asano et al. features an extendible hook. This features a bend that can be extended by a wire in order to detach from its target, though this is too large for use in a nuclear cave.

A final option for grappling is to use pre-installed tether points [227] [80]. However, as the nuclear cave is inaccessible to humans the installation of such points is difficult.

The grapple is an excellent and underexplored concept. The difficulty is repeatability. Making a detachable grapple appears to be challenging, except for magnetic grappling. A grapple would be useful in a nuclear cave due to the prevalence of pipework, which presents an ideal target for a grapple. Later in this chapter the design of a novel detachable grappling hook for use in a nuclear cave environment will be explored [27].

4.5 Comparing Ground Locomotion Strategies

Ground locomotion is important within a nuclear cave as it provides the most likely form of entry. This is because the entry hole can only be up to 15cm in diameter and ground locomotion methods are most easily miniaturised.

Having reviewed the literature covering the various locomotion strategies, it was considered prudent to compare the most promising ground locomotion methods through experimentation. The locomotion strategies compared are wheels, tracks, whegs and spherical locomotion.

This section aims to outline the experiments undertaken to compare wheeled, tracked, whegged and spherical locomotion strategies and thus make suggestions on the best strategies for a heterogeneous swarm traversing a nuclear cave environment. Thus, this section will detail: the

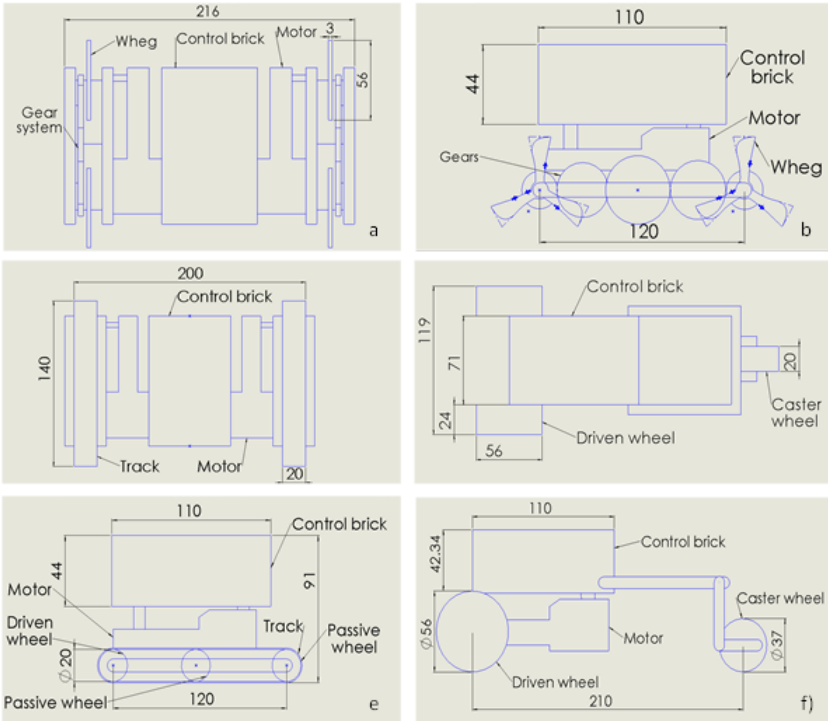


Figure 4.7: Shows the layout of each robot used; all units are in mm. The front of the robot is on the left for side views and upwards for birds eye view diagrams. a) & b) show the top and side views of the whegged robot respectively. c) & e) show the side and top view of the tracked robot respectively. d) & f) show the side and top view of the wheeled/ speherical robot respectively.

robotic platform and design of the comparative robot; the methods and metrics for comparison; and the results from the experiments.

4.5.1 Robotic Platform and Robot Design

In order to compare the different locomotion strategies, first a suitable robotic platform was required. It was important that the robot is reconfigurable, so that it could be used to test the various locomotion strategies. In addition, it was desirable for the robot to be low cost and readily available.

The LEGO Mindstorm EV3 platform fulfilled all these requirements. This robot has been widely used in education and is capable of an array of configurations and control modes [246] [131]. The Mindstorm kit includes two stepper motors for propelling robot designs, a control brick, gears and support structures; allowing rapid reconfiguration.

The layout of each design is shown in figure 4.7. The wheeled and spherical robots utilised the same underlying design. To adapt the wheeled design to spherical locomotion, the robot was placed inside a spherical ball of diameter 32cm. The wheeled robot used two front wheels driven by motors, with a passive caster wheel at the rear. The whegged robot used two pairs of whegs, the front of each pair was driven by a motor. The rear whegs were connected to the driven whegs via gears, giving four-wheel drive. The whegs themselves were designed in SolidWorks and printed using a 3D printer. Finally, the tracked robot used two driven wheels at the front, with 4 passive wheels to ensure the track remains in place and holds its shape.

4.5.2 Methods for Comparison

The comparison was made through adapting criteria used by the National Institute for Standards and Technology (NIST). The selected criteria for comparison were gap width able to overcome, obstacle clearance and climbable incline. The test document states: "Test trials consists of 30 repetitions to demonstrate statistical significance to at least 80% reliability with 80% confidence. During the first trial within a particular apparatus setting, the test administrator may stipulate that the robot was dominating the apparatus at that setting after demonstrating the first 10 successful repetitions with no failures. However, if there are any failed repetitions, a second set of 10 repetitions is required. For a trial to be noted as statistically significant, no more than 1 failure in 20 repetitions, or 3 failures in 30 repetitions are allowed." [115]. These test methods were implemented for the locomotion comparison tests. The selected criteria were gap width, obstacle clearance and incline as these are the most important aspects of traversing a nuclear cave; due to the sumps and channels on the floor, the obstacles caused by debris and incline used to collect leakages in the centre of the cave.

In order to alter the obstacle height 10cm x 20cm pieces of acrylic were used, with thicknesses of 2mm, 3mm and 5mm. These varying thicknesses were stacked until the robot was no longer able to surmount them. The incline test was implemented using a 100cm x 60cm x 1cm piece of track. The start point and end point of the test were marked 65cm apart, 17.5cm from each end of the piece. One end of the track was attached to an arm whose height could be varied, the other laid on the ground. The angle of this slope was then varied in increments of 3 degrees until the locomotion method being tested could no longer climb the required 65cm portion. At this point variations of 1 degree were made to find the angle of incline, to the nearest degree, that the robot was able to climb. Finally, the gap width test was made using two 30x30cm platforms, of height 6cm. These platforms were moved apart 1cm at a time until the robot was no longer able to surpass the gap.

4.5.3 Results

The results are shown in figure 4.8. The whegs and spherical locomotion strategies were repeated with increased traction. The traction was increased using rubber on the outside edge of the whegs, and in a ring around the outside of the sphere. The extra traction was used because the performance of the lower traction was considerably less than expected; traction was determined to be the reason. This was due to the fact that when conducting the experiments, it was observed that the robot would not adequately grip the surface. An additional obstacle clearance test was

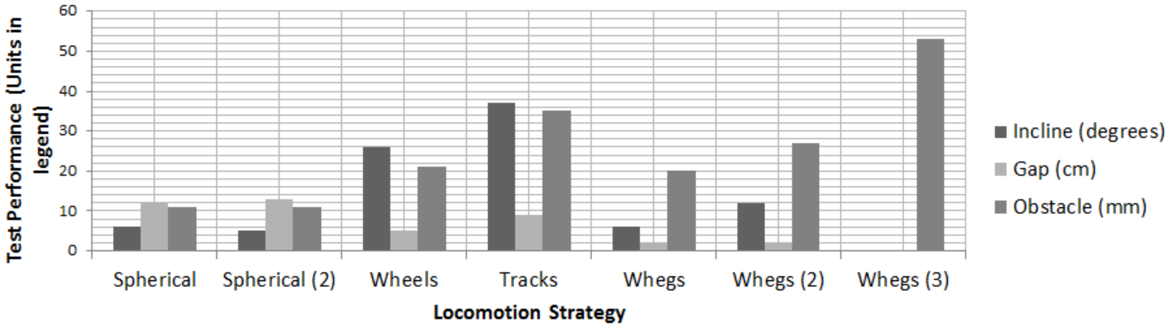


Figure 4.8: Shows the results from the comparative test. The (2) denotes addition traction tested on spherical and whegged robots. The (3) denotes an additional obstacle clearance test carried out with whegged robot with increased traction; in this test only the front whegs were required to surmount the obstacles.

carried out with the whegged robot with increased traction. This test focussed on the front whegs climbing the obstacle, rather than the entire robot overcoming it. This was implemented because the literature suggested that whegs are able to climb obstacles up to 25% larger than their diameter [175]. Despite this extra test, the whegs were still only able to climb obstacles of 51mm, compared to their 56mm diameter.

It was found that overall tracks perform best. This was due to their ability to overcome the largest obstacle and incline. This result is expected, as tracks offer the most traction when compared to the other locomotion strategies due to their contact area. However, the spherical robot was found to be capable of crossing the largest gaps, likely due to its large diameter. Interestingly, the additional traction added to the spherical and whegged robot only slightly increased performance.

Overall these experiments suggest that a combination of spherical and tracked locomotion strategies would give the best results when traversing the floor of a nuclear cave. If both types of locomotion were used together in a heterogeneous swarm then the inclines, sumps, channels and debris could be more easily surmounted in order to give the best area coverage for mapping of the nuclear cave environment.

4.6 Design of a Novel Detachable Grappling Hook

Having completed a review of the available locomotion strategies within a nuclear cave environment it was found that there was little work on robotic grappling. This method appears to be ideal for use in a nuclear cave environment, since the intricate network of pipes presents multiple grappling targets.

A robot equipped with a grapple possesses multiple useful features to aid in the characterisation of a nuclear cave environment. First, the robot would be capable of hoisting itself over obstacles in order to continue mapping otherwise inaccessible areas. Furthermore, once the robot has lifted itself off the floor it is able to attain a bird's eye view of its surroundings, which would aid the mapping process and could potentially be used as a localisation beacon for other robots. Finally, the slow ascent of the robot could be used to generate a scan of the environment. This could provide a three-dimensional map of the upper areas of the cave, without having to use complex flying or wall-climbing robots.

The most significant downside of traditional grappling hooks is that they are single use; they cannot be detached once grappled to a target. For a mobile robot seeking to characterise a nuclear cave environment this would be inadequate, as it would only be capable of surmounting a single obstacle. A potential solution to this problem is for a robot to possess multiple hooks, however this adds unnecessary weight and bulk to a robot. A more elegant solution is a detachable grappling hook, that may be utilised for multiple deployments.

This section aims to outline the design and testing of a detachable robotic grappling hook for use in a nuclear cave environment. Much of the work in this section was presented at the Mechatronics 2016 conference in a paper entitled 'A Novel Design for a Robot Grappling Hook for use in a Nuclear Cave Environment' [27]. This section will explore: the design of the detachable grapple; the experimental methodology used to test the performance of the grapple; and the results from the experimentation.

4.6.1 Design of the Grapple

The complex pipework present in the nuclear cave environment presents an excellent target for a grappling device. Earlier work examining the use of pipework and scaffold structures for robot locomotion has focussed on the use of grippers, or robots that surround the pipework and travel along it [273] [5]. The design of a detachable grapple to take advantage of pipework has not previously been examined.

The design of the grapple focussed on the following specifications:

1. **Grip size** - The grapple should be capable of clasping pipework of diameter 40mm and below
2. **Grapple mass** - The grapple should be lightweight (100g or less) so that it may be easily launched.
3. **Mass held by grapple** - The grapple should be capable of supporting a small robot, in this case the Foot-bot from the 'Swarmanoid' project was chosen as a reference [65]. This corresponds to a mass of 1.8kg.
4. **Detachability** - The grapple should be detachable, preferably remotely.

The design of the grapple utilises a ratcheted swivel and lock pin to allow for the grapple to be locked and released, similar to the design of a handcuff, as can be seen in figure 4.9. The lock pin is tensioned with a spring to prevent accidental release. The grapple can be manually

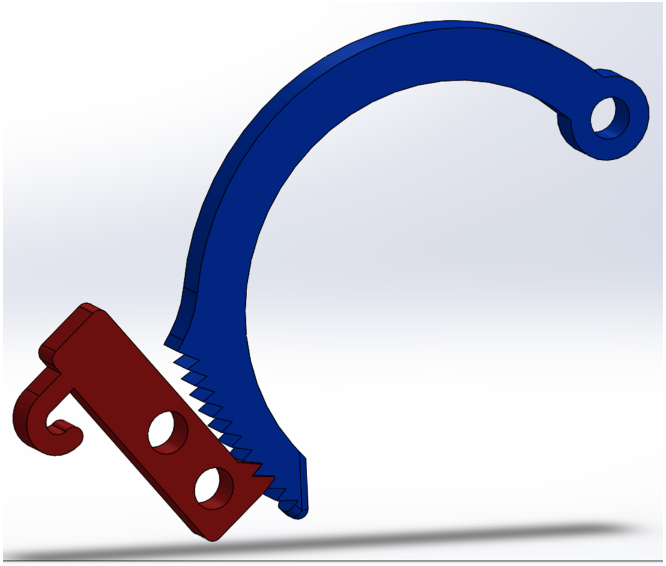


Figure 4.9: Shows the design of the ratcheted swivel (right) and the lock pin (left) that are used to secure the grapple to pipe work.

released using a small lever, in future designs it is hoped that this will be made possible using a solenoid switch, to better fulfil specification (4). A semi-circular recess was implemented, in cooperation with the swivel, to encapsulate and grasp the pipe. This was designed to have a diameter of 44mm, in order to align with specification (1). A counter weight was added on the opposing side to the locking mechanism. This is to encourage the grapple to stay level whilst in flight and once it has collided with its target. A two-dimensional technical drawing of the grapple is shown in figure 4.10, with a three-dimensional rendering in figure 4.11.

The main body and ratcheted swivel of the grappling device were produced using a 3D printer. The remaining parts were made from 3mm acrylic and laser cut. Pieces were fastened together using metal screws. In addition, metal screws were used as the pivot points for the ratcheted swivel and lock pins in order to reduce friction. Having constructed the grapple, it was weighed and found to have a mass of 80.86g. This is within the mass defined in specification (2).

The grapple is designed so that when it collides with a pipe, or any cylindrical target, the ratcheted swivel rotates. This causes the swivel to enter the locking system, which only allows rotation to occur in one direction. Due to this the grapple is secured to the pipe in a manner analogous to a hand cuff on a perpetrator's wrist.

Having designed the grapple, the next step was to test its capabilities. The experiments conducted on the grapple are outlined in the next section, with the results being presented subsequently.

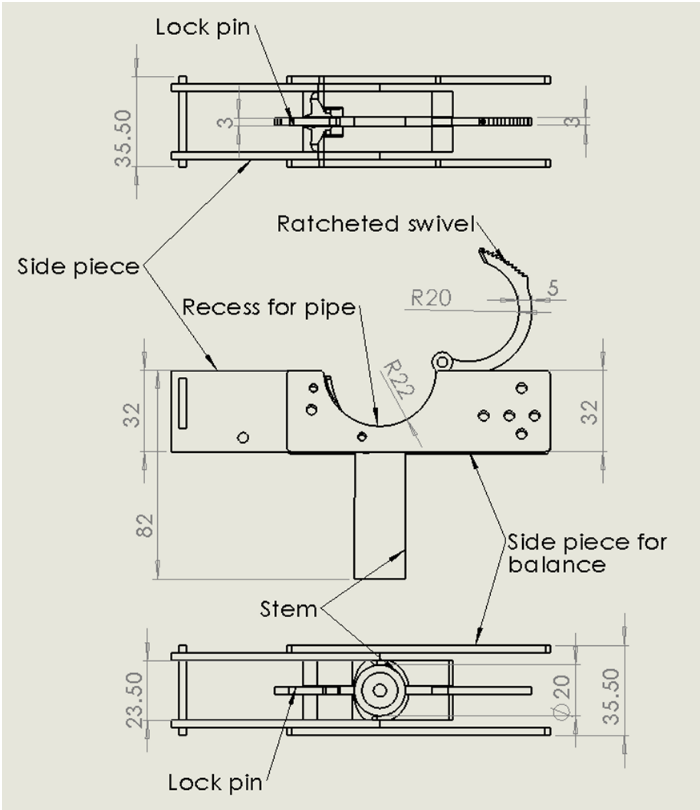


Figure 4.10: Shows the design and dimensions of the grapple in two dimensions.

4.6.2 Experimental Methodology

It was decided that the three most important metrics for assessing the grapple were: the maximum mass it can support; the consistency with which it is able to attach; and the minimum speed required to initiate grappling. These metrics were selected due to the desire for a grapple to support the weight of a robot and the need to reliably grapple during operation.

To assess the maximum mass the grapple is capable of supporting a section of pipe was suspended at a height of 30cm using a clamp and clamp stand; the pipe had a 2.5cm diameter and was 40cm long. The grapple was locked around the piece of pipework in a fully closed position. Following this, weights were suspended from the grapple using a slotted mass set with a hook. The mass was increased in increments of 50g, until the grapple failed and detached. The mass was then recorded and the test repeated. As with the locomotion experiments discussed earlier, the test was repeated 30 times in accordance with the National Institute for Standards and Technology (NIST) guidelines for statistical significance [115].

For testing the consistency of attachment and minimum activation speed it was decided that the grapple should be dropped, rather than launched. This was to enable experimentation to focus on the performance of the grapple and avoid compounding errors that may be produced by a launching device. A test rig was designed in order to reliably and repeatedly drop the grapple.

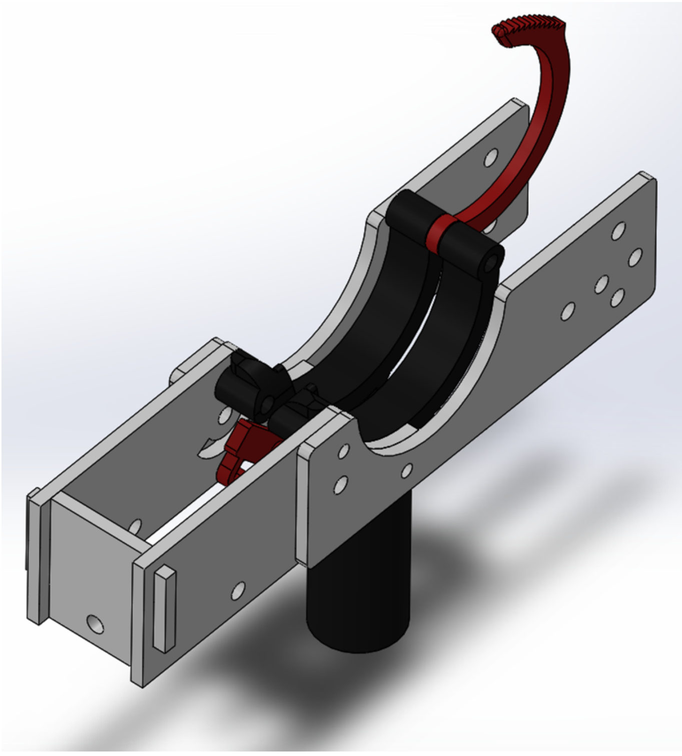


Figure 4.11: Shows a three dimensional rendering of the grapple's design. The red components show the locking mechanism, comprising of the ratcheted swivel and lock pin. In black the main body of the grapple is shown. Finally in white, the support (left) and balance (right) side and back pieces are shown.

This rig utilised a clamp holding the same section of pipe used in the mass test, suspended at a height of 15cm. To enable consistent dropping of the grapple a wooden piece was created with a cavity designed to hold the stem of the grapple. The height and angle of this wooden piece could be varied. A three-dimensional rendering of the test apparatus is shown in figure 4.12, with the two-dimensional technical drawing in figure 4.13.

The consistency of attachment was assessed from five heights: 7.5cm, 10cm, 12.5cm, 15cm and 17.5cm. The height was measured from the base of the wooden drop rig to the pipe. At each height the grapple was dropped onto the pipe. If the grapple was able to engage and hold itself in place then a success was recorded, if instead it fell, a failure was recorded. Thirty iterations were completed at each height, in keeping with the NIST test criteria [115].

To determine the minimum activation velocity of the grapple, it was first necessary to establish the minimum height that the grapple could reliably engage from. This involved progressively lowering the height of the drop rig, shown in figures 4.12 and 4.13, in increments of 1cm. This process was repeated until the grapple failed to attach. From this height the minimum activation velocity could be calculated using equation 4.1.

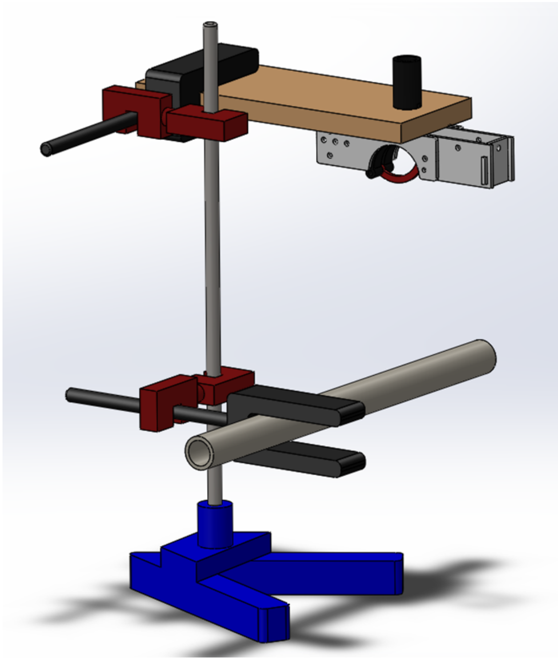


Figure 4.12: Shows the three dimensional layout of the test rig used for the consistency verification.

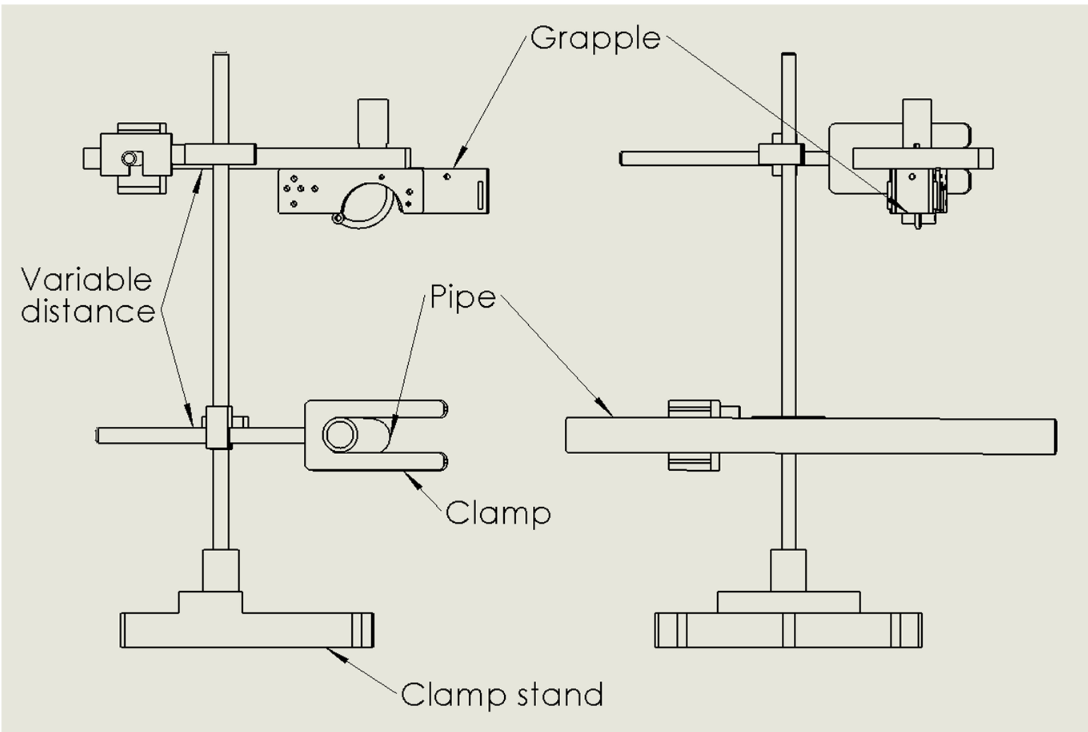


Figure 4.13: Shows the two dimensional layout of the test rig used for the consistency verification.

$$v = \sqrt{2gh} \tag{4.1}$$

Where v is the minimum speed, g is acceleration due to gravity and h is the minimum drop height. The results from these experiments will be presented in the next section.

4.6.3 Results of Grapple Experiments

On average it was found that the grapple could support a mass of 2.4kg, or thirty times its own weight. This means that the grapple fulfilled specification (3) and can support a robot of mass 2.4kg or less. Having a robot suspend itself from a grapple in nuclear cave would require little energy and allow the robot to attain a bird's eye view of its environment. This would enable a ground robot to generate a more complete map of a nuclear cave environment.

The minimum height which the grapple was able to secure itself from was found to be 6cm. This means that the minimum speed required to engage the grapple is:

$$v = \sqrt{2gh} = \sqrt{2 * 9.81 * 0.06} = 1.08m/s \tag{4.2}$$

The knowledge of this speed serves as a specification for the design of a future launching mechanism; a launching mechanism should be capable of achieving this speed at the point of contact between the grapple and its target. This would then allow for the grapple to be utilised by a ground robot in a nuclear cave environment.

The results from the consistency tests, from the five varying heights are summarised in table 4.6.3:

Drop Height (cm)	Successful Engagements	Percentage Success
7.5	26/30	87%
10	19/30	63%
12.5	20/30	67%
15	19/30	63%
17.5	3/30	10%

Table 4.1: Shows the results of the consistency investigation

These provide interesting results. It was found that when the grapple was dropped from a height of 7.5cm it was able to achieve a success rate of 87%. This shows the design of the grapple is capable of grasping pipework. The high rate of success is deemed to be a combination of two factors: the attainment of the minimum activation speed; and the predictable and consistent ballistic stability.

Consistency at heights of 10cm, 12.5cm and 15cm is stable around 65%. The reduced performance at these heights when compared to 7.5cm is due to the uneven weight distribution of the grapple. Attempts were made to remedy this instability using a counter weight. However, ballistic instability remained. In future it is hoped that the locking mechanism of the grapple could be centralised to reduce this effect. This instability was further realised at a height of 17.5cm, where only a 10% success rate was recorded.

The results of the grappling experiments provide proof of concept. It was shown that the grapple was capable of latching onto pipework and supporting the mass of a small robot. In the future, it is hoped that a detachable grapple could aid a heterogeneous swarm of robots in the task of exploration and mapping of a nuclear cave environment through providing a supplementary modality to overcome obstacles and attain a bird's eye view of the cave.

4.7 Chapter Summary

The focus of this chapter was to provide an analysis of the various locomotion strategies that are offered to robots within a nuclear cave environment and present the novel design of a supplementary modality, in the form a detachable grappling hook [27]. Having reviewed the literature on robotic locomotion, the most promising ground locomotion strategies were compared through experimentation using a reconfigurable LEGO Mindstorm EV3 robot. These strategies were: wheels, whegs, tracks and spherical locomotion. After conducting these experiments and examining the literature it was found that the most promising methods of locomotion within the cave are as follows:

- **Ground locomotion -** tracks and spherical robots
- **Wall-climbing -** utilising suction for adhesion
- **Flying -** rotorcraft utilising a gimball to prevent fatal collision
- **Supplementary modalities -** robotic grappling, to aid ground locomotion by allowing such robotics to extend into three dimensional exploration with low energy requirements compared to flying

It has been shown that there is a paucity of work focussing on the detachable grappling of mobile robots. Grappling is a useful tool in the nuclear cave environment due to the array of complex pipework presented as a target. In this chapter the design and testing of a novel detachable grappling hook was presented. It was found that the grapple could support the weight of a small robot and could be utilised to hoist a robot over obstacles within the nuclear cave. It is inherent in this method of transferring a ground robot into the third dimension of movement that it could be achieved with very low energy requirements compared with any flying methodology, and this could be a very significant advantage in this application domain.

Overall choosing the correct locomotion strategy within a nuclear cave is of paramount importance, due to the complex environment that it presents. The results of this chapter suggest that it would be prudent to use a combination of locomotion strategies to overcome the obstacles present within a nuclear cave. This motivates the use of a heterogeneous swarm of autonomous robots for the remote characterisation of a nuclear cave environment.

The design of such a swarm is comprised of three key components: sensing, locomotion and control. So far, chapter three has discussed the various sensing modalities available to robots within a nuclear cave and made suggestions on the most applicable. Chapter four has discussed the potential locomotion strategies that could be utilised to explore the nuclear cave. In addition, it outlined the design of a detachable grapple that could be used to increase the capabilities of ground locomotion strategies. In chapter 5 and 6 the control component will be discussed, with particular focus on the implementation of the 'reactive virtual forces' framework used to control a group of heterogeneous robots in the exploration and mapping of the floor of a nuclear cave environment.

CHAPTER 5

Reactive Virtual Forces

The three key characteristics that a swarm must possess in order to explore and map a nuclear cave environment are: sensing, locomotion and control. Having reviewed the sensory and locomotive modalities available to a heterogeneous swarm within a nuclear cave, it is next necessary to examine the control of such a swarm.

As was discussed in chapter one, potential fields have largely been used for spatial distribution, pattern formation and path planning [251] [19] [274] [223] [199] [124]. These applications are not unlike exploration: robots must move to specific areas of an environment whilst avoiding collision. These similarities give rise to a question – if spatial distribution, pattern formation and path planning may be dictated by potential fields, is it possible to employ the same method for exploration using a heterogeneous swarm? Answering this question is the focus of this chapter.

Some work has sought to answer this question with regards to a homogeneous team of robots [155]. However, heterogeneity appears to be an under-investigated topic within exploration and mapping. As discussed previously, a heterogeneous swarm is likely to be the best solution to the exploration and mapping problem presented by a nuclear cave due to the need for diverse sensing and locomotive capabilities. This diversity motivates the design of a control strategy capable of commanding a heterogeneous swarm in the exploration and mapping of a nuclear cave environment: this gave rise to the 'Reactive Virtual Forces' (RVF) framework described in this chapter.

The RVF framework treats robots as particles under the influence of virtual analogues of three of the four fundamental forces of nature: the electromagnetic force, the gravitational force and the strong nuclear force. These forces guide the exploration and mapping behaviour of a swarm of robots in conjunction with an occupancy grid representation for geometric mapping.

This chapter seeks to describe the design and testing of the RVF framework on a group of robots and compare its performance on a heterogeneous and homogeneous group of robots. This section is organised as follows: first, the occupancy grid representation used to define the map will be outlined; second, the forces utilised to guide robots in the RVF framework will be explained; third, the simulation design and experimental methodology will be described; fourth, the embodied simulations and associated experimental methodology will be highlighted; subsequently the results from these experiments will be presented; and finally, conclusions will be drawn.

Much of the work described in this chapter was presented at the TAROS 2017 conference, where it was shortlisted for best student paper [28].

5.1 Occupancy Grid Representation

The representation used to define a geometric map for the RVF framework was the occupancy grid. An occupancy grid divides an environment into discrete sub-spaces and stores the likelihood that each sub-space is occupied by an obstacle [77]. As a robot moves through the environment this likelihood is updated based on sensor data. This representation was chosen for two reasons, the first is that it is a prevalent representation in the robotics literature and therefore straightforward to implement. The second reason is that the output of an occupancy grid is easily interpreted, which could be important for use by plant workers who are required to plan decommissioning of a nuclear cave environment.

The implementation used in this work splits the environment into squares, requiring only knowledge of the perimeter of the nuclear cave. This is a reasonable assumption of knowledge, as plans can show the size of the room being mapped. Having split the environment into these squares, each is represented by an element in a matrix. Elements in the matrix are searched through recursively and updated based on a robot's sensor data. The possible updates are as follows:

- Obstacle detected – corresponding grid value increased by 3
- No obstacle detected – corresponding grid value decreased by 1
- Robot occupies grid square – corresponding grid value decreased by 5

The discrepancy in update value between an obstacle being detected and not detected is because the presence of an obstacle is more accurately detected than the lack of an obstacle; this was important to reflect in the update of the occupancy grid. If a robot lies within a grid square then the likelihood that it contains an obstacle is severely reduced, hence the larger decrease in occupancy value associated with this scenario. The maximum likelihood of occupancy is 100 and the minimum is 0, cells are initialised with a value of 50. The update values of 1, 3 and 5 were chosen as they allowed the map to tend towards an accurate representation at an acceptable rate. An example of an occupancy grid can be seen in figure 5.1.

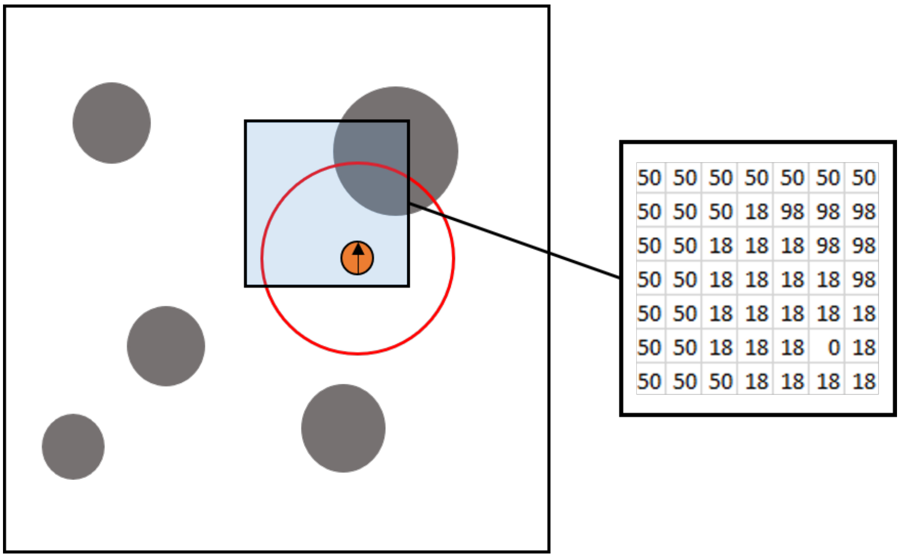


Figure 5.1: Shows a robot navigating an obstacle filled environment with an example occupancy grid.

The update process leads to three classifications of cell. These will later be utilised in the RVF framework to aid in exploration and mapping. The classifications are:

- Known cell: $v \geq 60$ or $v \leq 40$
- Unknown cell: $40 < v < 60$
- Frontier cell: an unknown cell next to a known cell, hence on the frontier of exploration and thus also with a value in the range $40 < v < 60$

Where v is the occupancy value. The values of 40 and 60 were chosen as this meant that repeat observations of a cell were necessary in order to classify it as known or unknown. These cells will later be used to determine attractive regions for the RVF framework.

Robots communicate their maps to one another when they are in sensor range. When a map is received it is compared cell by cell to the map the robot currently holds. The average between the communicating robots' cell values are then found. Subsequently, these values replace the corresponding cell value in each robots' map. This method allows robots to correct false occupancy measurements over time. In addition, this allows the speed of the mapping process to be increased. This is because, if maps are shared, a single robot does not need to visit all areas of the map.

This section has described the implementation of occupancy grid mapping that is utilised in the RVF framework. In the next section the forces used in the RVF framework will be outlined.

5.2 Forces

The fundamental forces of nature are the electrostatic force, the gravitational force, the strong nuclear force and the weak nuclear force. These forces give rise to the complex interactions present in nature. If these forces could be utilised for the control of a robotic swarm then it could be possible to have complex behaviour emerge from a few simple rules.

The RVF framework utilises virtual analogues of the fundamental forces of nature to guide robots in exploration, mapping and collision avoidance. This not only enables complex behaviours from basic laws, it also allows heterogeneity to be defined intrinsically within the system. This is achieved through varying the virtual physical properties of robots, such as charge or mass.

This section aims to outline the virtual forces that are used in the RVF framework and explain how these forces are converted into motor velocities to actuate a differential wheel drive robot. This will explore: the electrostatic force; the gravitational force; the strong nuclear force; and finally actuation. It should be noted that the weak nuclear force is responsible for radioactive decay, and though no analogue is drawn in this paper, its utility could lie in distributing a swarm at a given rate, among other potential uses.

5.2.1 Electrostatic Force

The electrostatic force governs how two charged particles will interact. Like charges will repel, whilst opposing charges will attract; both in proportion to the total charge between the particles. The RVF framework implements the electrostatic force for collision avoidance. As a robot approaches an obstacle, it is repelled by a force proportional to the distance from the obstacle. In contrast to the infinite range of this force present in nature, the RVF framework limits the range of the electrostatic force to a robot's sensor range. To prevent the robot accelerating infinitely, a viscous friction coupling term was added, proportional to the speed of the robot. The equation used to calculate the magnitude of the virtual electrostatic force is given in equation 5.1.

$$F_e = \frac{Qqk_e}{r^n} - \mu v \tag{5.1}$$

Where k_e is 8.99x10^9, q is the robot charge, Q is the obstacle charge and was determined through trial and error to be 2.5x10^{-7}, μ is the coefficient of friction, r is the distance to the obstacle, v is the velocity of the robot, and n is the order to which r is raised to (in the case of the electrostatic force in physics this is 2). These parameters were determined experimentally, this is detailed in the subsequent section. The electrostatic force is calculated independently for each wheel of a differential wheel drive robot; this is because the viscous friction term is dependent on the individual velocity of each wheel.

In order to decide the direction of the electrostatic force, the robot increments its bearing 45 degrees away from the detected obstacle. The value of 45 degrees was chosen through trial and error and was determined to give the best collision avoidance response.

5.2.2 Gravitational Force

In nature the gravitational force attracts bodies of mass. The reactive virtual forces framework seeks to use this attractive quality to promote discovery of unexplored regions of the map. In this case the gravitational force is used to attract the robot towards the centre of mass of the unknown cells. The centre of mass is calculated by averaging the position of all unknown cells in the map, then finding the closest unknown cell to this average position. The magnitude of the gravitational force may then be calculated using equation 5.2.

$$F_g = \frac{GMm}{r^2} \tag{5.2}$$

Where M is the mass of the centre of mass of the unknown cells, m is the mass of the robot, G is the gravitational constant and r is the distance to the centre of mass. M was determined experimentally and is a fixed value, this is detailed in section 5.3.2.

The direction of the gravitational force is determined to be the bearing given between the robot's position and the position of the centre of mass of the unknown cells.

5.2.3 Strong Nuclear Force

The strong nuclear force bonds most matter together and acts over minute distances. Within the RVF framework it is used to attract robots to nearby goals, in the form of frontier cells. If a frontier cell is found to be in sensor range of a robot, then it becomes the robot's goal. In the case where there is no frontier cell in range, the robot reverts to using the centre of mass of the unknown cells as a goal, in conjunction with the gravitational force.

This means that the robot is often moving towards frontier cells and thus areas that are yet to be explored. However, when the robot enters in an entirely explored region the gravitational force takes over and attracts the robot to a further unexplored area. Due to this the robot is nearly always gathering new data.

Currently there exists no simple analytical method for calculating the strong nuclear force. However, its relative strength is known when compared to the electrostatic force. This is a value of 137 times stronger than the electrostatic force. This leads to equation 5.3 for calculating the strong nuclear force in the reactive virtual forces framework.

$$F_s = 137 * F_e \tag{5.3}$$

Where F_e is the magnitude of the electrostatic force.

5.2.4 Actuation

Having calculated the forces acting on a robot, these forces must then be converted into motor velocities. This involves combining the two parts of the acting forces: the magnitude and the direction. It should be noted that only two forces are ever acting on a robot: either a combination of the electrostatic force and the gravitational force, if there are no frontier cells within sensor range; or a combination of the electrostatic and the strong nuclear force, if frontier cells are found within sensor range. If there are no obstacles in sensor range, then the electrostatic force is determined to be zero.

The magnitude of the resultant force is calculated as the sum of the magnitudes of the forces acting on the robot. This force is then converted into a change in motor velocity by rearranging Newton's second law, the resulting equation is given in equation 5.4.

$$\Delta v = \frac{F\Delta t}{m} \tag{5.4}$$

Where Δv is the change in motor velocity, F is the total force, Δt is the time the force is acting over and m is the mass of the robot.

The direction of the resultant force is found by averaging the direction of the two acting forces. In order to actuate towards the appropriate heading, robots calculate the smallest angle between their current heading and their desired heading. This allows the robot to determine whether it should turn clockwise or anti-clockwise. After this decision is made the wheels are actuated as follows:

- Clockwise turn – Δv is subtracted from the right wheel and added to the left wheel.
- Anti-clockwise turn – Δv is added to the right wheel and subtracted from the left wheel.

The robot continues turning until it reaches its desired heading ± 10 degrees. This value prevented the robot from continuously turning due to missing the desired heading repeatedly, whilst also enabling a suitable level of accuracy.

5.3 Simulation Design and Methodology

After designing the Reactive Virtual Forces framework, it was necessary to test its performance for exploration and mapping of an unknown environment. Specifically, it was desirable to compare the performance of the framework on both heterogeneous and homogeneous swarms. This was achieved through two means: simulation and embodied simulation.

This section aims to describe the design of the simulation used to test the RVF framework, in addition to outlining the experiments that were conducted in this simulator. This section will outline: the simulation design; the method by which individual virtual parameters were selected; experiments conducted to validate the strong nuclear force's performance; experiments conducted to compare the performance of the algorithm on different swarm compositions; an additional test to observe swarm behaviour; and finally, further experiments to determine whether the RVF framework could be used to determine unreachable zones.

5.3.1 Simulation Design

In order to test the virtual reactive forces method for exploration and mapping, a two-dimensional simulation was designed using the MATLAB software. MATLAB was used as it presented a familiar user interface and programming language that would allow for rapid prototyping of the RVF framework. It was decided that design of a simulator would allow for:

1. Heterogeneity to be easily defined and varied
2. Individual parameters pertaining to the forces to be changed and examined
3. Visualisation of the robot as a particle travelling in an environment
4. Simplifying assumptions to be made to allow the simulation to run faster and allow more experiments to be conducted
5. Sensing in the embodied simulation to match that in the MATLAB simulation

The MATLAB simulation designed for analysis of the 'reactive virtual forces' framework combines both macroscopic and microscopic models; some simplifying assumptions are made to allow for faster runtime, whilst each robot and artefact in the environment are individually modelled.

The simulations aimed to emulate the E-Puck robot [171]. This was so that once the simulation experiments had been completed, they could be verified in using a group of real E-Puck robots with augmented sensor range. This method of experimentation was dubbed 'embodied simulation', and will be further described in section 5.4. Additionally, these E-Pucks would need to be imbued with virtual heterogeneity which having designed the simulator, could be ported to the real E-Pucks. The virtual heterogeneity involved allowing the E-pucks to act as heterogeneous robots despite being physically homogeneous, as will be outlined in section 5.4. The simulated properties of the E-Puck are given in table 5.3.1.

Specification	Associated Property
Diameter	75mm
Mass	200g
Max Speed	13cm/s
Locomotion	Differential drive

Table 5.1: Shows the Epuck specifications used when designing the simulation

As well as adhering to the E-Puck specifications, some simplifying assumptions were made to make the simulation run faster. The first assumption was that the E-Puck is capable of sensing in a circle of diameter 40cm about itself. This was so that the sensing capabilities of the E-Puck could be upgraded and varied to generate heterogeneity in sensing. This sensor specification was a

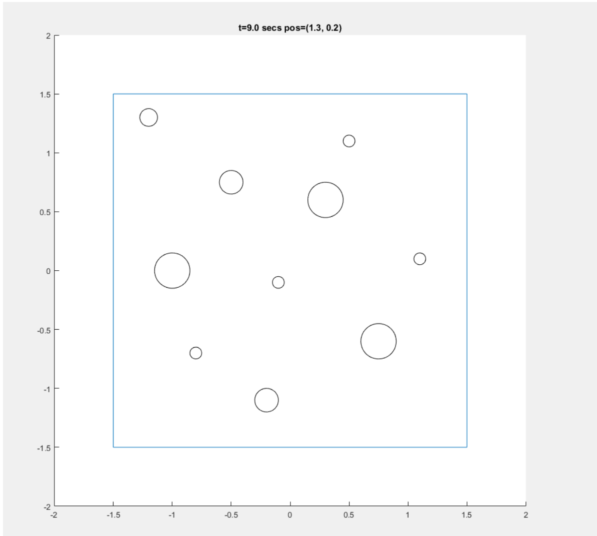


Figure 5.2: Shows the test arena used to test the reactive virtual forces framework.

conservative emulation of the RPLIDAR A2M8 360° sensor, a LIDAR sensor that is small enough to be carried by an E-Puck robot into a nuclear cave environment. The next assumption was that the robot can estimate its position and bearing with Gaussian noise, with self-localisation being implemented later in chapter six. The penultimate assumption is that the robot can control its differential wheel drive with Gaussian noise. Finally, it is assumed a robot's communication range is the same as its proximity sensor range.

The Runge-Kutta method was used to update the state of the robot at each time step [37]. This method is used to solve ordinary differential equations by estimating four slopes at different points and combining them via a weighted sum to give a final estimate. For the E-Puck differential drive robots these are equations 5.5 and 5.6:

$$\dot{\Theta} = \frac{v_r - v_l}{d} \tag{5.5}$$

$$v = \frac{v_r + v_l}{2} \tag{5.6}$$

Where v_l and v_r are the left and right linear wheel velocities, v is the total linear velocity of the robot, $\dot{\Theta}$ is the angular velocity and d is the diameter of the robot (distance between the two wheels).

Finally, a test arena needed to be generated. This was decided to be a 3x3m square arena. Obstacles representing the pressure vessels on the floor of a nuclear cave were randomly generated at random diameters in this arena. An example environment can be seen in figure 5.2.

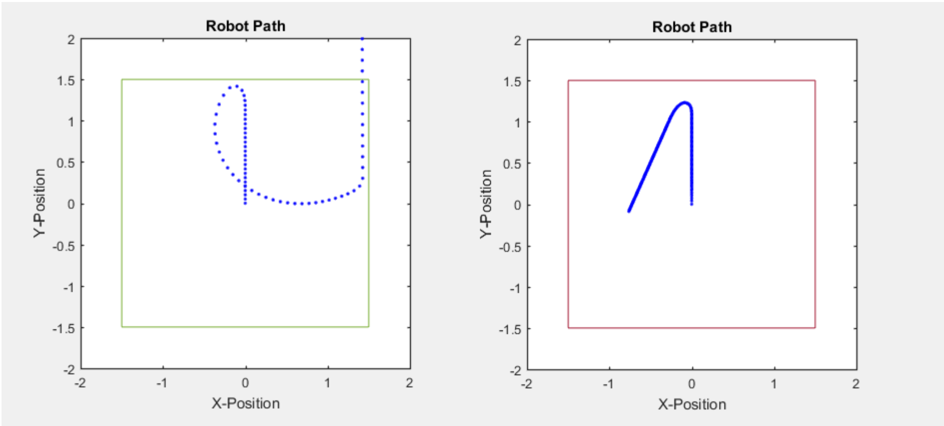


Figure 5.3: Illustrates an undesirable path (left), due to the looping back on itself and leaving the arena, and a desirable path (right).

5.3.2 Force Parameter Selection

Both the electrostatic and gravitational force equation utilised in the RVF framework contain virtual parameters that need to be selected. For the electrostatic force these parameters are q, n and μ as defined in equation 5.1. In the case of the gravitational force this is M, defined in equation 5.2. The ideal values for these parameters were determined experimentally, the details of these trials will be outlined subsequently.

5.3.2.1 Electrostatic Parameters

To conduct the electrostatic parameter investigations it was decided that each parameter would be varied 5 times leading to 125 combinations. μ was varied in between 0.01 and 0.05 in increments of 0.01. q was varied in the range 1x10^{-8} to 5x10^{-8} in increments of 1x10^{-8}. Finally, n was varied from 1 to 5 in increments of 1. These values were determined to be suitable ranges as they gave an electrostatic force of the appropriate order of magnitude.

Each combination was examined for 350 seconds of simulation time and ten trials were conducted for each of these combinations. As the electrostatic force is being used for collision avoidance, in each experiment a simulated robot was directed towards a wall. The path of the robot was then observed and qualitatively assessed on its suitability for collision avoidance. A path was deemed poor if it looped back on itself, or did not successfully complete a turn. A desirable trajectory, alongside an undesirable trajectory can be seen in figure 5.3.

After completing the 350 seconds simulations, the parameters producing the most promising paths were continued for a second 1000 second simulation to observe how they evolved. Having completed these 1000 second simulations the effect that each parameter had on the path of the robot became clear:

- μ – changes how quickly a robot's velocity stabilises to a straight trajectory after turning, a larger mu means the robot is less likely to loop back on itself and the turn has less angle

- q – changes the magnitude of the force causing the robot's acceleration to increase and making turns tighter
- n – allows the robot to respond more severely to a closing distance between itself and an obstacle

Once the simulations were completed the parameters giving the best path were chosen to be: $\mu = 0.04$, $q = 4\text{x}10^{-8}$ and $n = 2$.

5.3.2.2 Gravitational Parameters

The only parameter that needed to be determined for the gravitational force was the goal mass, M. To determine the best value, it was first necessary to calculate a desired order of magnitude. It was decided that the magnitude of the gravitational force should match that of the electrostatic force, so that total resultant force would give an even effect on velocity. To attain the same order of magnitude as the electrostatic force, the goal mass was required to be between $1\text{x}10^{8}$ and $1\text{x}10^{9}$. Thus, M was varied from $1\text{x}10^{8}$ to $1\text{x}10^{9}$ in increments of $1\text{x}10^{8}$ to find the best value.

To determine the best value for M, robots were initialised in random positions in the test arena, with a goal of mass M placed at (1.3, 1.3). Robots would then move from their starting position to the goal and the time taken was recorded. These tests were repeated 10 times for each mass and averaged. Whilst running these experiments it was also noted that if the robots moved too quickly their paths became erratic, thus it was decided to limit the maximum speed of the robots to 0.07m/s.

For each trial the minimum time that was achievable was calculated. This was the time taken for the robot to travel from its initial random starting position to the goal if travelling in a straight line at maximum speed. This could then be compared against as a measure of efficiency. After running the trials it was found that the fastest time coupled with the minimum variation from the comparison time was given by a mass of $4\text{x}10^{8}$.

5.3.3 Experimental Methodology

Having designed the simulator and ascertained reasonable values for the virtual parameters of the forces, it was necessary to design test criteria to examine the RVF framework. It was decided that a heterogeneous and a homogeneous swarm would be compared, along with individual robots.

In this section the experimental methodology used to examine the RVF framework in simulation will be described, with the results being presented later. This section will describe: an experiment designed to verify the utility of the strong nuclear force in the framework; investigations into the performance of the RVF framework on homogeneous and heterogeneous swarms;

test ran to examine the effect of individual parameters; and finally, research methods to observe whether the RVF framework could be used to determine unreachable zones.

5.3.3.1 Verifying Strong Nuclear Force

It was considered important to examine whether the inclusion of the strong nuclear force benefitted the efficiency of the RVF framework, or just added unnecessary complexity. To this end two experiments were run, using a single robot. The first test utilised only the gravitational force, with the centre of mass of the unknown cells as a goal. The second test used the full RVF framework, with the strong nuclear force used for attraction to frontier cells in sensor range. Trials were conducted in which the robot sought to achieve 80% coverage of the environment. This value was chosen as it shows that a robot could cover an environment, whilst tending to completion in a reasonable time frame. The robot was initialised in a random position each time, with the number of collisions being recorded. Trials were repeated 30 times, in keeping with the NIST statement that 30 trials give an 80% reliability [115].

5.3.3.2 Examining Performance in Differing Swarm Compositions

As exploration of a nuclear cave environment is likely to be carried out by a heterogeneous swarm of robots, it seemed important to examine whether the RVF framework performs well on such a swarm. To do this, the efficiency of the RVF framework was compared between a homogeneous and heterogeneous swarm of four robots.

The homogeneous swarm was comprised of four robots utilising the specifications of an augmented E-Puck (diameter 0.07m, mass 0.2kg, imposed maximum speed 0.07m/s, augmented sensor range 0.4m and virtual charge $4x10^8$). To ensure a fair comparison it was decided that the specifications of the heterogeneous swarm should share the same average values across the four robots. This was achieved by halving the values for one robot, doubling for another and keeping two the same as in the homogeneous swarm. This led to one small robot, one large robot and two medium robots with the following criteria:

- Small Robot – diameter 0.035m, mass 0.1kg, maximum speed 0.035m/s, sensor range 0.2m and virtual charge $2x10^8$
- Two Medium Robots – diameter 0.07m, mass 0.2kg, maximum speed 0.07m/s, sensor range 0.4m and virtual charge $4x10^8$
- Large Robot – diameter 0.14m, mass 0.4kg, maximum speed 0.14m/s, sensor range 0.8m and virtual charge $8x10^8$

Robots were able to communicate with one another when in sensor range and shared their occupancy grid to determine the average of the two, as described earlier. Robots were initialised

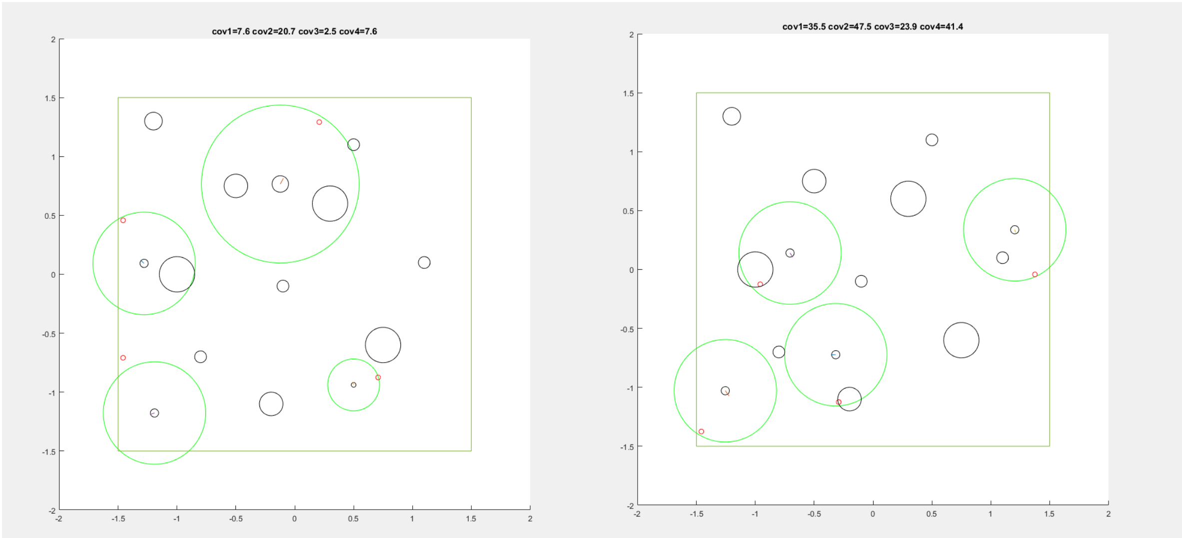


Figure 5.4: Demonstrates the experimental set up for the comparison between heterogeneous and homogeneous robots. On the left is the heterogeneous experiment, and on the right the homogeneous.

in random positions and explored their environment until three of the four robots had reached 80% coverage. As with the verification of the strong nuclear force, this value was chosen as it shows that a robot could cover an environment, whilst tending to completion in a reasonable time frame. When this value was reached the time taken was recorded and a new experiment initialised. Trials were conducted thirty times for each swarm composition. The test arena with both heterogeneous and homogeneous set-ups may be seen in figure 5.4.

5.3.3.3 Individual Parameter Investigation

Having conducted experiments using an entirely heterogeneous swarm of robots, it was considered prudent to investigate the effect on exploration time of each parameter defining heterogeneity. To do this the diameter, mass, sensor range, maximum speed and charge were changed to their heterogeneous values individually, whilst keeping the remaining parameters homogeneous. As with the other investigations the time taken to reach 80% coverage for three out of the four robots was recorded. Thirty trials were conducted for each of the five parameters defining heterogeneity.

5.3.3.4 Determining Unreachable Zones

The final experiment was devised to investigate whether the RVF framework could be used to determine whether a region was unreachable. To do this, robots that are in the same area for more than 10 seconds change their goal. When this happens, the robot drops a ‘virtual goal’ that it may pass to other robots. Each robot should only attempt to visit this goal once, as if a robot is unsuccessful it is deemed that it cannot reach that area. The goal is also associated with a counter, once this counter equals the number of robots in the swarm then it is determined that the region is unreachable by the swarm and marked as such. This simple method allows robots to determine if an area is unreachable without complex analysis, and is easily implemented via a finite state machine with the following states:

1. **Unknown** - the robot has not encountered the goal or another robot carrying it, robots are initialised in this state.
2. **Visiting** - The robot has received the goal from another robot and is currently making its way towards that goal.
3. **Carrying** - The robot has visited the goal and is currently waiting to encounter another robot that has not visited the goal, so that it may pass the goal.
4. **Visited** - The robot has visited the goal and is currently continuing with mapping.

To test the efficiency of this concept the time taken for a goal to be passed between all the robots by random encounter needed to be assessed. This was achieved by first initialising robots in random positions, with a random robot set to be in state (2) in the finite state machine. This robot then makes its way to the goal at (1.3,1.3), which represents the access point to a previously unreachable region. Once it has reached the goal the robot moves through the finite state machine and passes the goal to other robots when it encounters them. The experiment concludes when all robots have reached state (4) in the finite state machine. Thirty tests were first conducted on a homogeneous swarm, then repeated on a heterogeneous swarm.

5.4 Embodied Simulation Design and Methodology

Having examined the reactive virtual forces framework in simulation, the next step was to move this towards the real world. It was decided that it was important to isolate the performance of the RVF framework and so a tracking system was used to localise the robots, to prevent errors from a localisation algorithm being compounded with any issues with the algorithm itself. In chapter six, localisation of the RVF framework will be discussed.

Comparing the performance of the RVF framework on a heterogeneous and a homogeneous swarm fairly is a difficult task; using different robots would increase the number of variables that could not be controlled. To overcome this problem the 'embodied simulation' was created.

An embodied simulation allows for homogeneous robots to be imbued with virtual heterogeneity. This section aims to outline the design of the embodied simulation, along with the experiments conducted to verify the results attained in simulation. On top of this, additional experiments conducted to observe the effect of occupancy grid resolution will be outlined. This section will describe: the design of the experimental environment; and the experiments conducted to verify the reactive virtual forces framework.

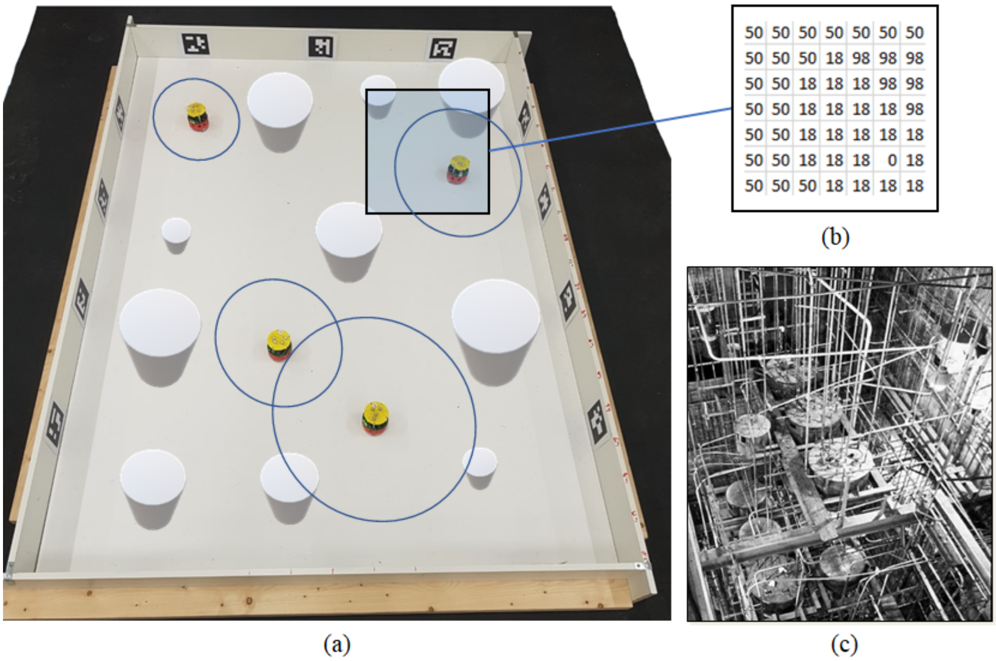


Figure 5.5: a) The arena in which the experiments were conducted, the virtual obstacles have been overlaid onto the environment. Sensor ranges are represented by rings around each e-puck. b) An example occupancy grid, after multiple updates. c) A photograph of a nuclear cave environment, taken before the cave was sealed.

5.4.1 Experimental Environment

The embodied simulation was designed so that investigations into the effect of heterogeneity could be conducted using a homogeneous team of robots. This involved imbuing robots with virtual heterogeneity in sensing and through restricting maximum speed, whilst also varying the virtual parameters of charge and mass.

The robots used to conduct the experiments were the E-pucks [171]. They were localised using a VICON tracking system [253]. This system can determine the pose of a robot to an accuracy of 1mm.

Accurate knowledge of a robot's position allows for virtual obstacles to be created, and hence virtual sensing to be implemented. The range of this virtual sensing could easily be changed to allow heterogeneity to be defined between robots. The positions of obstacles are randomly generated in the map. As with the MATLAB simulation, the sensor was taken to be a circle with variable radius about the robot. When an obstacle enters the sensor range of a robot the Euclidian distance to that obstacle is calculated, then Gaussian noise is added to this reading. Sensing is the only virtual parameter used in the embodied simulation; the communication, robots, arena and associated physical noise are all real.

The test arena is a 1.5x2m area, in which ten virtual obstacles are randomly generated at the beginning of each mapping effort, this is shown in figure 5.5. The arena represents an unknown and cluttered environment; as such, though the experimental environment is simplified, it represents the unknown and cluttered surroundings a robot could encounter when exploring a nuclear cave, and thus allows preliminary conclusions to be drawn about the suitability of the control algorithm. The experiments conducted will be outlined subsequently.

5.4.2 Experimental Methodology

The aim of these experiments was to investigate the suitability of the RVF framework for the exploration and mapping of a nuclear cave environment, and to compare its results on a single robot, a homogeneous swarm, and a heterogeneous swarm. In addition, the effect of the occupancy grid resolution was examined in each case. The hope was that the results in the embodied simulation would verify those acquired in the MATLAB simulation.

In this section the experiments that were run on the single robot, the homogeneous swarm and the heterogeneous swarm will be outlined. In each case 30 experiments were run, in keeping with the guideline put forward by the national institute for standards and testing [115]. This states that thirty experiments give an 80% reliability. This section will detail: the single robot experiments; the homogeneous experiments; and finally, the heterogeneous experiments.

5.4.2.1 Single Robot Experiments

The initial aim of the single robot experiments was to examine the effect of the occupancy grid resolution on the algorithm and mapping time, as well as investigate the performance of the RVF framework on a single robot. When exploring the 1.5x2m test arena, the area was divided into smaller regions defining the occupancy grid to be filled by the robot. To inspect the effect of a varied occupancy grid resolution, the following divisions were used:

1. **13x10** - each grid square is approximately twice the diameter of the robot.
2. **26x20** - each grid square is approximately the diameter of the robot.
3. **52x40** - each grid square is approximately half the diameter of the robot.

These divisions provide a trade-off between computation time and accuracy: as the matrix storing the occupancy grid grows so does the processing time, whilst a finer grid allows a more accurate definition of the location of obstacles.

Each grid resolution was examined with three virtual sensor ranges: 20cm, 40cm and 80cm. This is because robots comprising the heterogeneous swarm would later use these sensor ranges, so it was prudent to have a baseline for comparison on each member.

In each case the robot was initialised at a random location at the edge of the map, to simulate entry into a nuclear cave. The robot then proceeds to map the environment until 80% coverage is reached, at which point the time is recorded and the experiment repeated.

5.4.2.2 Homogeneous Swarm Experiments

The homogeneous experiments were conducted on a group of four E-Puck robots, each given a virtual sensor range of 40cm using the embodied simulation method described earlier. During these tests there were two communication modes explored: *local* communication and *global* communication. In the local communication mode, robots were only able to communicate with each other when within their sensory range. In the global communication mode, robots communicated with each other continuously, regardless of the distance between them. Communication was achieved over WiFi, using ROS nodes that published and received [195]. The occupancy grid was the only item being communicated between robots. To do this it was first converted into a one-dimensional matrix, whose elements were transmitted one at a time. This matrix was then converted back into the appropriate occupancy grid form when it was received. The average between the receiving robot's own occupancy grid and the occupancy grid it was being sent was then found to be the new occupancy grid. If multiple messages were sent at once, due to multiple robots' being within communication range, they are randomly ordered and resolved based on this order.

Each communication paradigm was examined at the three grid resolutions used in the single robot case: 13x10, 26x20 and 52x40. This was to investigate the effect the grid resolution has on the exploration time, as it was expected the higher communication overhead associated with a finer resolution would cause exploration time to increase.

As with the single robot examinations, each member of the homogeneous swarm was initialised randomly at the edge of the mapping area. The experiments were run until three of the four robots had reached 80% coverage, to match the end condition used in the MATLAB simulations. At this point the experiment was stopped and task completion time was recorded.

5.4.2.3 Heterogeneous Swarm Experiments

The heterogeneous experiments were run on a group of four E-Puck robots. In this case, two robots were given a 40cm sensor range, one a 20cm sensor range and the last robot a 80cm sensor range. In addition, their speeds were limited to 0.07m/s, 0.035m/s and 0.14m/s respectively. This was to allow for virtual heterogeneity to be defined using the homogeneous E-Puck robots. These values were chosen so that the average parameter values of both the heterogeneous and homogeneous swarms were kept the same, to allow for a reasonable comparison. These values also matched those used in the MATLAB simulations to enable verification of the results produced.

The experiments were conducted in the same manner as for the homogeneous swarm. This involved comparing global communication to local communication, over the three occupancy grid resolutions. Communication in the heterogeneous case was achieved in the same way as the homogeneous scenario. The robots were again set at random start locations about the perimeter of the arena. Each experiment was ended when three of the four robots reaches 80% coverage, and the time taken to do so was recorded.

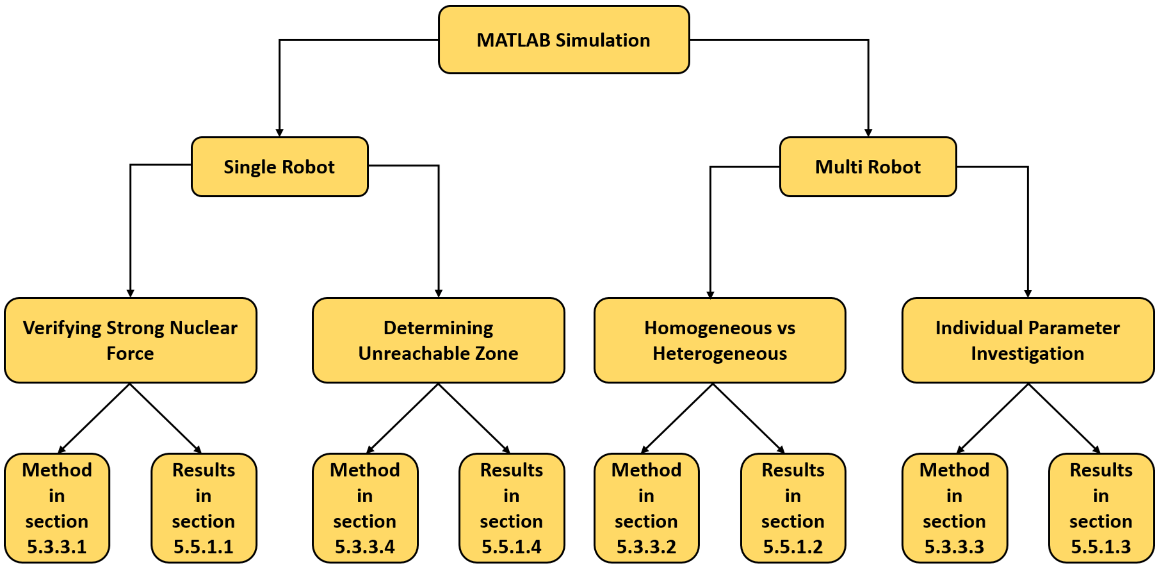


Figure 5.6: A delineation of the experiments conducted in the MATLAB simulation, along with the location of methodology and results within the thesis.

5.5 Results

The experimental methodology used to examine the RVF framework has been detailed in the previous sections. This involved using a MATLAB simulation to rapidly prototype and examine the RVF framework on a homogeneous and a heterogeneous swarm. An embodied simulation was then used to verify the MATLAB simulation results and observe the behaviour on real robots.

This section aims to present the results from the comparative experiments and examine their statistical significance. This section is structured as follows: first, the results from the MATLAB simulations will be presented; second, the results from the embodied simulations will be detailed. In order to delineate the experiments conducted in this chapter, figures 5.6 and 5.7 are provided; these figures detail the sections in which experimental methodology and results can be found for each experiment, for ease of reference.

5.5.1 MATLAB Simulation Results

The MATLAB simulation was designed to prototype and examine the RVF framework rapidly. Multiple experiments were conducted to investigate the efficiency of the RVF framework, the results from these trials will be presented in this section. In addition, statistical tests conducted to determine the significance of the results will be detailed.

This section will present: results from the verification of the strong nuclear force; results from the investigations into the performance of the RVF framework on homogeneous and heterogeneous swarms; results from the tests that were run to examine the effect of individual parameters; results from attempts to determine unreachable zones; statistical analysis to deter-

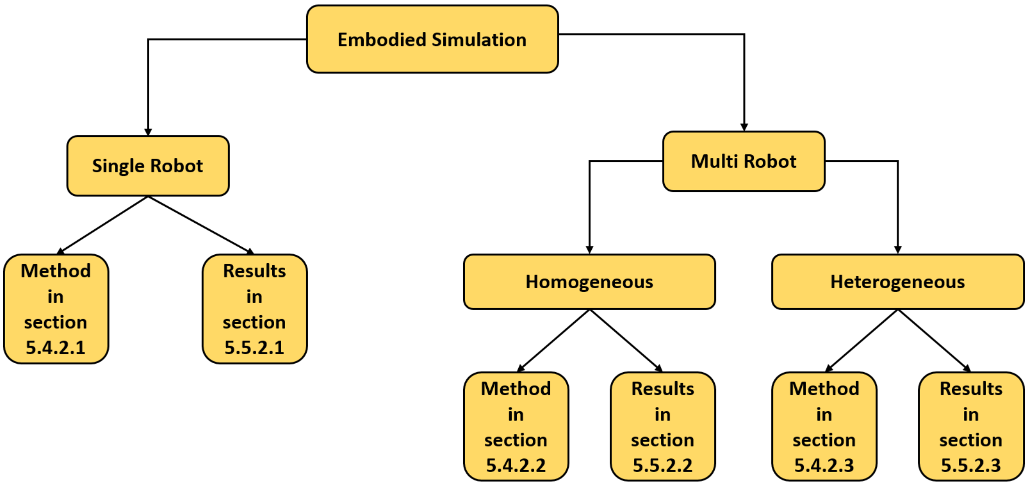


Figure 5.7: A delineation of the experiments conducted in embodied simulation, along with the location of methodology and results within the thesis.

mine the significance of the results; and finally, results from an additional test to examine the behaviour of the heterogeneous vs homogeneous swarm.

5.5.1.1 Verifying Strong Nuclear Force

This experiment was used to verify the utility of the strong nuclear force in the RVF framework. The assessment was completed by comparing the time taken for a single robot to reach 80% coverage both with and without the strong nuclear force.

The average time taken without using the strong nuclear force was 708 seconds, with a standard deviation of 146 seconds. When the strong nuclear force was introduced to the framework this average time dropped significantly to 330 seconds, with a standard deviation of 52 seconds.

In addition to the time take to reach 80% coverage, the average number of collisions in each scenario was recorded. In the case where only the gravitational force was used the average number of collisions was found to be 3.7 per run, however when introducing the strong nuclear force this decreased to an average of 0.8 per run.

This was the result that was expected. When the robot uses only the gravitational force to explore the unknown environment, it will spend much of its time revisiting previously explored areas. The introduction of the strong nuclear force means that the robot is more often exploring new regions. This is because it will continue to push the frontier of exploration until there are no longer frontier cells within its sensor range, at which point the gravitational force takes it to a new area. This result reinforces the utility of the strong nuclear force in the RVF framework.

Swarm Composition	Time (seconds)	Standard Deviation
Homogeneous	231	36
Heterogeneous Sensing	222	43
Heterogeneous Speed	223	34
Heterogeneous Charge	221	34
Heterogeneous Diameter	232	50
Heterogeneous Mass	242	38

Table 5.2: Shows the results of making individual parameters of the swarm heterogeneous.

5.5.1.2 Examining Performance in Differing Swarm Compositions

These experiments compared the effectiveness of the RVF framework on a heterogeneous and homogeneous swarm. To compare the swarm's efficiency, the average time taken for three of the four robots in the swarm to reach 80% coverage was calculated over thirty trials. This end condition allowed for the experiments to conclude in a reasonable amount of time for comparison, whilst also giving a coverage of the map that is similar to what is expected in the real environment, taking into account unreachable zones.

The average time for the homogeneous swarm was found to be 231 seconds with a standard deviation of 36 seconds, whereas the time for the heterogeneous swarm was found to be 181 seconds with a standard deviation of 41 seconds. This was not the expected result. As both swarms utilise the same average values for all parameters that were varied, it was assumed a similar exploration time would be recorded. Instead, the heterogeneous swarm appears significantly more efficient at exploring the environment.

This was an interesting result and warranted further investigation to understand why the heterogeneous swarm performed better. This investigation was twofold: first the statistical significance of these results needed to be verified; second, it was decided that a further experiment with swarms initialised in the same starting positions was useful to observe the behaviours of the swarm. These additional investigations will be described later in the 'Statistical Testing' and 'Further Investigation into Homogeneity vs Heterogeneity' sections respectively.

5.5.1.3 Individual Parameter Investigation

The individual parameter investigations were conducted to examine the effect of each parameter defining heterogeneity on the exploration time. These parameters were speed, sensor range, charge, mass and diameter. The results are summarised in table 5.2.

The results show that introducing heterogeneity to single parameters only very slightly affects the result. In the case of sensor range, charge and speed the average exploration time compared to the homogeneous swarm was decreased by a small amount. For mass, the exploration time was increased marginally. Finally, for diameter the exploration time remained roughly the same. These results are interesting and suggest that no one parameter greatly effects the exploration time, instead it is the combination of the heterogeneous characteristics. The statistical significance of these results will be discussed in the 'Statistical Testing' section.

5.5.1.4 Determining Unreachable Zones

This simulation was designed to investigate the feasibility of using goal passing to determine unreachable areas within a nuclear cave. A goal point was defined as the edge of an unreachable zone, which was then passed between robots when they encountered one another until all robots had visited the goal. Once all robots have attempted to enter the zone and failed, it is determined to be unreachable by the swarm. The time taken to for all robots to attempt to enter the zone was recorded both for the heterogeneous and homogeneous swarms.

The average time taken to pass the goal between all the robots in the homogeneous case was 561s with standard deviation of 202 seconds, whereas in the heterogeneous case this reduced to 518s with a standard deviation of 129 seconds.

As these results fall within each others standard deviation it suggests that the homogeneous and heterogeneous swarms took a similar time to pass the goal between all robots. This result was not expected because it was assumed that the heterogeneous swarm would underperform, due to the robot with a reduced sensor range. It was assumed that this robot would cause a bottleneck, as robots are only able to pass the goal when another robot in within sensor range. It is possible that the robot with enhanced sensor range made up for this bottleneck.

The results show that it is possible for the robots to pass a goal between themselves. This goal could represent an area that a robot could not traverse, or an area that requires further investigation due to its importance. The active use of this function is to mark areas that could not be explored due to all the robots not being able to reach it. This experiment captured the essence of this, showing that it is a feasible concept.

5.5.1.5 Statistical Testing

To discern whether the improved efficiency of the heterogeneous swarm over the homogeneous swarm was statistically significant, T-test were conducted to compare the results. A T-test postulates a null hypothesis, which is rejected if the calculated T-value is below a certain threshold. The T-value used for thirty trials is 0.05, this gives a certainty of 98% in the rejection of the null hypothesis. Two null hypotheses were investigated during these T-tests, the first was to examine the significance of the results compared to a homogeneous swarm; the second was to investigate the significance when compared to a heterogeneous swarm. These hypotheses were:

1. **Null hypothesis 1 -** 'the mean time for exploration for the heterogeneous swarms should be the same as that of the homogeneous swarm'

Swarm Composition	T-value under Hypothesis 1	T-value under Hypothesis 2
Homogeneous	N/A	$4.9\text{x}10^{-6}$
Heterogeneous	$4.9\text{x}10^{-6}$	N/A
Heterogeneous Sensing	0.40	$3.1\text{x}10^{-4}$
Heterogeneous Speed	0.35	$8.0\text{x}10^{-5}$
Heterogeneous Charge	0.26	$1.4\text{x}10^{-4}$
Heterogeneous Diameter	0.96	$7.1\text{x}10^{-5}$
Heterogeneous Mass	0.27	$1.6\text{x}10^{-7}$

Table 5.3: The results of the T-testing individual parameters defining heterogeneity.

2. **Null hypothesis 2 -** 'the mean time of exploration for the entirely heterogeneous swarm should be the same as that of the swarm when individual parameters defining heterogeneity are changed, keeping all other parameters homogeneous'

The results from the T-tests are shown in table 5.3.

An interesting result comes from hypothesis 1; only in the entirely heterogeneous case can we reject the null hypothesis. This shows that in the case where all parameters are heterogeneous, a significant difference is made to the exploration time. However, in the case of individual heterogeneity no significant difference is recorded.

The second hypothesis compares the results to the entirely heterogeneous case. From the T-values we see that making all parameters heterogeneous has a considerably more significant effect on the results than changing any one parameter.

5.5.1.6 Further Investigation into Homogeneity vs Heterogeneity

Having observed that the heterogeneous swarm was significantly more efficient at exploring the environment when compared to its homogeneous counterpart, it was decided that further investigation was necessary. A test was devised to observe the behaviour of both swarms while mapping the same environment. This involved initialising both swarms in the same starting locations and having them explore the same environment until 80% coverage was achieved by at least three robots. It was decided each robot would be given an initial starting location of one of the four corners. During these experiments, the exploration behaviour of the swarms was observed and noted quantitatively.

After completing numerous runs of this experiment, it became clear that the asymmetry of the heterogeneous swarm seemed to be benefiting the exploration effort. This was down to the movement of the robots before and after sharing maps.

In the homogeneous case, each robot would explore its initial corner and then moved towards the centre of the map. As all robots are the same in the homogeneous case, they would all reach the centre of the map at approximately the same time. This led to robots all sharing their maps at the same time and subsequently exploring similar regions.

In the heterogeneous case, robots followed a similar behavioural pattern; they would explore their initial corner and then move towards the centre of the map. However, as the robots are heterogeneous, they would reach the centre at different times. This meant that maps are not shared at the same time in the centre and thus robots do not seek to explore the same regions after a map has been shared. Interestingly, the two robots that were given the same parameters in the heterogeneous swarm tended to pair off and explore similar regions. This is an example of physical form effecting behaviour in a way that is beneficial to the desired outcome.

Overall, these experiments highlighted an unexpected benefit of the heterogeneous swarm: asymmetry between agents. This meant that the robots tended to explore different regions of the map and were less likely to follow similar paths to those taken by their teammates.

5.5.2 Embodied Simulation Results

The embodied simulation was designed so that virtual heterogeneity could be instigated on a homogeneous swarm. This was to allow for the MATLAB simulation results to be verified on real robots. Several experiments were conducted to examine the efficiency of the RVF framework on virtually heterogeneous E-Puck robots. In addition to verification of the simulation results, the embodied simulations sought to examine the effect of varying the occupancy grid resolution.

This section will detail: results from experiments conducted on single robots of varying sensor range and speed; the results from the homogeneous experiments; the results from the heterogeneous swarm; and finally, the results from statistical testing conducted to ascertain the significance of the results.

5.5.2.1 Single Robot Experiments

The average times, and associated standard deviations, for the single robot experiments results are presented in the box plot in figure 5.8. The first conclusion that can be drawn from examining the values is that increasing the sensor range decreases the required exploration time. This is entirely expected, as a larger sensor range means that a robot can assess more of the area at any one time.

A result that was not anticipated is that, in general, both the 13x10 and 52x40 grid resolutions have a lower exploration time than the 26x20 grid. In the 13x10 case this is thought to be because each of the squares is worth a greater percentage of the overall coverage. Due to this, when new cells are discovered the coverage percentage rises more quickly, thus lowering the exploration time. For the 52x40 grid, the lower search time is likely to be due to the larger number of unexplored cells. If there are more frontier cells in range then the robot can discover unexplored cells more often, and therefore complete the exploration task more efficiently. The fact that the time for the 13x10 grid resolution is lower than the time for the 52x40 resolution suggests that the percentage value of cells has a greater effect than being constantly moving towards new cells, in the single robot case.

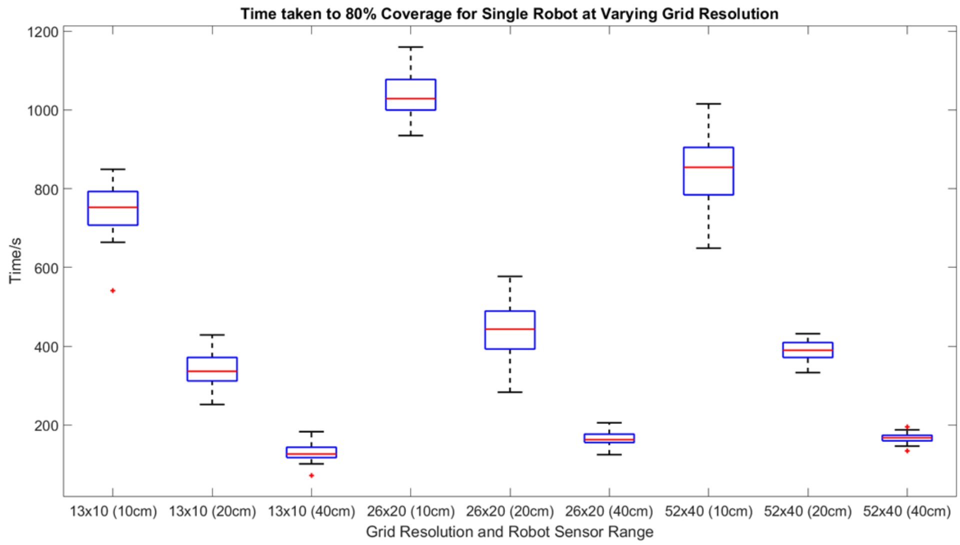


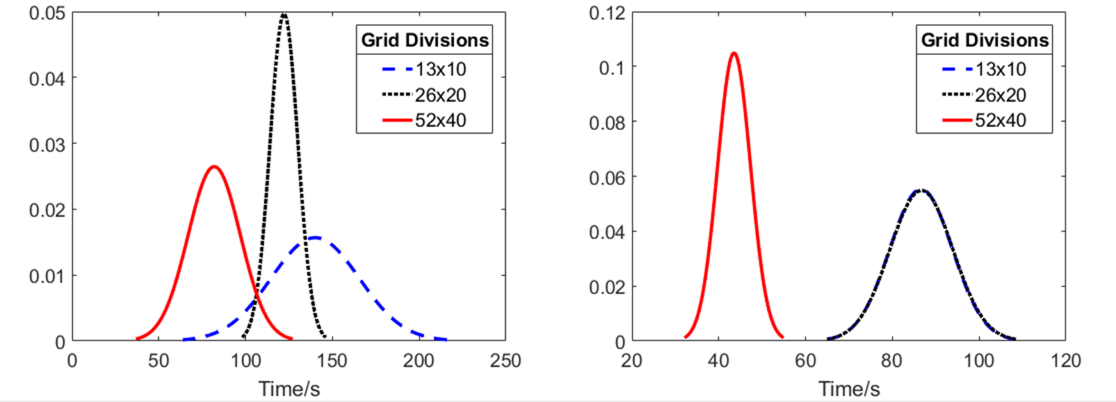
Figure 5.8: Box plot showing the results of the single robot experiments conducted in embodied simulation.

Overall the single robot results display interesting qualities. Though both the 13x10 grid and the 52x40 grid were faster, they have drawbacks. The 13x10 provides less accurate information about the environment. Also, although the 52x40 resolution leads to the robot having good information about the environment, due to the size of the grid each update step takes roughly twice as long as when the 26x20 grid is used. This often leads to the robot colliding with obstacles as it cannot react in a timely manner. This means that though the exploration time is slower for the 26x20 grid, it is possible that it is the best choice, providing a reasonable trade off between map accuracy and processing time.

5.5.2.2 Homogeneous Swarm Experiments

The normalised distribution of the results for the homogeneous swarm can be seen in figure 5.9. The first, and obvious, conclusion that may be drawn from both the local and global communication results is that using a homogeneous swarm to map the environment is more efficient than using a single robot. A second obvious result is that using global communication produces a faster exploration time than having the robots communicate locally. This is because the robots are constantly able to share their maps and thus have a full knowledge of the explored workspace.

In the case of local communication, the results seem to change from the single robot experiments; as the grid resolution becomes finer, the search time decreases. This is believed to be the result of having more cells to explore. As the robots' exchange maps, areas are filled in more quickly. In the case of the 13x10 grid, this is likely to mean that after exchanging maps with other swarm members, the robot is not going to be in range of a frontier cell. This means that the robot must travel to the centre of mass of the unexplored region and thus move through



(a) Local Communication (b) Global Communication

Figure 5.9: The normalised distribution of results for the homogeneous swarm, at the three varying grid resolutions and using the different communication modes with probability density on the y-axis. Note: The 26x20 line is overlaying the 13x10 in (b).

previously discovered regions to do so. The probability of this being true reduces as the grid resolution increases, due to the increase in the number of grid squares.

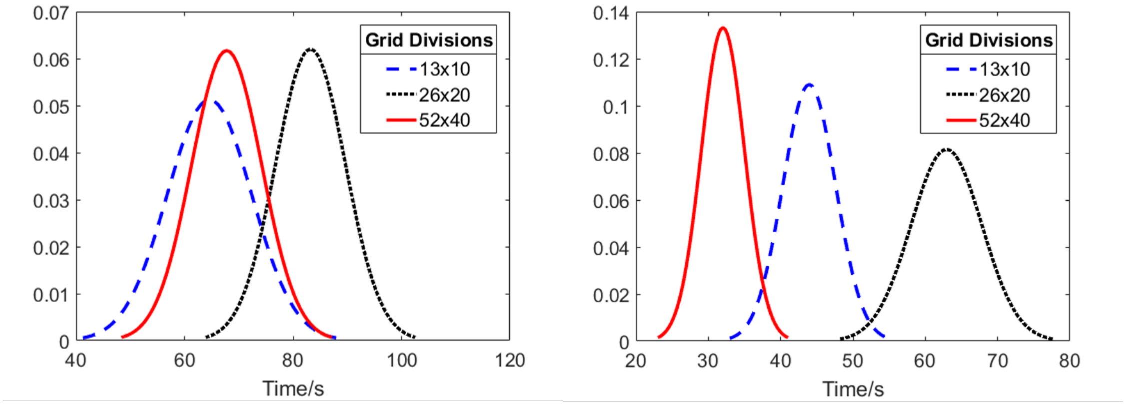
For global communication, it is found that the 13x10 and the 26x20 search times are similar, whereas the 52x40 time is shorter. This is again down to the prevalence of unexplored cells. As the exploration times were comparable between the 13x10 and 26x20 grids, it seems that introducing global communication reduces this discrepancy. The 52x40 grid provides considerably more cells to be explored, thus the robots are usually able to move towards unexplored cells.

Overall it is clear that the homogeneous swarm performs better than a single robot. It is also shown that a 52x40 grid generates a faster exploration time. It should be noted however that as the size of the grid resolution increases, so does the communication overhead required to exchange maps. For this reason, the robots required their batteries be changed more often during the 52x40 experiments. This could be a problem in a nuclear cave environment, where the robots may not be able to be retrieved easily.

5.5.2.3 Heterogeneous Swarm Experiments

As for the homogeneous swarm results the normalised distributions have been plotted for both the local and global communication cases and can be seen in figure 5.10. As with the homogeneous results, having the robots in constant communication decreased the average exploration time.

In the local communication paradigm, the 52x40 and the 13x10 grid resolution results are comparable, whereas the exploration time for the 26x20 grid was slower. This is akin to the single robot case. The 13x10 grid allows for a larger percentage increase in the coverage when a cell is discovered, whereas the 52x40 grid means that robots are more often exploring new cells. The



(a) Local Communication (b) Global Communication

Figure 5.10: The normalised distribution of results for the heterogeneous swarm, at the three varying grid resolutions and using the different communication modes.

26x20 grid seems to fall in the middle of this trade off, and as such the exploration time in this case is slower.

When the heterogeneous swarm utilises global communication it seems that the 52x40 grid performs best. As with the homogeneous swarm this is likely due to the robots being able to spend more time exploring unexplored cells. The 13x10 grid performs better than the 26x20 grid, this is because each grid square is worth a higher percentage of the overall coverage. Interestingly, the trade-off between higher percentage cell value and density of unexplored cells seems to invert when compared to the single robot case. This is likely because when robots communicate, they are more likely to have explored the same cells in the 13x10 case, and thus in the 52x40 grid case the probability of finding new frontier cells is greater.

Overall, it has been shown that the heterogeneous swarm performs the exploration task more efficiently than the homogeneous swarm. This is in line with results found in previous work in the MATLAB simulation. In the next subsection, the statistical significance of these results will be explored.

5.5.2.4 Statistical Testing

Having found that both the swarm composition and the grid resolution influence the exploration time of the swarms, the next step was to determine the significance of these results. To do this, as in the MATLAB simulation case, T-tests were performed [75]. This involved the postulation of a null hypothesis which is rejected if the calculated T-value is below some threshold value. In this case a value of 0.05 was used, this gives a 98% confidence in the rejection of the null hypothesis.

These tests were performed when comparing the heterogeneous swarm results to the homogeneous results, for the same value of grid resolution. They were also performed within each

Grid Resolution	T-Value
13x10	$4.2\text{x}10^{-16}$
26x20	$9.2\text{x}10^{-19}$
52x40	$4.8\text{x}10^{-5}$

Table 5.4: T-values for the comparison of the heterogeneous to the homogeneous swarm results for varying grid resolutions.

Grid Resolution	Homogeneous T-Value	Heterogeneous T-Value
13x10 vs 26x20	$6.1\text{x}10^{-4}$	$7.1\text{x}10^{-12}$
13x10 vs 52x40	$1.3\text{x}10^{-12}$	0.07
26x20 vs 52x40	$1.0\text{x}10^{-13}$	$3.1\text{x}10^{-9}$

Table 5.5: T-Values for the comparison of grid resolutions.

swarm composition, for the local communication paradigm. This was to determine whether the grid resolution has a significant impact on the exploration time.

Firstly, the homogeneous and heterogeneous swarms were compared. In each case the null hypothesis was ‘the swarm composition has no effect on the efficiency of the exploration time’. The T-values for these tests are collated in table 5.4. This table shows that for each grid resolution the null hypothesis may be rejected. That is to say that the performance of homogeneous and heterogeneous swarms was significantly different for each grid resolution. This proves that utilising a heterogeneous swarm decreases exploration time when using the RVF method when compared to a homogeneous swarm.

The second set of T-tests were conducted to observe whether the grid resolution has a bearing on the exploration time of the swarms. In each case the null hypothesis was ‘the grid resolution has no effect on the exploration time of the swarm’. The results of these tests are shown in table 5.5. The results show that in all except the heterogeneous 13x10 vs 52x40 case, the null hypothesis may be rejected. This shows that the grid resolution, in most cases, affects the exploration time of robots in a statistically significant way.

5.6 Chapter Summary

The aim of this chapter was to investigate the Reactive Virtual Forces framework as a potential control algorithm to guide a robotic swarm in the exploration and mapping of a nuclear cave environment. This was achieved through two experimental means: a MATLAB simulation designed to rapidly prototype and test the RVF framework; and an embodied simulation, designed to verify the MATLAB results and allow for homogeneous robots to be imbued with virtual heterogeneity.

In both cases, the RVF framework was compared with a homogeneous and heterogeneous swarm. It was found that the heterogeneous swarm can explore the environment more efficiently than its homogeneous counterpart, when using the RVF framework. This was found to be due to the inherent asymmetry of the heterogeneous swarm.

Additionally, the effect of occupancy grid resolution on swarm performance was studied. It was found that changing the resolution has a statistically significant result on the exploration time of the swarm. However, the resolution that led to the best performance was different depending on the swarm composition. Finally, the utility of the method for assigning areas as unreachable was explored. It was found that both homogeneous and heterogeneous swarms performed similarly. This experiment investigated whether it was possible for all robots to pass the goal simply by random encounter and showed that it is.

Overall, it has been shown that the reactive virtual forces framework, in combination with an occupancy grid, can be used to explore and map an unknown environment. So far in the RVF framework, it has been assumed that the pose of the robot is known. Within a nuclear cave environment this is not possible, thus a localisation method is required. Chapter six will outline the implementation of localisation within the RVF framework, and experiments designed to test it under this new paradigm.

The three key characteristics that a swarm must possess in order to explore and map a nuclear cave environment are: sensing, locomotion and control. Having reviewed the sensory and locomotive modalities available to a heterogeneous swarm within a nuclear cave, this chapter has put forward a solution to the control of such a swarm. Chapter six will further explore this control architecture and how it can be better applied to unknown environments.

CHAPTER 6

LOCALISATION

The aim of this thesis is to explore the three key components of a heterogeneous swarm capable of exploration and mapping of a nuclear cave environment: sensing, locomotion and control. Chapter three examined the sensing modalities that could be utilised in a nuclear cave. Subsequently, chapter four examined possible locomotion strategies that could be applicable to a nuclear cave environment. The reactive virtual forces framework was introduced in chapter five as a potential solution to controlling exploration and mapping within a nuclear cave environment. This control architecture has been shown to operate more efficiently on a heterogeneous swarm compared to a homogeneous swarm.

During the initial investigations into the effectiveness of the RVF framework it was assumed that the robots' pose was known. Within a nuclear cave environment, this is not possible. Instead the robots will have to localise themselves without absolute positioning. Additionally, the performance of the RVF framework was not compared to other methods that exist. Thus, the aim of this chapter is twofold: to instigate localisation on robots using the RVF framework so that they may explore unknown environments without absolute positioning; and to assess the RVF framework on a performance scale.

As the MATLAB simulation had its accuracy verified by the embodied simulations, it was decided that the work in this chapter would be carried out within the simulation. For a full description of the MATLAB simulation environment, the reader should refer to chapter five.

This chapter is structured as follows: first, the Extended Kalman Filter used to localise the robots will be described; second, the comparative scale used to assess the performance of the RVF framework will be outlined; third, the experimental methodology used to investigate localisation will be explained; fourth, the results from these experiments will be presented; and finally, conclusions will be drawn about the effectiveness of the localised RVF framework.

6.1 Extended Kalman filter for Simultaneous Localisation and Mapping

The extended Kalman filter (EKF) has been widely used in mobile robotics for simultaneous localisation and mapping (SLAM) [112] [110] [111] [51] [85] [201]. This method allows the estimation of a robot's position and orientation based on odometry and distance sensor readings. In addition, EKF SLAM allows for a full definition of uncertainty for each landmark and the robot, through a covariance matrix. As discussed in chapter two; the full definition of uncertainty coupled with the prevalence of EKF SLAM in the literature, motivates the decision to use this method over more computationally efficient solutions such as FastSLAM [174] [173].

EKF SLAM works by finding landmarks in an environment and localising a robot relative to these. This process involves three steps:

1. **The Predict Step -** This involves a robot examining its odometry data and using this to estimate its position
2. **The Update Step -** This involves merging the odometry data and sensor data to update the position of the landmarks and robot in the state vector
3. **Data Association -** performed to decide if a robot believes it has discovered a new landmark or is instead observing a previously discovered landmark.

The robot position and position of landmarks are stored in a state vector of size 1 x (3 + 2n), where n is the number of landmarks. This is coupled with a covariance matrix of size (3 + 2n) x (3 + 2n), which stores the uncertainty in the position of landmarks.

EKF SLAM provides a robot with localisation and a system for generating a landmark based map, however it does not have an inherent exploration method. As it stands, the RVF framework is an exploration algorithm without a method for localisation. It therefore seems logical to combine these two approaches to attain an algorithm capable of exploration, mapping and localisation in an unknown environment.

This section seeks to explain how EKF SLAM was implemented to work in conjunction with the RVF framework. This section will explore: the prediction step of the EKF, the update step of the EKF, methods for achieving data association in the EKF and the integration of the EKF into the RVF framework.

6.1.1 Predict Step

The first step of the EKF SLAM process is to update the robot's estimate of its position and orientation within the environment. This is achieved by using a motion model of the robot, along with odometry or control data. In the case of a differential wheel drive robot, such as the E-Puck, the motion model is given by:

$$\hat{x} = x + dt * V * cos(\theta) \tag{6.1}$$

$$\hat{y} = y + dt * V * sin(\theta) \tag{6.2}$$

$$\hat{\theta} = \theta + \omega * dt \tag{6.3}$$

Where $\hat{x}$, $\hat{y}$ and $\hat{\theta}$ are the updated position and orientation of the robot; x, y and θ are the previous position and orientation of the robot when control was initiated; dt is the time step for which the control was implemented; and V and ω are the average velocity and angular velocity of the robot, given by:

$$\omega = \frac{v_r - v_l}{D} \tag{6.4}$$

$$V = \frac{v_r + v_l}{2} \tag{6.5}$$

Where v_r and v_l are the velocity of the right and left wheels of the robot respectively; and D is the diameter of the robot. Using these equations, a robot is able to predict where it is after applying controls v_r and v_l for time dt.

Having predicted its new position, the robot must also update its estimate of covariance that is associated with this new position. This involves updating the first three rows and columns of the covariance matrix; as these are the elements associated with robot position. To do this the Jacobian matrices corresponding to position and control, G_v and G_u, are required:

$$G_v = \begin{pmatrix} \frac{\delta F_x}{\delta x} & \frac{\delta F_x}{\delta y} & \frac{\delta F_x}{\delta \theta} \\ \frac{\delta F_y}{\delta x} & \frac{\delta F_y}{\delta y} & \frac{\delta F_y}{\delta \theta} \\ \frac{\delta F_\theta}{\delta x} & \frac{\delta F_\theta}{\delta y} & \frac{\delta F_\theta}{\delta \theta} \end{pmatrix} = \begin{pmatrix} 1 & 0 & -V * dt * sin(\theta) \\ 0 & 1 & V * dt * cos(\theta) \\ 0 & 0 & 1 \end{pmatrix} \tag{6.6}$$

$$G_u = \begin{pmatrix} \frac{\delta F_x}{\delta v_r} & \frac{\delta F_x}{\delta v_l} \\ \frac{\delta F_y}{\delta v_r} & \frac{\delta F_y}{\delta v_l} \\ \frac{\delta F_\theta}{\delta v_r} & \frac{\delta F_\theta}{\delta v_l} \end{pmatrix} = \begin{pmatrix} \frac{dt * cos(\theta)}{2} & \frac{dt * cos(\theta)}{2} \\ \frac{dt * sin(\theta)}{2} & \frac{dt * sin(\theta)}{2} \\ \frac{dt}{D} & \frac{dt}{D} \end{pmatrix} \tag{6.7}$$

Where F_x is the motion model associated with the x position, F_y is the motion model associated with the y position and F_θ is the motion model associated with the orientation of the robot. The predicted covariance, $\hat{P}$, can now be calculated as:

$$\hat{P} = G_v P G_v^T + G_u Q G_u^T \tag{6.8}$$

Where G_v and G_u are the Jacobians defined previously, P is the previous covariance matrix and Q is a fixed matrix associated with the control noise defined as:

$$Q = \begin{pmatrix} \sigma_{v_r}^2 & 0 \\ 0 & \sigma_{v_l}^2 \end{pmatrix} \tag{6.9}$$

Where $\sigma_{v_r}^2$ and $\sigma_{v_l}^2$ are the noise associated with the right and left wheel velocity respectively.

Using the equations presented in this section, a robot is able to predict its new position based on the control data. Following this the robot can estimate the covariance associated with this new position. This is the goal of the prediction step of the EKF. The next section will outline the update step in which odometry error may be corrected for through use of the robot's distance measurements.

6.1.2 Update Step

The update step allows for the robot to incorporate sensor readings into its estimate of position. This gives increased accuracy to the estimate as it means the robot does not have to rely on dead reckoning alone. This requires that the robot have an observation model so that it can use the sensor readings to estimate the position of new landmarks or derive a better estimate of its position from re-observation of previously discovered landmarks. In the case of a robot able to measure distance and bearing, the predicted observation, z, is given by:

$$z = \begin{pmatrix} Range \\ Bearing \end{pmatrix} = \begin{pmatrix} \sqrt{dx^2 + dy^2} \\ tan^{-1}(\frac{dx}{dy}) - \theta \end{pmatrix} \tag{6.10}$$

Where dx is the distance to the landmark along the x axis, dy is the distance to the landmark along the y axis and θ is the robot's orientation. This observation model is associated with the following Jacobian:

$$H = \begin{pmatrix} \frac{\delta z_1}{\delta x} & \frac{\delta z_1}{\delta y} & \frac{\delta z_1}{\delta \theta} \\ \frac{\delta z_2}{\delta x} & \frac{\delta z_2}{\delta y} & \frac{\delta z_2}{\delta \theta} \end{pmatrix} = \begin{pmatrix} \frac{x-\lambda_x}{r} & \frac{y-\lambda_y}{r} & 0 \\ \frac{\lambda_y - y}{r^2} & \frac{\lambda_x - x}{r^2} & -1 \end{pmatrix} \tag{6.11}$$

Where λ_x and λ_y define the x and y position of the landmark respectively, x and y define the robot position and r is the Euclidian distance to the landmark.

Using this observation model, a robot can estimate the position of landmarks in the environment. These landmarks are then associated with already existing landmarks, if no match is found then a new landmark is added to the state vector. This data association process is covered in more detail the next section.

Having calculated the Jacobian of the observation model, it is now possible to determine the Kalman gain. The Kalman gain is essentially a matrix determining how much the observation model is trusted, which defines the quality of the sensors. The Kalman gain, K, is calculated using:

$$K = P * H^T * (HPH^T + R)^{-1} \tag{6.12}$$

Where P is the covariance matrix, H is the observation Jacobian and R is the noise matrix associated with the sensors defined as:

$$R = \begin{pmatrix} \sigma_r^2 & 0 \\ 0 & \sigma_b^2 \end{pmatrix} \tag{6.13}$$

Where σ_r is the noise associated with the range measurement and σ_b is the noise associated with the bearing measurement.

The final step in updating the robot is to use the Kalman gain to update the state vector X, defining the robot position and position of landmarks, along with updating the covariance P, defining the uncertainty associated with the state vector. This is achieved using the following update equations:

$$\hat{X} = X_p + K(z - HX_p) \tag{6.14}$$

$$\hat{P} = (I - KH)P_p \tag{6.15}$$

Where X_p is the state vector after having the robot position updated by the predict step, K is the Kalman gain, P_p is the covariance matrix after it has been updated during the predict step, H is the observation covariance and I is the identity matrix.

The combination of the update step and the predict step allow for a robot to consider both its odometry and sensor data. The Kalman gain then enables the robot to weight these data depending on whether the odometry or distance sensors are considered more accurate. The last step is to associate the landmarks that are observed and add new landmarks to the state vector. This is discussed in the next section.

6.1.3 Data Association

The state vector contains the x-y position of all the landmarks in the map, along with the x-y position and orientation of the robot. During the update step of the EKF the state vector is updated to contain the new best estimates for the position of the robot and landmarks, considering both the odometry and sensor data. For this to occur the robot must be able to determine whether its sensors are observing a new landmark or re-observing a previously visited landmark; this is the purpose of data association.

Data association is implemented in this project through nearest neighbour gating. This involves comparing a measurement to all features in the environment and determining which is the closest match. This closest match is then compared to a threshold value, defined by a number of standard deviations. If the closest match is below the threshold then the measurement is associated to that landmark, if it is not then the measurement is assumed to be related to a new landmark and this is added to the state vector. The threshold value used in this project was chosen to be 20.

The metric used to compare the measurement to the landmarks in the map was the Mahalanobis distance. To calculate the Mahalanobis distance, first the innovation, v, and innovation covariance, S, are required. The innovation is the difference between the predicted measurement, obtained via the observation model, and the actual measurement. The innovation and innovation covariance are determined by the following equations:

$$v = z - z_p \tag{6.16}$$

$$S = HPH^T + R \tag{6.17}$$

Where z is the actual measurement, z_p is the predicted measurement, H is the observation Jacobian, P is the covariance matrix associated with the state vector and R is the observation noise.

Once these values have been calculated, it is possible to determine the Mahalanobis distance, M. This is calculated as follows:

$$M = v^T S^{-1} v \tag{6.18}$$

This process is then repeated for each measurement that the robot takes, to compare them to each feature in the map. At the end of this process all measurements are either associated to pre-existing landmarks or added to the state vector as new landmarks.

Data association is the most important part of the SLAM process for ensuring map accuracy. If a measurement is incorrectly associated, then it can cause compounding errors that cannot be corrected for. Overall, using the predict step, update step and data association the robot can accurately localise itself within an unknown environment. The remaining task is to explore that environment, this is the utility of the RVF framework. The next section will discuss how the RVF framework was implemented in conjunction with EKF SLAM.

6.1.4 Integration with Reactive Virtual Forces Framework

Thus far, using the EKF to localise the robot has been discussed. In order to explore and map an unknown environment, such as a nuclear cave, the RVF framework needed to be integrated. This section will explore the changes required to implement the RVF framework in conjunction with the EKF.

The EKF SLAM is capable of producing its own map; this is in the form of landmarks that have an associated error ellipse, as shown in figure 6.1. However, the RVF framework requires that an occupancy grid be used so that the forces may attract a robot to unexplored cells. This

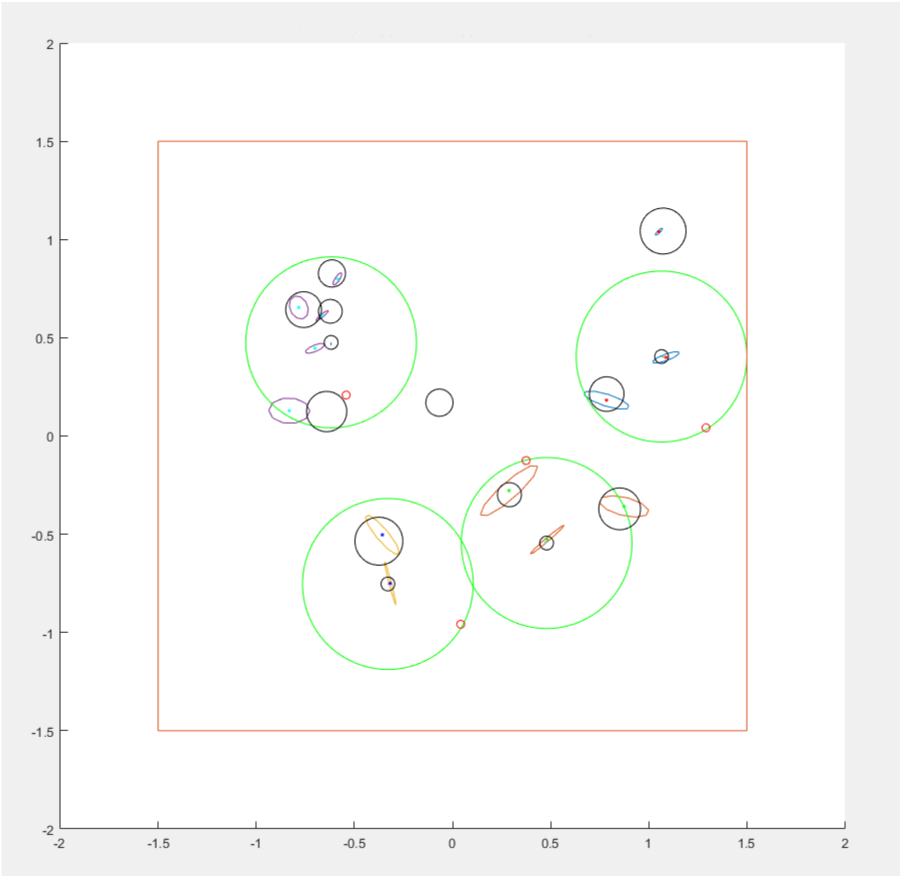


Figure 6.1: The SLAM map generated by the robots. The ellipses and dots near obstacles represent the error ellipse and estimated position of the landmarks. Ellipses around robots represent their uncertainty in their own position. Circles around robots represent their sensor range.

also provides a better definition of free space compared to the landmark representation used by the EKF. The occupancy grid was implemented in the same manner as described in chapter five. The difference is that instead of using the known position of the robot, the estimated position is used. The benefit of introducing the occupancy grid is twofold: first, it allows the exploration algorithm to function; second, it means that two maps are generated and can be compared to glean more information about the environment.

As the robots now have two maps that they are generating, it seemed logical to allow them to share both these maps with other robots within communication range. The method for sharing the occupancy grid map is already in place; robots exchange maps and take the average of the values for each grid square accounting for both maps. However, there was not currently a method for communicating EKF state vector maps, thus this required that a new system was implemented for sharing the EKF maps.

Communicating EKF maps is more challenging than exchanging occupancy grids, especially if the robots are not operating in the same global coordinate frame. For this implementation it was assumed that the robots are operating in the same coordinate frame, as their deployment position within the nuclear cave is known. This reduces the complexity of the communication problem, as it now means that robots can communicate their state vectors without having to determine a transformation matrix.

When robots are within communication range, they share their state vectors and associated covariances with one another. It is then necessary to perform data association between communicated state vectors, to examine whether landmarks match. This process is completed in the same way as described in the previous section, using the Mahalanobis distance. If landmarks are determined to match, then the average position is taken to be the new landmark position in each state vector. If a landmark is found to not exist in one of the maps, it is added to the state vector.

When a landmark's position is altered in the state vector, the associated rows and columns in the covariance matrix must be updated. In the case where the landmarks are found to match, the average between the associated rows and columns in the covariance matrices are calculated, these values are used to update both matrices. If a landmark is determined to be new, then a new row and column are added to the appropriate covariance matrix using the values from the communicated covariance matrix.

This process allows robots to communicate the maps generated through EKF SLAM. The communication of these maps means that the robots have more landmarks with which to localise themselves and thus can more accurately estimate their own position.

6.2 A Comparative Scale

The RVF framework has been found to operate more efficiently on a heterogeneous swarm than a homogeneous swarm. This comparison is interesting and shows that it could be an appropriate choice for the exploration and mapping of a nuclear cave environment utilising a heterogeneous swarm of robots. Though the RVF framework has been compared to itself under different operating paradigms, its general efficiency has not been explored.

The aim of this section is to define a comparative scale on which the RVF framework may be placed. On the lower end of the scale is the 'best worst solution', this is the Levy walk [200] [21]. The Levy walk is a random walk that has been found to be used by animals and is optimised for searching unknown environments for food. This is the 'best worst solution' as random walks are the least efficient way to search an environment but of the random walk implementations, the Levy walk is the best suited to this task.

On the top end of the scale is the theoretical perfect raster. This is the fastest possible time that a robot, or swarm of robots, could possibly explore an environment. It is calculated by assuming that robots are always exploring previously unexplored regions of the map.

The hope was that the RVF framework would be closer to the perfect raster time than the Levy walk time. This section will show how the Levy walk was implemented and how the perfect

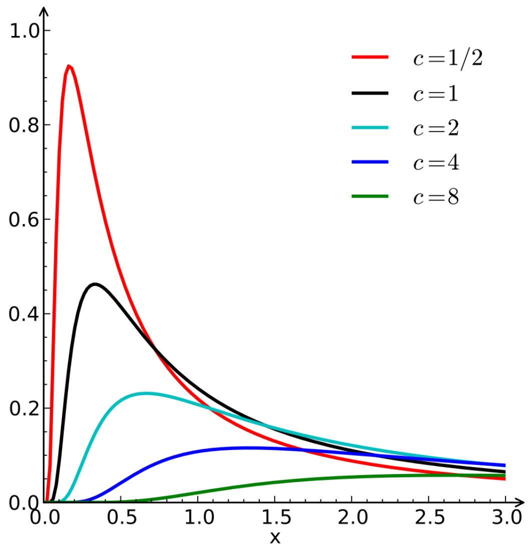


Figure 6.2: The Levy distribution for several values of the scaling parameter, c.

raster time was calculated. The experiments used to compare the RVF framework to the Levy walk will be detailed in the next section.

6.2.1 Levy Walk

The Levy random walk is used by many animals to explore unknown environments whilst foraging for food [200] [21]. As the Levy walk is optimised for exploration of unknown environments it seems an obvious choice for comparison to the RVF exploration framework. The Levy walk is still a random walk and is surpassed in efficiency by algorithms specifically designed for exploration; this makes it a suitable choice for the lower end of a comparative scale.

To perform a Levy walk a robot is first required to turn through a random angle, in the range 0 - 2π radians. Having turned, the robot must then move in that direction for x steps, where x is randomly drawn from the Levy Distribution shown in figure 6.2. The Levy probability distribution is defined by:

$$F(x:\mu,c) = \sqrt{\frac{c}{2\pi}}\,\frac{e^{-\frac{c}{2(x-\mu)}}}{(x-\mu)^{3/2}} \tag{6.19}$$

Where c is the scale parameter, μ is the location parameter and x is the number of steps. In this project c was chosen to be 0.2 and μ was chosen to be 0.07, in order to achieve step lengths of the appropriate size for the test arena.

To generate the x steps for the robot the inverse cumulative distribution is needed, this allows the robot to draw a random number of steps from the probability distribution. The numbers of steps, x, is given by:

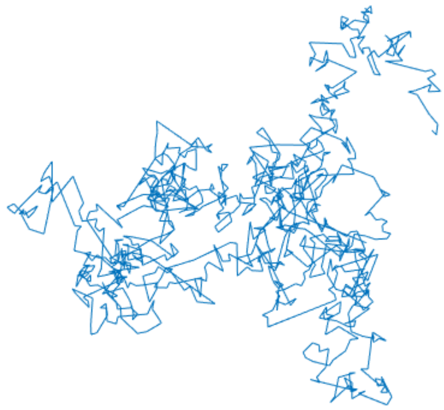


Figure 6.3: One thousand steps of a Levy random walk, generated in MATLAB.

$$x = \frac{c}{2}\text{erfcinv}(N_r)^2 + \mu \tag{6.20}$$

Where N_r is a random number that is being mapped onto the Levy distribution, c is the scale parameter and μ is the location parameter; erfcinv is the MATLAB function for calculating the inverse complementary error function.

To make the robot turn a random angle, the MATLAB *rand* function was used to generate a random number in the range 0 - 2π radians. The robot then calculates the number of seconds it must actuate its wheels for to turn this number of degrees. Wheels are actuated with one at negative maximum velocity and the other at positive maximum velocity. After turning to the appropriate angle, the robot moves forwards x steps and then repeats the process. A Levy walk that was repeated for one thousand iterations is shown in figure 6.3.

After implementing the foundation for the Levy walk, it was necessary to instigate an obstacle avoidance strategy. It was decided that this would be achieved by having the robot turn thirty degrees away from any detected obstacle and then continuing its random walk. This simple strategy allows a robot to perform a Levy random walk, whilst simultaneously avoiding collision. Whilst executing the Levy random walk, the robot localises itself using the EKF as described in the previous section.

This section has described how the Levy random walk is implemented in this project. Experiments designed to compare this method to the RVF framework will be detailed in the 'Experimental Methodology section'.

6.2.2 Perfect Raster

The Levy walk defines the lower end of the comparative scale. At the opposite end of this scale is the perfect raster. This is the minimum exploration time possible in an environment and assumes that a robot is always maximising its coverage per second. To determine this minimum time, first the coverage, C, of a robot needs to be calculated. This is achieved through finding the circular area about the robot defined by its sensor range, which is 0.4m for the simulated E-Pucks:

$$C = \pi r^2 = \pi * 0.4^2 = 0.503 \tag{6.21}$$

The coverage per second, C_p for a single robot can then be calculated by multiplying its coverage by its maximum speed, in this case 0.07m/s:

$$C_p = Cv = 0.503 * 0.07 = 0.035 \tag{6.22}$$

Finally, the minimum search time t_{min} can be calculated by dividing the total area by the coverage per second. In the case of the 3x3m arena used in the MATLAB simulation environment, this area was determined to be 9m^2:

$$t_{min} = \frac{A}{\pi r^2 v} = \frac{9}{\pi * 0.4^2 * 0.07} = 255.8 \tag{6.23}$$

This gives the minimum exploration time for a single robot in the environment. As the RVF framework was tested on a swarm of four robots, it was necessary to account for this in the minimum exploration time. Minimum exploration time is achieved if the robots are able to plan their paths so that they explore different areas of the map and are able to communicate their individual maps to one another at the moment they reach 25% coverage. For example, this could be achieved if each robot was initialised in a corner and moved towards the centre in a zig-zag as shown in figure 6.4. In this case the minimum exploration time for homogeneous robots is one quarter that of a single robot, or 63.9 seconds. As the average values are maintained for the heterogeneous and homogeneous swarms, this value remains true for both swarm compositions.

This section has described the comparative scale that will later be used to assess the performance of the RVF framework. At one end of the scale is the exploration time of the Levy random walk, which will be determined by experimentation. The other end of the scale is defined by the perfect raster, which has been calculated for the MATLAB simulation to be 69.3 seconds for a swarm of four robots. The subsequent section will outline the experimental methodology used to examine the localised RVF framework and place it on the comparative scale.

6.3 Experimental Methodology

The aim of these experiments was twofold: first, to further investigate the effectiveness of the RVF framework whilst incorporating localisation using the EKF; second, to establish the Levy walk exploration time as a means for comparison.

As the embodied simulations verified the results gathered in the MATLAB simulation, it was decided that these experiments would be conducted in simulation. This decision was made both

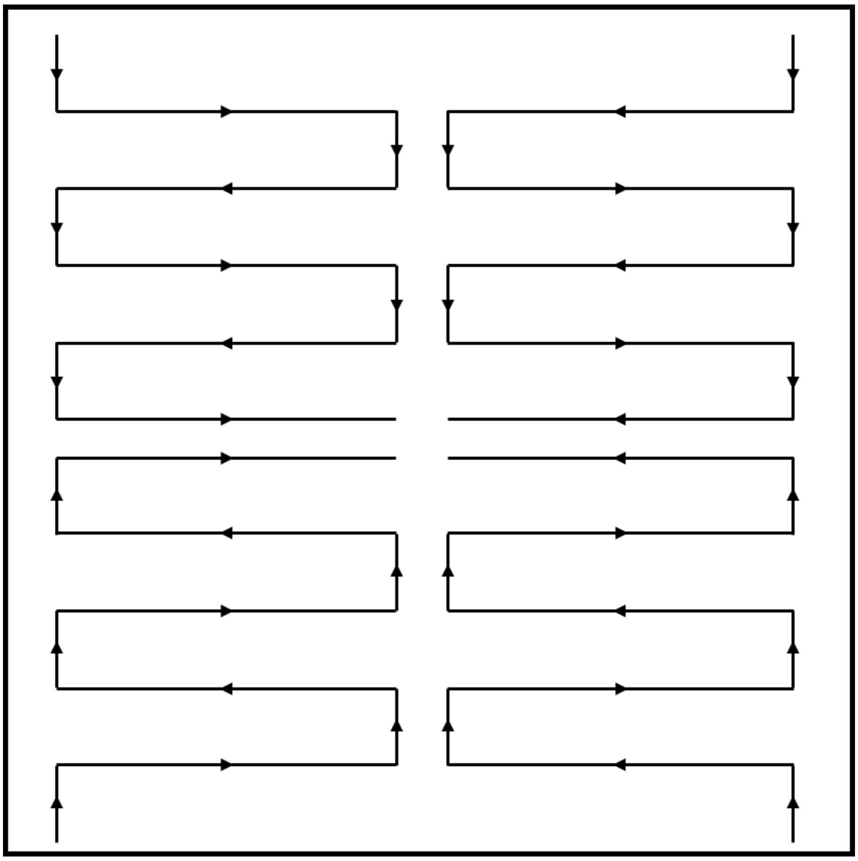


Figure 6.4: An example of a potential implementation of a perfect raster for four robots.

because it allowed more experiments to be undertaken rapidly and prevented the computational complexity of the SLAM algorithm being used on the real E-Pucks, which are prone to crashing.

This section will first detail experiments used to find the Levy random walk comparative time. Following this, the experiments conducted on the RVF framework will be explained. The results from these experiments will be presented in the subsequent section.

6.3.1 Random Walk Experiments

Having defined the lower end of the comparative scale as a Levy random walk, it was necessary to ascertain the exploration time that this method was capable of. This could then be compared to the exploration time of the RVF framework.

Experiments were implemented on both a homogeneous and heterogeneous swarm, in the 3x3m MATLAB test arena. As in the previous MATLAB simulation experiments, the homogeneous swarm was comprised of four robots utilising the augmented E-Puck parameters (diameter 0.07m, mass 0.2kg, imposed maximum speed 0.07m/s, augmented sensor range 0.4m and virtual charge $4x10^8$). The heterogeneous swarm also utilised the same composition as the previous experiments, with one large robot, two medium robots and one small robot with the following parameters:

- Small Robot – diameter 0.035m, mass 0.1kg, maximum speed 0.035m/s, sensor range 0.2m and virtual charge $2x10^8$
- Two Medium Robots – diameter 0.07m, mass 0.2kg, maximum speed 0.07m/s, sensor range 0.4m and virtual charge $4x10^8$
- Large Robot – diameter 0.14m, mass 0.4kg, maximum speed 0.14m/s, sensor range 0.8m and virtual charge $8x10^8$

The average values in both swarms remained the same so that a fair comparison could be made.

In addition to using the swarm compositions described above, additional tests were run at a lower speed. This was because the EKF localisation can more accurately determine a robot's position if the robot is travelling at a lower speed. Due to this it was decided that it would be valuable to investigate the effect of speed on the quality of exploration and map accuracy. To accomplish this the homogeneous robot speed was changed to 0.02m/s, whilst the heterogeneous swarm used speeds of 0.04m/s, 0.02m/s and 0.01m/s for the large, medium and small robots respectively, keeping all other parameters the same. From now on the swarms using the average value of 0.07m/s will be referred to as *fast swarms* and those using an average value 0.02m/s will be referred to as *slow swarms*.

In order to more fairly compare the Levy walk strategy to the RVF framework, it was important to introduce the same end condition for both sets of experiments. To do this an occupancy grid was introduced into the Levy walk. The occupancy grid was filled in the same manner as with the RVF framework, however it had no bearing on Levy walk exploration. This allowed the end condition for the Levy walk to match that of the RVF framework: time taken for three of the four exploring robots to reach 80% coverage of the environment. Using this end condition, tests were repeated thirty times both for the homogeneous fast and slow swarms and the heterogeneous fast and slow swarms.

After each of the thirty trials, three metrics were recorded: time, distance and accuracy. Time is the time taken for three of the robots to reach 80% coverage. Distance refers to the total distance travelled by all the robots during each experiment. Finally, accuracy is a measure of how similar the occupancy grid produced using the exploration method is when compared to a perfect occupancy grid. This is determined by comparing each cell of a perfect occupancy grid to each cell of the occupancy grid filled by a robot and dividing by the total number of grid squares. The average accuracy of all robots' is then determined and recorded.

Using the experimental methodology detailed above, the performance of the Levy random walk can be assessed. This allows for a comparison to be made to the RVF framework. The next section will detail the experiments conducted on the RVF framework.

6.3.2 Reactive Virtual Forces Experiments

The aim of the RVF experiments was to instigate localisation using the EKF and examine how the exploration algorithm performed under this new paradigm. This would entail comparison between EKF localised swarms and 'absolute position known' (APK) swarms.

Both the EKF localised and the APK experiments were conducted using homogeneous and heterogeneous swarms. As with the Levy walk it was decided that the experiments should be run at two different speeds, to examine the effect on map accuracy and exploration, along with enabling comparison to the Levy walk experiments. The swarm compositions used for the RVF experiments are the same as those used in the Levy walk experiments, both for fast and slow swarms.

Using the EKF for localisation meant that the time between each update step was lowered to 0.1 seconds, rather than using the 1 second increments used in the initial MATLAB simulation. Though this increases the time taken for each simulation, it also allows the EKF to be updated more frequently. This is akin to the update rate achieved by real robots and allows the EKF to operate more accurately. This permits fair comparison to the Levy walk and localised RVF framework experiments.

The experiments conducted were as follows:

- **Slow Homogeneous APK** – this experiment used a homogeneous swarm whose absolute position was known. The average speed of the swarm was 0.02m/s.
- **Fast Homogeneous APK** – this experiment used a homogeneous swarm whose absolute position was known. The average speed of the swarm was 0.07m/s.
- **Slow Heterogeneous APK** – this experiment used a Heterogeneous swarm whose absolute position was known. The average speed of the swarm was 0.02m/s.
- **Fast Heterogeneous APK** – this experiment used a Heterogeneous swarm whose absolute position was known. The average speed of the swarm was 0.07m/s.
- **Slow Heterogeneous EKF Localised** – this experiment used a Heterogeneous swarm localised using the EKF. The average speed of the swarm was 0.02m/s.
- **Fast Homogeneous EKF Localised** – this experiment used a Homogeneous swarm localised using the EKF. The average speed of the swarm was 0.07m/s.
- **Slow Homogeneous EKF Localised** – this experiment used a Homogeneous swarm localised using the EKF. The average speed of the swarm was 0.02m/s.
- **Fast Heterogeneous EKF Localised** – this experiment used a Heterogeneous swarm localised using the EKF. The average speed of the swarm was 0.07m/s.

Test	Average Time/ s		Average Distance/ m		Accuracy/ %	
	Slow Swarm	Fast Swarm	Slow Swarm	Fast Swarm	Slow Swarm	Fast Swarm
Homogeneous	908.33	1448.42	13.38	31.34	93.62	68.26
Heterogeneous	899.27	1219.19	13.14	28.79	95.31	73.68

Table 6.1: Results from the Levy Random walk experiments.

Each experiment concluded when three of the four robots comprising the swarm reached 80% coverage. Thirty trial were conducted for each scenario described above. In each case the time taken to reach 80% coverage was recorded, along with the total distance travelled by the robots. For the EKF localised experiments the occupancy grid accuracy was also noted, calculated in the same manner as for the Levy walk. The results of these experiments will be presented in the next section.

6.4 Results

The aim of this chapter is both to examine the effect of localisation on the RVF framework and to evaluate the RVF framework based on a comparative scale. In the previous sections, the comparative scale and the experiments used to assess the RVF framework have been detailed. This section will present the results from these experiments and aim to gauge the efficiency of the RVF framework based on these results.

This section will present: results from the random walk experiments, results from the RVF experiments, an evaluation of the RVF framework based on the comparative scale and statistical testing to examine the significance of the results.

6.4.1 Random Walk Results

The random walk used in these experiments was the Levy walk, a random walk optimised for the exploration of unknown environments. The Levy walk experiments were conducted to allow for the bottom end of a comparative scale to be realised. Four experiments were conducted: a fast homogeneous swarm, a slow homogeneous swarm, a fast heterogeneous swarm and a slow heterogeneous swam. The results from these experiments are collated in table 6.1.

The first interesting result from this is that it does not appear that homogeneity vs heterogeneity makes a marked difference to the exploration time, distance or accuracy in the case of the slow swarm. For the fast swarm it makes a small difference, with the heterogeneous swarm exploring marginally more efficiently and attaining a 5% increase in accuracy. This result is expected as the average values of the two swarm compositions are the same. The statistical significance of these results will be explored later.

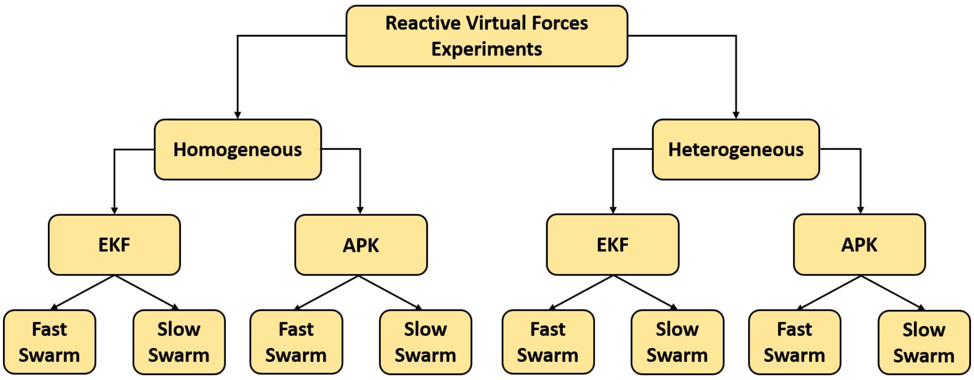


Figure 6.5: The experiments conducted with the RVF framework to examine the effect of localisation.

Another noteworthy result is that the fast swarm explores the environment significantly slower than the slow swarm, in both the homogeneous and heterogeneous case. This was not expected, as it was thought that a faster swarm will explore the environment more rapidly. The reason for this result is likely to be the fact that the fast swarm encounters obstacles more frequently. This is because whilst performing a Levy walk the robots move forward for a random amount of time. The fast swarm will move further in this amount of time and is hence more likely to encounter an obstacle, interrupting its random walk.

The last result to be discussed is the disparity in accuracy presented by the slow and fast swarms. This result was anticipated, as the EKF used to localise the swarms whilst performing the Levy walk is less accurate when robots are travelling at increased speeds. Additionally, the multiple sharp turns undertaken during the Levy walk are also expected to reduce the accuracy of the EKF localisation. Finally, as time passes the EKF can slowly lose accuracy and as the fast swarm experiments ran for longer on average, this is also a factor in the reduced map accuracy.

6.4.2 Reactive Virtual Forces Results

The RVF experiments were conducted to examine the effect of localisation on the RVF framework. Eight experiments were conducted as can be seen in figure 6.5. The results from these experiments are summarised in table 6.2.

The results show that using the EKF localisation, compared to having the absolute position known, has no significant effect on the exploration time or distance travelled by the swarm in either the fast or slow case. This is to be expected as the robots are still exploring the same environment with the same control algorithm, whether they are self-localised or not. However, it was found that the accuracy of the occupancy grid generated was lower when the swarm was travelling faster. There was an average difference of 7% accuracy between the slow and fast swarms. As with the random walk, this was assumed to be due to the fact the EKF becomes less accurate at higher speeds. Interestingly, the time taken for exploration was almost halved

Test	Average Time/ s		Average Distance/ m		Accuracy/ %	
	Slow Swarm	Fast Swarm	Slow Swarm	Fast Swarm	Slow Swarm	Fast Swarm
Homogeneous APK	477.73	191.60	6.67	6.86	n/a	n/a
Homogeneous EKF	474.58	193.60	6.78	7.15	98.45	91.41
Heterogeneous APK	213.52	116.21	3.37	3.82	n/a	n/a
Heterogeneous EKF	211.12	110.21	3.28	4.21	99.93	92.97

Table 6.2: Results from the RVF framework experiments with absolute known position (APK) and EKF localisation (EKF).

between the slow and the fast swarms. This leaves an interesting choice between the benefit of a more accurate map and the advantages of exploring the environment more quickly. For larger environments where battery life of the robots might be a concern a faster exploration time might be more beneficial. Conversely, in a small cluttered environment a greater accuracy may be desired. A nuclear cave can range in size and is likely to be cluttered. In this case it is assumed that the decision would be made based on the size of the nuclear cave, as the contents are unknown.

As well as demonstrating the effect of localisation on the RVF framework the results from these experiments, both in the fast and slow cases, corroborate those found in the previous MATLAB simulations and the embodied simulations. That is the heterogeneous swarm explores the environment more efficiently than the homogeneous swarm. Additionally, it was found that both the homogeneous and heterogeneous swarm exhibit a similar level of accuracy when localised.

This section has examined the results from the RVF experiments, in the next section these results will be compared to the random walk and perfect raster to evaluate the performance of the RVF framework on a comparative scale. In the following section the statistical significance of these results will be detailed.

6.4.3 Evaluating Reactive Virtual Forces

It has been shown that the reactive virtual forces framework operates more efficiently on a heterogeneous swarm when compared to a homogeneous swarm utilising the same average abilities. In addition, the previous section showed that introducing localisation into the framework did not affect the exploration time, or distance travelled.

As well as examining the effect of swarm composition and speed on the RVF framework, it is also important to assess it as a general method for exploration. To do this a comparative scale was formulated. At the lower end of this scale is the Levy random walk, described earlier in this chapter. The exploration time for this method was determined experimentally in the same MATLAB environment as the RVF framework. The results are collated in table 6.1.

The upper end of the scale is occupied by the perfect raster, for which the exploration time

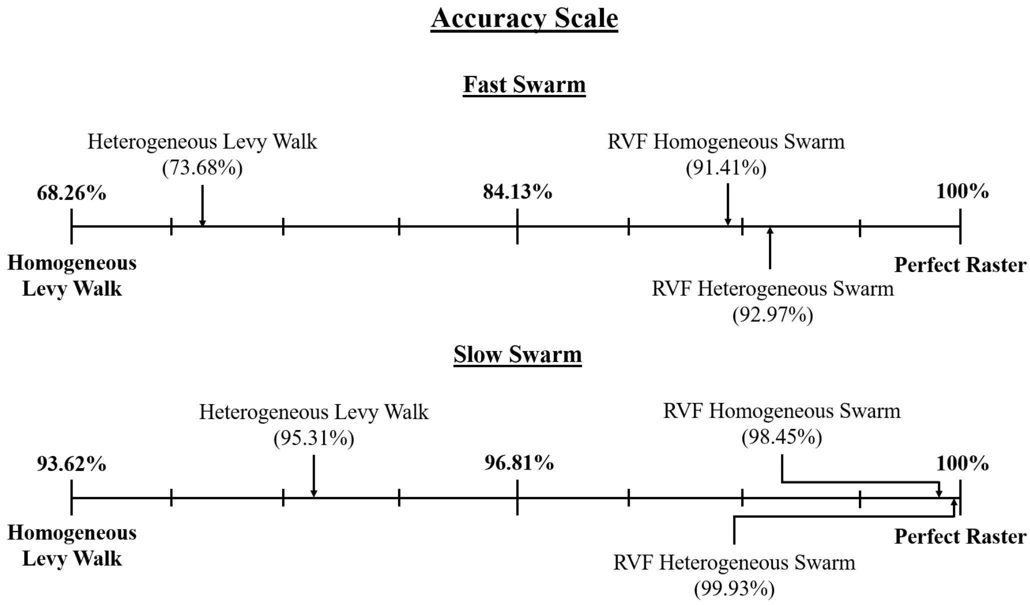


Figure 6.6: Shows where accuracy of the RVF framework sits on the comparative scale.

to cover 100% of the environment for four robots was calculated to be 69.3 seconds. This value needs to be adjusted to account for the end condition of 80% of the environment being explored and needs to consider both the fast swarm and the slow swarm. This yields values for the perfect raster of 51.2 seconds for the fast swarm and 179 seconds for the slow swarm. As the average values are the same for the homogeneous and heterogeneous swarm, these values remain constant regardless of swarm configurations. It is also assumed that the perfect raster allows robots to attain 100% accuracy when exploring their environment. It should be noted that a perfect raster requires that robots can plan their path without obstruction and have accurate knowledge of their position at all times. These requirements make it impossible to implement for exploration of a nuclear cave and thus represents a perfect scenario.

Two scales can be defined using the results from the RVF experiments: an accuracy scale and an exploration time scale. The first of these scales to be examined is the accuracy scale, as shown in figure 6.6. On this scale, only the EKF localised RVF method is placed as both the Levy random walk and the RVF method used the same method for localisation in this case.

It can be seen from figure 6.6 that the reactive virtual forces method is near the top end of the scale in terms of accuracy. The slow RVF swarm is superior in terms of accuracy compared to the fast swarm, but both the fast and slow swarms perform significantly better than the random walk. The random walk instigates many random turns and short bursts forwards, which can cause the EKF to lose accuracy for localisation. This is thought to be the reason for the increased performance of the RVF for accuracy. Additionally, the RVF method causes robots to interact more often as they are using an exploration algorithm that may cause them to explore similar

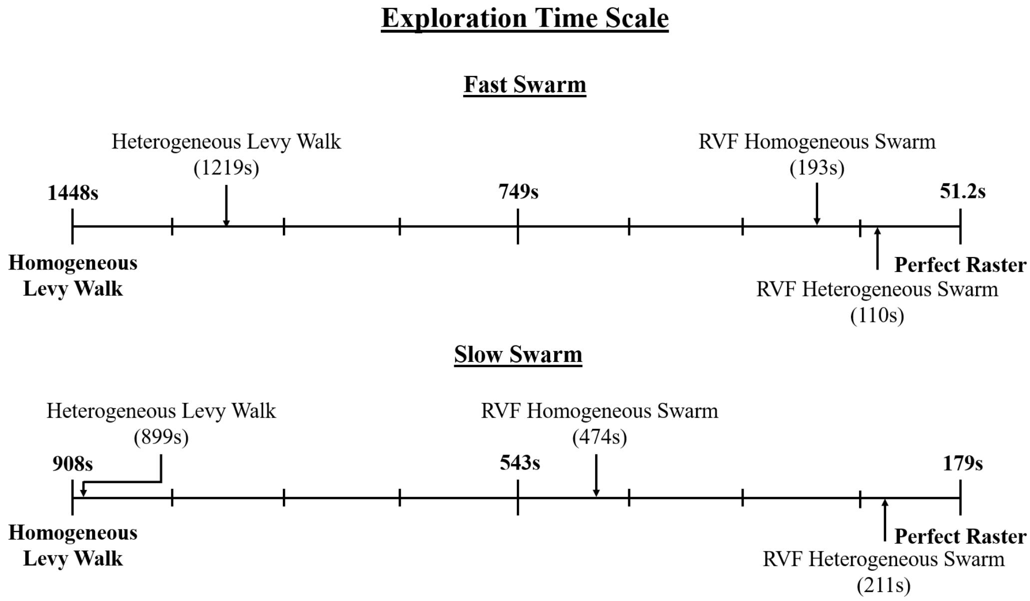


Figure 6.7: Shows where exploration time of the RVF framework sits on the comparative scale.

areas. This allows robots to share their maps more often, which in turn increases their accuracy.

The second scale to be inspected is the exploration time scale, shown in figure 6.7. As before, only the EKF localised RVF method is placed as both the Levy random walk and the RVF method used the same method for localisation in this case.

Figure 6.7 shows that the reactive virtual forces method is near the top end of the exploration time scale for both the heterogeneous and homogeneous swarm. This is true for both the fast swarm and the slow swarm case. As has already been shown, the heterogeneous swarm explores the environment more efficiently than the homogeneous swarm. The fact that the RVF framework is at the upper end of the scale is promising for it as an exploration strategy. It shows that the RVF exploration method is an efficient way to search an environment, especially when using a heterogeneous swarm.

Overall, the results show that the reactive virtual forces framework is an efficient exploration strategy that can be used to explore complex unknown environments. In addition, it has been shown that a swarm using the RVF framework can localise itself within an unknown environment. This suggests that the RVF framework is an effective solution to exploration and mapping within a nuclear cave environment using a heterogeneous swarm of autonomous robots.

6.4.4 Statistical Testing

The aim of this section is to examine the statistical significance of the results that have been presented. To achieve this T-tests were used. A T-test involves the postulation of a null hypothesis that is rejected if the T-value is below a certain threshold; in this case a value of 0.05 was chosen

	T-Values: APK vs EKF Localised RVF framework			
	Fast Swarm		Slow Swarm	
	Time	Distance	Time	Distance
Homogeneous Swarm	0.86	0.42	0.91	0.74
Heterogeneous Swarm	0.58	0.23	0.81	0.48

Table 6.3: T-test values examining the statistical significance of the EKF localised RVF experiments vs the absolute known position RVF experiments.

	T-Values: Levy Walk vs EKF Localised RVF Framework					
	Fast Swarm			Slow Swarm		
	Time	Distance	Accuracy	Time	Distance	Accuracy
Homogeneous Swarm	$1.5\text{x}10^{-13}$	$3.3\text{x}10^{-14}$	$7.6\text{x}10^{-13}$	$4.77\text{x}10^{-6}$	$8.3\text{x}10^{-7}$	$2.3\text{x}10^{-4}$
Heterogeneous Swarm	$6.7\text{x}10^{-11}$	$1.6\text{x}10^{-10}$	$1\text{x}10^{-13}$	$5.4\text{x}10^{-9}$	$6.4\text{x}10^{-8}$	$2.8\text{x}10^{-7}$

Table 6.4: T-test values examining the statistical significance of the Levy random walk experiments vs the EKF localised RVF experiments.

to represent 98% significance.

The first set of T-tests conducted were to compare the EKF localised swarms to the APK swarms. For each parameter the null hypothesis was that 'localisation should not affect the result'. The results for these T-tests are summarised in table 6.3.

These results show that no matter the swarm composition, or speed, the null hypothesis may be accepted. That is to say that localisation does not affect the performance of the RVF framework.

The second set of T-tests were to investigate the Levy walk results when compared to the RVF framework results. For each parameter the null hypothesis was 'the RVF framework does not explore an environment more efficiently than the Levy random walk'. The results from the Levy walk T-tests are presented in table 6.4.

These results show that in each case the null hypothesis may be rejected. Thus, utilising the RVF framework produces a statistically significant effect on the efficiency of exploration when compared to a Levy random walk.

Overall, the T-tests show that the results gathered in this chapter are statistically significant; the efficiency of exploration is considerably improved by using the RVF framework over the Levy random walk; and the introduction of EKF localisation to the RVF framework does not affect the exploration time.

6.5 Chapter Summary

The aims of this chapter were: to investigate the effectiveness of the RVF framework whilst incorporating localisation using the EKF; and to evaluate the RVF framework based on a comparative scale.

It was found that the efficiency of the RVF framework was not affected by the introduction of localisation. This result was shown to be statistically significant regardless of the speed of the swarm or the swarm composition. Additionally, it was found that the accuracy of the occupancy grid generated by the RVF framework diminished as the speed increased.

A comparative scale was defined so that the effectiveness of the RVF framework could be analysed. At the lower end of the scale is the Levy random walk, whilst the top of the scale is occupied by the perfect raster. The RVF framework was placed on this scale both to assess the exploration time and the accuracy of the map that it produced. It was found that the RVF framework was significantly closer to the perfect raster on both scales. This suggests that it is an efficient and accurate exploration strategy.

Overall, the RVF framework has proven itself to be an efficient method for instigating exploration in an unknown environment. It has been shown that it is possible to use the RVF framework to produce simultaneous localisation and mapping. In addition, the RVF framework performs more efficient exploration when implemented on a heterogeneous swarm. Thus, if a heterogeneous swarm were to be utilised for exploration and mapping of a nuclear cave environment, the RVF framework would serve as a suitable control architecture.

This chapter completes the examination of the RVF framework as a control method. This thesis has examined the three key components that comprise a swarm capable of exploration and mapping of a nuclear cave environment: sensing, locomotion and control. The final chapter of the thesis will conclude by discussing each of these elements and how they might combine, along with providing suggestions for future work.

CHAPTER 7

Conclusions and Future Work

This thesis examined three main components of a heterogeneous robot swarm tasked with characterising an unknown nuclear cave environment: sensing, locomotion and control. It is the belief of the author that through study of these three characteristics, this thesis has demonstrated that it is possible to utilise a heterogeneous swarm of autonomous robots to characterise a nuclear cave environment.

This chapter will draw together the work from this thesis and discuss its findings in a wider context. The structure of this chapter is as follows: first, a summary of the work from this thesis will be provided; second, a discussion about the key findings of the thesis will be presented; and finally, remarks and suggestions for future work will be given.

7.1 Thesis Summary

In chapter two the literature surrounding nuclear and swarm robotics was reviewed. It was shown that there is a paucity of material that focuses on the use of heterogeneous swarms, especially in the fields of autonomous mapping and nuclear environments. It was also discovered that there exist few implementations of virtual potential fields for use in exploration and mapping; the main applications in the literature were pattern formation, path planning and spatial distribution. This motivated investigation into the physical parameters that could define heterogeneity (sensing and locomotion) and the use of potential fields for control of such a swarm.

Having found that utilisation of a heterogeneous swarm for exploration and mapping of a nuclear cave environment was a novel concept, it was decided that the physical traits defining heterogeneity should be investigated, these were sensing and locomotion. In chapter three the sensing modalities that are most desirable in a nuclear cave were explored, relying on the expertise of an industrial expert from the Nuclear National Laboratory; these modalities are: distance, radiation, pressure, humidity, image capturing, temperature, chemical and tactile perception. In each case the applicable sensor technologies were reviewed and compared, with the chapter concluding with suggestions for the most suitable sensor for each modality.

Following a review of the sensory capabilities of a heterogeneous swarm, it seemed prudent to examine the second feature that could define heterogeneity, locomotion. The first part of chapter four reviewed the locomotion strategies applicable to traversing a nuclear cave environment: ground locomotion, wall climbing robots, flying robots and supplementary modalities. Subsequently, the most promising ground locomotion strategies were compared experimentally using a LEGO mindstorm EV3. It was found that a spherical robot, coupled with a tracked robot would give the greatest locomotive benefits whilst exploring a nuclear cave. Finally, chapter four described the design of a novel detachable grappling hook that could allow for ground robots to surmount obstacles and attain a bird's eye view of the environment.

Chapters three and four represent a study into the first two elements comprising a heterogeneous swarm: sensing and locomotion. The remaining component was control. Chapter five introduced the 'Reactive Virtual Forces' framework, designed to control a heterogeneous swarm of robots in the exploration and mapping of a nuclear cave environment. This control architecture utilises virtual analogues of the fundamental forces of nature to guide robots to unexplored regions of an occupancy grid. The 'Reactive Virtual Forces' framework was tested in MATLAB and embodied simulations and found to operate more efficiently with a heterogeneous swarm, when compared to a homogeneous swarm.

Chapter six extended the work on the 'Reactive Virtual Forces' framework conducted in chapter five. It was found that it is possible to utilise the 'Reactive Virtual Forces' framework in conjunction with an extended Kalman filter to produce simultaneous localisation and mapping. The 'Reactive Virtual Forces' framework was then placed on a comparative scale. The lower end of this scale was occupied by a Levy random walk, while the top end was defined by the perfect raster. It was found that the 'Reactive Virtual Forces' framework was close to the top of this scale, showing that it is an efficient exploration algorithm.

Overall, the key contributions of the thesis are:

- The consolidation of knowledge relating to the characterization of a nuclear cave environment utilizing a heterogeneous swarm of autonomous robots

- A review of sensors for use in a nuclear cave environment, carried by a heterogeneous swarm of mobile robots. This lead to the finding that a heterogeneous swarm that explores a nuclear cave is the most likely to benefit from using: a LIDAR sensor for range finding; a scintillator detector to determine the presence of radiation; a piezoresistive sensor to acquire information about pressure; a capacitative sensor to measure humidity; a cheap disposable camera to attain images of the cave; a thermistor to determine temperature; an electrical transducer to examine the presence of chemicals; and finally, whiskers to enable tactile perception.

- The review of, and experimentation comparing, locomotion strategies that are of benefit in a nuclear cave environment. This lead to the discovery that a swarm exploring a nuclear cave should utilise multiple locomotion strategies including: tracked and spherical locomotion for ground robots; suction to enable adhesion of wall climbing robots; rotorcraft as flying robots, implementing a gimball to prevent fatal collision; and finally, a robotic grappling device as a supplementary modality.
- The novel design of a detachable grappling hook that could be used to supplement ground locomotion strategies.
- The design of the 'Reactive Virtual Forces' framework, capable of efficiently controlling a heterogeneous or homogeneous swarm for exploration and mapping. Within this framework novelty lies in the sole use of potential fields for mapping and organization, without the use of a shared map, along with the examination of performance on both a heterogeneous and homogeneous swarm.
- The utility of simultaneous localisation and mapping of an unknown environment through the combination of an extended Kalman filter and the 'Reactive Virtual Forces' framework. Previously, SLAM has not been achieved with virtual fields alone. The design of an exploration performance scale that can be used to assess the quality of exploration strategies and it is applied to the 'Reactive Virtual Forces' framework.

The implications of these finding are discussed in the subsequent section.

7.2 Discussion

The author posits that there are three cardinal points of discussion that this research has provoked, these are:

- The potential benefits of heterogeneity for exploration
- The utility of virtual forces for exploration and mapping
- The advantages of robotics in the nuclear industry

In this section, each of these topics will be discussed drawing on information gained from the research conducted within this thesis.

Benefits of Heterogeneity for Exploration - It has been shown that heterogeneity provides diverse sensing and locomotive capabilities and can outperform a homogeneous swarm in exploration due to its intrinsic asymmetry; these benefits are discussed in this section. However, these benefits come with a drawback: the swarm has more capabilities spread across more agents, but if one fails there are less agents with the same capabilities to replace it. This makes a heterogeneous swarm inherently less robust. This can be accounted for by having multiple agents with the same capabilities so that a single robot failure does not significantly reduce the swarm's performance. In the author's view, the benefits of increased sensing, locomotive and explorative capabilities outweigh the reduced robustness.

Chapter three showed that to gather the necessary data within a nuclear cave, multiple sensing modalities would be required. A single robot would not be capable of carrying the diverse range of sensors due to size restriction imposed by entry into the nuclear cave, thus a heterogeneous swarm is required. Though heterogeneity is a necessity in this case, it is also a benefit; if a robot has a specialised sensing modality, it can examine areas of the cave that may not be of interest for other robots, while they continue to explore areas that their sensory capabilities are specialised for.

The benefit of heterogeneous locomotion was made apparent in chapter four; if a single locomotion method was used, robots would not be capable of surmounting all obstacles within a nuclear cave. Therefore, a heterogeneous approach to locomotion allows a swarm to maximise coverage of a nuclear cave. Combining locomotion methods and implementing supplementary modalities, such as a detachable grappling hook, would enable a full view of the nuclear cave. An interesting point to note is that when deciding on locomotion strategies for a swarm, the choice is usually left to the designers 'expert knowledge'. Instead, it is possible to use comparative experiments to empirically decide the most suitable locomotion strategies once appropriate metrics are selected. This allows the benefits of heterogeneous locomotion to be fully realised.

A combination of heterogeneity in sensing and locomotion could allow robotic agents to increase their data gathering efficiency. This would encourage locomotive and sensor pairings that are of most benefit to the exploration effort. As an example, a flying robot utilising a thermal contact sensor, is likely to be unable to adequately maintain contact. However, if this sensor was placed on a wall climbing robot that could remain static during inspection, the temperature of the same area could be analysed with greater accuracy.

During the examination of the 'Reactive Virtual Forces' framework it was found that the heterogeneous swarm performed a more efficient exploration of the environment than its homogeneous counterpart. This was discovered to be due to the intrinsic asymmetry imposed by the heterogeneous swarm. This asymmetry led to robots exploring different regions of the map and communicating their maps at different times. As the asymmetry of a heterogeneous swarm is implicit, this benefit does not need to be specifically designed and can hold true across many implementations. Exploration was achieved using the same control architecture for both heterogeneous and homogeneous swarms, which also suggests that the heterogeneous swarm did not require a more complex control strategy.

The benefit of a heterogeneous swarm is the diversity that it provides, allowing more data to be gathered and more terrain to be traversed. However, this diversity comes with a drawback; if there is only one robot with a specialism and it becomes incapacitated, then the swarm can no longer gather data, or move to areas, associated with that specialism. This problem is reduced as the size of the swarm increases, as there are more agents that are alike.

Utility of Virtual Forces for Exploration and Mapping - The utility of virtual potential fields in exploration and mapping was shown. 'Reactive Virtual Forces' were used to control a swarm of heterogeneous and homogeneous robots in the task of exploration and mapping. This represents a novel investigation into control of a heterogeneous swarm using virtual potential fields. The drawback of the 'Reactive Virtual Forces' framework is that currently it may only be used to generate geometric maps of an environment. Though this is the most important information regarding a nuclear cave, this might not be the case for exploration of other unknown environments.

Previous work has mostly implemented virtual potential field for pattern formation, path planning and spatial distribution [251] [19] [274] [223] [199] [124]. Work that has examined exploration with virtual potential fields has focussed on the use of homogeneous swarms [155]. The 'Reactive Virtual Forces' framework represents a novel study into the use of virtual fields for the guidance of a heterogeneous swarm of autonomous robots in the task of exploration and mapping.

The 'Reactive Virtual Forces' has shown that simultaneous localisation and mapping of an unknown environment is possible using virtual fields. This is achieved solely through distance measurements and odometry. Thus, it allows for a homogeneous swarm and a heterogeneous swarm to be controlled using the same architecture, with the only changes being some virtual parameters. Virtual potential fields have shown themselves in this thesis to be a powerful tool for exploration, especially when utilised with a heterogeneous swarm.

Exploration in this case has been achieved using analogues of three forces: the gravitational force, the electrostatic force and the strong nuclear force. This shows that complex behaviour is possible through the implementation of simple rules on multiple interacting physically instantiated agents. An interesting point for discussion is that the implementation of more forces, or alteration of the interaction between forces, could allow for more complex behaviours to be generated. Robots could be assigned more virtual parameters to define heterogeneity and thus increase their specialisation. Though this might impact the complexity of the control architecture, it may also allow for increased performance in exploration.

The 'Reactive Virtual Forces' control architecture currently enables efficient exploration and geometric mapping. However, it does not allow for other metrics to be characterised. Geometric information is the foundation of mapping and is important within a nuclear cave, however in the future it would be useful to fuse other sensor data into the map. Additionally, the 'Reactive Virtual Forces' requires that robots utilise accurate range finding devices and does not allow for mapping via imaging. Though this is not a problem for exploration of a nuclear cave due to its dark nature, if the 'Reactive Virtual Forces' framework were to be used for other exploration efforts it would be necessary to address this.

The Advantages of Robotics in the Nuclear Industry - The nuclear industry could benefit from the implementation of more autonomous robotic systems. This would enable exploration of environments that are currently inaccessible, such as a nuclear cave, whilst also increasing plant worker safety by reducing exposure to harmful conditions. In addition, it would allow for the ongoing costs of decommissioning to be reduced, as robotic systems can work more efficiently and for longer hours than a team of plant workers.

To date there are very few robotic systems that are implemented in the nuclear sector. However, it seems they could be of great benefit. Nuclear environments present dangerous surroundings for plant workers. The radiation, temperature and fatigue that are presented can often mean that workers must work in short shifts to prevent prolonged exposure to these conditions. If an autonomous robotic system were introduced, workers could avoid these dangers and productivity could be increased.

This is exemplified by a heterogeneous swarm of autonomous robots for the remote characterisation of a nuclear cave environment. Such a swarm allows exploration of an environment that is not accessible to human workers due to the adverse conditions. If the same swarm were implemented in an area that workers could enter, it would bring about other benefits. One of these is reduced fatigue. Robots do not tire and can perform tasks that could become exhausting for a human worker, such as examination of an environment whilst wearing a fully protective suit. This would enable a single plant worker observing a robotic swarm to work longer hours and likely gather more accurate data. Additionally, the worker is kept away from the harmful environment if the robots are operated remotely.

To enable current plant workers to operate a robotic swarm, the user interface should be simple or familiar. This would allow workers to interact with a swarm without having specialist training. If a swarm were fully autonomous, a worker does not need to interact with it, instead they may act as a supervisor enabling intervention if a particular event requires it.

7.3 Final Remarks

This thesis has assessed the utility of a heterogeneous swarm for the remote characterisation of a nuclear cave environment. It has been shown that heterogeneity benefits a swarm as it provides diverse sensory and locomotive capabilities, which enables a swarm to maximise coverage and data acquisition with a nuclear cave. This discovery led to the novel design of a detachable grappling hook that could be used to allow ground robots to map the higher reaches of a nuclear cave. In addition, it was shown that the 'Reactive Virtual Forces' framework may be used to efficiently control a heterogeneous swarm for exploration and mapping. Overall, it has been revealed that a heterogeneous swarm would be the preferred method for exploration and mapping of a nuclear cave environment. The work in this thesis could be supported, and built upon, by future work; suggestions are put forward subsequently.

The first piece of further work suggested, is extending the 'Reactive Virtual Forces' framework to three dimensions. So far, work has focussed on ground locomotion and exploration of the floor of the nuclear cave using this algorithm. Extending this control architecture to three dimensions would allow for the full cave to be mapped with multiple locomotion strategies. As the rules of the framework would remain the same, this is a matter of ensuring sensing in three dimensions and allowing the occupancy grid to represent three dimensions, by dividing the environment into three dimensional sub-spaces.

Further, the occupancy grid could be extended beyond the third dimension to allow for mapping of additional data. If each cell of the occupancy grid had multiple layers, then each sub-space would be capable of storing more than just geometric information. For example, an occupancy cell could store the likelihood of occupancy as well as the level of radiation that was present in that cell. This would allow for easily interpreted characterisation of the environment.

Finally, future work could examine the design of a launching mechanism for the detachable grappling hook presented in chapter four. This would allow ground robots to launch a grapple and attain information about the higher reaches of the nuclear cave, without the need for complex flying mechanisms with greatly reduced inherent energy limitations.

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