Localization and Coordination in Decentralized Multi-Robot Systems

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ABSTRACT

In this thesis, a problem definition, including motivation and research objectives is proposed to address localization and coordination issues in decentralized multi-robot systems. Through an in-depth literature review of current research in the field, ten issues in localization and eight issues in coordination methodologies warranting further investigation were identified. The optimal number of robots in a system and the scalability of the system were selected for analysis in the application of Urban Search and Rescue, and a problem definition to address these issues was developed. A preliminary methodology to address the problem definition is proposed and warrants further investigation.
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TERMINOLOGY

CBS – Consensus Based Systems

GPS – Global Positioning System

KF – Kalman Filter

MCL – Monte Carlo Localization

MRS – Multi-Robot System

ONR – Optimal Number of Robots

PDF – Probability Density Function

SAR – Search and Rescue

SLAM – Simultaneous Localization and Mapping

UofT – University of Toronto

USAR – Urban Search and Rescue
1. Introduction and Motivation
In all applications of mobile robotics the issue of localization is apparent. For a robot to perform a specified task, knowing where it is with respect to a target location or object is essential for the navigation and path planning to achieve the task. For applications that utilize solely one robot, the issue of determining a relative or global location has been addressed frequently. However, for multi-robot systems (MRS) cooperative localization, in which each robot’s localization uses the information of multiple robots, and task coordination is significantly more challenging. For many multi-robot applications a centralized command centre is used to coordinate communication between robots and compile information gained from each robot’s sensors to determine an overall image of the workspace. However, this is not always the most efficient method. Research into the development and feasibility of decentralized multi-robot systems is currently taking place. As a result, further investigation into this field is required, and the development of methodologies to further address these issues is needed.

2. Purpose
In this thesis a motivation and research objective for studies in decentralized coordination and localization in multi-robot systems at the graduate level will be developed. Through an in-depth investigation of current research, a literature review will be conducted to determine issues addressed, and the areas of the field that require further research and development. A methodology to address an issue in this field will be developed for future work in graduate studies. Upon completion of this thesis, preliminary research into the development of a problem definition for a formal research proposal will be completed.
3. Methodology
The development of the problem definition will be accomplished through a thorough and in-depth literature review of problems that have been addressed in the field. A literature search was completed to determine the types of problems addressed in both localization and coordination. In this, a general search through the databases of publications was performed using keyword searches to locate journal papers that are relevant to the topic. A minimum of 100 papers were reviewed for both topics. A high level review of this literature was conducted to determine the work that has been and is currently being completed in all areas of mobile robot localization and coordination.

Upon completion of the literature review, one issue from each of localization and coordination was selected to be addressed. After selecting a specific application in which both issues can readily be applied, a formalized problem definition and high-level methodology to begin approaching the issue was developed. Recommendations for future work were highlighted to identify areas that warrant further investigation in graduate studies.

4. Research in Localization
Localization is defined as the pose of a robot within a given environment, where the pose consists of the robot’s position and orientation in space. To gain a base knowledge of the topic and its applications a literature review of methodologies to address this task was performed. Papers were found using keyword searches in the e-resources databases of the UofT Library Catalogue. Search terms used consisted of multi-robot, cooperative,
localization, and decentralized. Different combinations of these words were used to uncover the maximum amount of literature available through these resources.

4.1. Methods of Localization
Different forms of probability estimation techniques have been used to address the localization problem. Across all papers surveyed, regardless of type of sensor information obtained, a probability estimation technique was used. In [1], Monte Carlo Localization (MCL) is used to address the global localization of a mobile robot. MCL approximates the precise location of a robot by determining the most probable location of the robot. By analysing the probability density of the sensor data using a Bayes filter, an estimate of the location can be determined [2]. MCL has been used widely with different forms of sensors such as vision [3], infrared sensors [4], and laser range finders [2]. MCL provides a robust and accurate method of determining the location of a robot [5] and is a commonly used method in many robot applications[6,7].

One particular form of probability estimation used is Kalman Filters (KF). Kalman filters act as a time-domain filter that determines the importance of new and old data in estimating the robots location [8]. Using the previously estimated state, and the new sensor measurements, the filter works recursively to predict the robots new location and then update it to refine the estimation. Kalman filters are commonly used in all forms of localization, whether for single or multi-robot systems [9, 10, 11, 12, 13] with Extended Kalman Filters being of particular interest [8, 14, 15, 16, 17].
Other methods which were found in literature, but were not utilized as extensively in the literature included: Markov models [17, 18, 19, 20, 21], particle filters [22, 23], Rao-Blackwellised filters [12, 24], bounded uncertainty algorithms [11, 23, 25], and potential fields [26].

4.1.1. Single Robot Localization
Localization of a single robot consists of determining the pose (location and orientation) of the robot with respect to its environment [1]. This problem is readily apparent in mobile robotics where knowing the location of the robot is required to determine the path to complete a specific task. Localization of the robot can be relative to specific features in the environment or absolute with regard to a global or fixed reference frame. This problem has been addressed using several methods.

4.1.1.1. Map Based Localization
One common form of localization is map based localization. In this, the location of the robot is determined with respect to an absolute map of the environment using different sensor measurements. Since the map of the environment is known to the robot a priori this allows it to match features or landmarks from the environment to this map to determine its precise location.

Two forms of mapping based localization exist. In the first, the robot knows its initial location on the map and using a combination of sensors can determine its new location on the same map [27]. An initial approach to solving this problem used odometry to
determine the new robot location based on movement from the start location. However, since odometry uses internal sensors (encoders) the errors compound and an external sensor is needed to be used in conjunction with it. In the second, the robot does not know its initial location on the map and needs to determine it [28]. In this method, a robot commonly searches for defining features in the environment that it can reference in the map to determine its location [29]. Usually, vision based sensors are used for this application as they can easily be used to extract features from an environment, and allow a greater range of features to be used (colour, size, shape, etc) [30, 31].

A novel approach to this problem has been developed from biomimetic design. In [32], a form of echolocation is derived from the use of sonar. Using a series of binaural spectral templates, the robot can determine its relative location based on the intensity of the sonar signal returned. Another similar approach to this problem was developed in [33] in which the strength of a WLAN signal was used to localize a robot. Through the intensity and direction of the signal from various access points in the workspace, the location of the robot could be determined using a radio map to correlate received sensor values to absolute locations.

4.1.1.2. Simultaneous Localization and Mapping

In environments that have not previously been surveyed, simultaneous localization and mapping (SLAM) is used. SLAM is useful for applications where the workspace is unknown, or prone to change. [34] outlines the methodology used to execute SLAM. As the robot maps the workspace, it constantly localizes using sensor measurements to
determine where it is in the map. As detailed in [35], if the sensor measurements do not match anything in the map, the robot determines that it is at a new location, and that is added to the map. If the sensor measurements match a reference in the map, the robot knows they have traversed the section of the workspace previously and can determine their location readily.

Several different implementations of SLAM based algorithms have been developed. Common implementations consist of vision and/or odometry based algorithms similar to that used in non-SLAM methodologies [8]. Nguyen et al. in [36] propose a method of SLAM that prioritizes descriptor matching based on a predetermined ranking of features to discern. Whereas [35] uses a word matching system in which features in the image are converted to words to determine their localization importance. In [37] ultrasonic sensors and an electronic compass are proposed for determining the relative and absolute location of the robot without any form of vision. As well, the grid and topology maps determined by the robot are fused to allow faster navigation and path planning. In [38] SLAM is performed using multiple time instances of sensor measurements instead of just the most recent, allowing for greater robustness in localization.

4.1.2. Multi-Robot Localization
Many applications of mobile robotics require more than one robot to complete a specific task. In such applications, multi-robot systems are required to control the robots simultaneously and ensure synchronicity between them. Localization of such systems requires the localization of each robot and a determination of their relations to each other.
Cooperative localization has been developed as a simpler and more robust method of addressing the localization problem. In this method, the sensor data from many robots is integrated to obtain a more precise localization of each robot. [2] As a result, once one robot has determined its relation to another, that robot can then use the localization information of the first and this relational information to better determine and its location with respect to the workspace and synchronize their localization with respect to each other [39].

4.1.2.1. Centralized Systems
Centralized multi-robot systems were developed as a method to coordinate communication between robots and the system. Centralization allows the main processing and computational requirements to be removed from the individual robots, and be completed on an external computer [22]. As well, more complex and precise sensors can be mounted within the workspace instead of on the physical robots [40]. By removing the sensors from the robots, they can be manipulated easier, and often provide the system with a better view of the workspace than an on-board sensor can provide [21]. As a result, centralized systems can work with more computationally complex algorithms and can provide greater synchronicity between system components.

Two forms of centralized localization are apparent today for mobile robots that have on-board sensors. In the first, each robot within the system localizes itself using solely their own sensor data [16]. While this can be a faster method of determining the pose, greater uncertainty in the estimation is probable as only one perspective of the workspace is
available [18]. Whereas, in cooperative localization systems, the sensor data from all robots in the workspace is combined to give greater accuracy in determining the pose of each robot [9]. For mobile robots that solely use external sensors, the localization is not considered cooperative or individual as each robot has the same access to all external data, and is only required to communicate with the central processor to gain the sensor data.

One common method of localization in a centralized system is by using vision systems [29]. In this method, a central processor, performs the image analysis and determines the kinematic controls necessary to operate the system [13]. Two forms of this system have been implemented successfully.

In [42], an overhead camera tracks the movement of the mobile robots on a workspace below. Using feature recognition the pose of the robots is determined and localization is completed. As a result of the centralization, cooperation between robots in task accomplishment is easily completed by streaming control commands to the robots from the central processor.

In [30], instead of having one overhead camera, each robot is equipped with an omni-directional camera that allows it to see the workspace around it. This system is less efficient than the previous system as it requires the central processor to analyse several images for features, in comparison to solely one. In [2] a different method of cooperative
Localization was performed in which the relative distance between robots was determined using the projected height of the other robot in the image. By linking the data from the two robots, this proved to be a relatively successful method of determining distance.

A novel approach to solving this issue was developed in [43] in which cooperative localization was completed through tracking a moving object in the workspace. In this method, the location of the object in the workspace served as a method of linking the localizations of two robots in the field. By fusing the known data of each robot across this link, uncertainty in the localization of each robot was reduced.

One method of optimizing this system is by varying sensor type across the mobile robots in the workspace [41]. By fusing the sensor data acquired across the robots in the system, a more precise pose can be determined [44]. Examples of systems like this include those which vary robots with absolute and relative localization sensors [45], those that have different views of the workspace [41], or by varying the weighting of certain sensors in the system [46].

4.1.2.2. Decentralized Systems
Decentralized multi robot systems have stemmed from the inability to adapt a fully centralized system to specific environments. Often the ability to develop a fully centralized system is difficult due to the number of robots or the capabilities of the central processor [10] and therefore decentralized systems are needed. These systems are highly applicable to outdoor and often unknown environments [47]. In these systems,
robots communicate amongst each other to cooperatively localize themselves using solely the sensor data gained from each robot. Since there is no central processor for the system, each robot must perform their own analysis of the sensor data gained from the robots in the system. Significantly fewer algorithms have been completed in this area of multi-robot localization than with centralized systems as they often provided coordination and control issues [48].

One major drawback of decentralized systems is the complexity of the communications network that needs to be developed between the robots [49]. Since each robot works independently, yet within the group to complete its mission, a great deal of cooperation needs to be developed to have the system work as a whole. However, decentralized systems can give greater range to the workspace, and allow for greater coverage during mapping or SLAM [26].

Current decentralized localization methods use a fixed reference frame for the entire system [49]. In [10], Global Positioning System (GPS) sensors were used to utilize the longitude and latitude coordinates of the earth as its reference frame. For this application, GPS worked well as the robots were outdoors and had a wide range of distance to travel. However, issues with this stem from the precision of the sensors. Often, non-military GPS devices have poor precision and give imprecise localization data [46]. As a result these sensors are not useful for environments where robots are closely located, or where the task requires great accuracy. In [50], one or two robots are left stationary in the
system while other robots move to create a fixed reference frame about the stationary robots. This system works well to develop the frame, however is not highly applicable to many applications where the use of all robots in the system is warranted at all times.

One method of decentralized localization consists of having markers or beacons in the environment that give the robots a reference to localize to. In [51] all robots have on-board sensors and cooperatively locate with each other and track a specific target. Using the target as the reference frame, the team of robots develop a specified formation with respect to the target, and triangulate their position based on sonar measurements. In [52] localization of a decentralized swarm of vehicles occurs based on source localization. Since the source in this case emits a measurable scalar field, by determining a robot’s location with respect to the source, and other robots, the robots can localize themselves in a fixed frame.

In [41] a centralized vision setup is proposed for a decentralized system. In this, a wall climbing robot would act as an overhead camera and view the robots below. Using the data of the two robots on the ground and the one overhead, all three can be localized with respect to each other and the reference frame of the image from the wall climbing robot. One major limitation of this method is that it is limited to indoor environments and those that have ceilings. Here, the robots act as “mobile sensors” in which they don’t have to achieve anything, but simply add information to the system to aid in other robot’s localization.
Mapping based approaches are also apparent in decentralized systems. In [53] the robots have a map of the environment a priori and only need to localize within that map. For cooperative goals, a map of each robot’s trajectory is projected onto this map and adjusted for each robot’s measurements.

4.2. Localization Issues in Decentralized Systems
From the algorithms investigated in the previous two sections it is apparent that there are issues in decentralized localization of multi-robot systems that still need to be addressed. With centralized localization algorithms, the central processor allows for a simple coordination scheme between the robots and an easy dissemination of sensory information. However, as there is no central processor in decentralized systems, the dissemination of sensory information can present a major problem for collaborative methodologies. In this section, apparent issues in decentralized localization will be discussed, and proposed areas of further study in these topics will be addressed.

4.2.1. Accuracy of Localization
The accuracy of the localization of a robot is highly imperative as incorrect localizations can lead to major systematic errors in task assignment or path planning [54]. This accuracy is even more important in mobile multi-robot systems. If a robot is determined to be in an area that it is not, it may collide with other robots or obstacles in the workspace and damage the physical robot if the sensors do not cause obstacle avoidance to kick in. Many probabilistic estimation, and uncertainty algorithms have been developed to deal with this issue [55]. Of the literature dealing with centralized
cooperative localization, approximately a quarter of the papers addressing localization have dealt with accuracy. However, this topic has not been rigorously investigated in decentralized systems. Localization accuracy is often related to the accuracy of sensor measurements [50] or algorithm implementation [18]. However, in cooperative systems, since the data of many sensors locating one device from different robots can be fused, it is probable that the localization error will decrease as a result of a better approximation from the measurements [29]. This has proven true in centralized systems, and these results should likely extend to decentralized systems as well. In decentralized systems, since each robot in the system operates independently greater accuracy is needed to avoid collisions. As a result, cooperative data sharing, precise sensors, and accurate mapping of the environment are necessary for determining a robot’s pose accurately [2]. Thus, further investigation into this field is necessary.

4.2.2. Computational Cost
Algorithm execution, and sensor processing can be largely taxing on a computer processor [44]. Decentralized systems require all data processing and analysis to be completed on-board the robot. As such, the computational abilities of the robot, and ultimately the system, are limited by the processing power available in a micro-controller. With decentralized systems, the processing requirements of the communications module must also be considered into the power requirements. Since decentralized systems depend heavily on the communications between robots in the system, this section of the developed methodology could take up a significant amount of processing power required by the robot, thereby limiting that which is left for analysis [56]. In [57], each robot in the
system use a PDA or on-board computer to analyse data and perform all necessary tasks. However, depending on the size of the robot and the use environment this may not always be a feasible solution. Therefore, further investigation must be conducted into the processing requirements of the robots in such systems.

4.2.3. Performance Time

Data acquisition and analysis of a robot’s sensory information requires processing time. As the speed of the processor increases so does the response time of the system. Even if the processor can speed up the data analysis component, performance time is still limited by the sampling rates of the sensors, and communications between robots. Similar in nature to the issue of computational cost, performance time is essential to accurately analysing and responding to changes in the system [58]. Optimal sensor type and scheduling can be employed to conserve resources, and increase performance time and accuracy [45]. As a result, only necessary data will be acquired for each robot task. However, due to the amount of communications necessary between the robots, performance time will be increased, even if you have the communications and analysis modules running on separate threads [56]. Currently, most systems are capable of running in near real-time as in [41], however for systems which change drastically rapidly, faster performance time is necessary. Therefore, further investigation is warranted to determine methods of improving performance time, and making the systems run in real-time.
4.2.4. **Robustness of Algorithm**
The localization algorithm used by the system needs to be robust enough to handle variability in sensor data. As all sensor measurements add noise to the system, the algorithm must be robust enough to ensure noise is attenuated. Individual sensor noise can compound across a decentralized system as sensor data is shared across robots in the system [45]. Measurement amalgamation in cooperative localization algorithms increases certainty by attenuating noise, however if the data from one sensor is consistently incorrect systematic errors can compound across the system. For accurate cooperative localization, the algorithm must be robust enough to sense when measurements are correct and utilize sensor data accordingly. Therefore, further investigation into the effects of systematic errors must take place, and the ability to eliminate them if the compound/develop after the sensor filtering stage.

4.2.5. **Optimal Number of Robots for Localization Accuracy**
As performance time and computational cost are important design factors, the amount of robots in the system becomes an optimization point. As more robots are added to a system, the amount of sensor processing and communications required increases. As a result, the performance time of the system will decrease with an increase in the number of robots. As with all systems, an optimal number of robots for the system type can be determined which will yield the greatest accuracy [50]. In [11] a method is proposed for determining the optimal number of robots for a specific system, and the unit increase or decrease in accuracy for the addition of each extra robot to the system. Both of these papers deal with the optimal number of robots in a centralized system. No such research at the decentralized level was found in this search. Therefore, research into the optimal
number of robots in a decentralized system is warranted for increased accuracy of the system.

### 4.2.6. Decentralized Communications
The ability to distribute sensor measurements across all robots in the system is required for accurate localization [58]. Thus developing a system that allows for robots to accurately send and receive communications to collaborate is essential [26]. Communication systems are likely to experience unforeseen conditions and noise during operation [59]. As such the system needs to be able to perform without failure or error in these circumstances. The failure of a module within the system, or the loss of a robot could seriously affect the localization accuracy of the other robots [11]. A failure in the communications would eliminate the cooperative aspect of localization and decrease the certainty of robot pose estimates. Hence, the communications framework for the system must be robust and be able to account for noise and losses in the system. Currently, no literature on methods of reliable communications have been found. Therefore, further investigation is warranted into the stability of the communications infrastructure.

### 4.2.7. Cooperative Controls
Intelligent task dissemination and coordination amongst robots in decentralized systems is key to the success of completing their required task. A coordination framework for control is required to ensure no redundancy, or intolerable time delay is created in the system. The lack of such a framework could result in two robots attempting to complete the same task. In [60] a behaviour based control method is proposed for cooperative task allocation and completion. In this a task is assigned to the robot with the “best” eligibility
to complete the task. Once the task is assigned, the receiving robot “inhibits” the other robots from accepting it. In this method however, a centralized control centre is used to disseminate the tasks amongst robots in the system and thus differs from a decentralized system. No literature on intelligent task dissemination was found for decentralized systems in this preliminary search, therefore further investigation into this field is warranted.

4.2.8. **Robot Kidnapping**

Robot kidnapping is defined as the problem in which a well localized robot is lost within the MRS [61]. When this happens in a centralized system, the system has two problems to solve, 1) finding and localizing the lost robot, 2) adjusting the system to work effectively with one less robot. As the system is decentralized, detecting that the robot is kidnapped can also serve as a problem. More investigation into this concept is warranted to determine its effects on the performance of the system. This topic needs further investigation to determine whether research is warranted in this field.

4.2.9. **Use of Relative Localization**

Localization of a robot can be determined relative to the other robots in the system, or absolutely with regards to a global or fixed reference frame [46]. For some applications, such as search and rescue, absolute localization is more applicable; however for systems in which the robots are confined to a set workspace, relative localization can often be enough. In centralized systems, relative localization is usually the sole form of localization completed as only the robots relation to the given workspace is required [18, 22, 62]. For example, in [62] cooperative localization is completed by fusing the relative
bearings between the robots. In [63] a method of map merging for cooperative exploration is explored. Through this method, no global localization occurs despite exploring a new environment. Decentralized applications of solely relative localization is an emerging field at the moment. With the variety of implementations in centralized systems, extending a methodology to work in a decentralized system proves probable. Therefore, further investigation into this field is warranted.

4.2.10. Frame of Reference
In decentralized collaborative systems a reference frame for localization is required. To correlate and coordinate sensor measurements of robots within the system a common reference is required to properly fuse the sensor information [49]. Several applications have been developed in centralized systems to overcome this problem such as GPS [46], and stationary robots [50]. In [19] a robo-centric reference frame is proposed for a centralized system. By the fusion of each robo-centric frame, an overall relative reference frame of the system is developed. Such applications have been implemented in decentralized systems for map generation and merging [63]. As such there is great reason to believe that implementation of a reference free localization infrastructure can be developed for decentralized systems.

4.3. Concluding Remarks
Localization is an important component of MRS. Regardless of whether a system is centralized or decentralized, many issues are apparent which warrant further investigation. In particular, the issues in decentralized localization often stem from the abilities of the coordination framework and the lack of a global view of the entire system;
such as frame of reference, optimal number of robots, cooperative controls. Many of these issues have been addressed for centralized systems, however they have not been readily addressed for decentralized systems, and require solutions which can adapt to the different local information of each robot to develop an accurate group and individual localization of the robots in the system.

5. Research in Coordination

Coordination is the act of organizing a group of mobile robots to perform specified actions simultaneously that can result in the completion of an overall system goal at the global-level. To gain a base knowledge of the topic and its applications a literature review of methodologies to address this task was performed. Papers were found using keyword searches in the e-resources databases of the UofT Library Catalogue. Search terms used consisted of multi-robot, coordination, collaborative behaviours, control, and decentralized. Different combinations of these words were used to uncover the maximum amount of literature available through these resources.

5.1. Coordination and System Type

For certain problems, there does not exist a solution that is either physically or economically viable with only one robot [64]. For applications such as these multi-robot systems are necessary. Often, in these situations, MRS are considered to be a more stable solution as they add redundancy to the system, and therefore the system can be more “fault-tolerant” than a single robot [65]. To ensure that these systems are working to
solve this global goal in a coherent and logical manner, coordination methods are necessary to synchronize the actions of the robots in the system [66].

One major drawback of centralized systems is their lack of applicability to real-life scenarios. For robotic missions such as search and rescue or terrain exploration and most use in outdoor environments, mobile robots often travel far from their initial start location. As a result, there is no optimal location to place a central processor for the system, and no way to make a system completely centralized [10]. However, for indoor locations, and small workspaces, centralized systems can offer a robust method of near real-time processing capabilities [41]. Coordination in centralized systems is simplified from those of decentralized systems, as a global-view of the system is constantly apparent. In this, two robots who would not normally be considered close enough to share information can adapt to each other’s movements through the central processor.

In decentralized systems, the act of coordination is significantly more complex [67]. Since there is no centralized processor to determine and disseminate the required information/actions to each robot in the system, each robot needs to be able to determine its own actions with respect to the entire system from the information available around them. Motion coordination methodologies for decentralized systems can be broken down into two main divisions; systems in which the robots communicate very sparsely with each other, and systems in which they communicate readily.
5.2. Limited Communication Methods
The simplest form of decentralized coordination is one in which several robots operate independently on the same task without communicating with the other robots in the system. In this, coordination is limited as each robot works apart from the others using the same controls methodology and viewing other robots as obstacles [68]. Geunho, et al in [69] present a coordination framework to maintain a formation and a reach a goal with no inter-team communication. In this method, robots are allowed only to determine their individual actions by “observing” the other robots in the system. Using image processing, the robots attempt to make their actions match those of the others as they appear in the images.

However, for tasks that require a more unified strategy, methods using little communication have been developed. In [65], a limited communication methodology for multi-robot cooperative exploration is detailed. Here, each robot individually computes the next target location it aims to reach for exploration, and as it passes other robots it acquires their target points. With this combined information, the robot is able to gain a better image of the workspace areas that have previously been explored, so as not to choose them as the next target point. As a result robot’s are less likely to repeat each other’s tasks and thus exploration time is reduced. This application is considered to be limited communication as the robots do not intentionally coordinate which robot will do what, but instead plan their actions around previously completed or in-progress actions in the system.
Decentralized, limited communication methods are becoming a more relevant topic of research as they allow for scalability and robustness in the system [70]. Therefore, if due to temporal communication errors one robot is effectively removed from the system, the rest of the robots can continue operating as they were without having to account for the missing robot. Since each robot can virtually be modelled as an independent system, it does not need there to be a constant connection with a particular robot in the system, but simply any robot in the system. Likewise, if a robot is added to the system, it adds an extra degree of redundancy to the system which allows for more information gain, however it does not affect the operation of the other robots as they simply begin merging the extra data of that robot with their own.

5.3. Full Communication Methods
In full communication methods, all robots in the system are continuously connected to a network that spans all the robots in the system. As a result, all robots have the opportunity to utilize the information obtained by all robots in the system, regardless of whether their methodology utilizes it. Full communication methods are common for systems in which the robots are required to undergo more than one type of action to achieve the desired goal. These communication methods also allow for greater scope in decision making, as more information is readily available for evaluation.

5.3.1. Single Task Methodologies
Many decentralized systems are comprised of robots of the same type that perform the exact same task [71]. For systems in which only one task needs to be allocated, simpler
task allocation methodologies can be employed as no division of tasks needs to take place.

5.3.1.1. Intentional Coordination

Independent data fusion methods are considered to be those in which robots acquire data from their surrounding robots and fuse the data to gain a better understanding of their workspace [72]. The main difference between these methods and those with limited communication is that here, a robot can talk to any other member of its system at any time as they are all continually on the communications network. Whereas in limited communication methods, the robots form a small communication network each time they talk, and therefore do not have the opportunity to talk to anyone as needed.

One type of these methods is peer to peer communication. In this, robots systematically communicate with each other in pairs when a certain desired distance threshold has been reached. For example, in [73], robots communicate with another peer in the system when the distance between them is below a certain threshold value. On communication, the robots determine whether there is a possibility of collision between the two robots, and if so they plan new trajectories around each other to avoid a collision, or worse possible deadlock.

Intentional coordination methodologies are good for systems which do not need a great degree of control, and do not need to have a global-view of the system [74]. This means that, each robot working independently could potentially achieve the overall goal of the
system, however it may not be completed in a time optimal manner. As a result, intentional coordination methods are used to eliminate potential time delays such as collisions, and deadlocks that could eliminate the use of a robot during operation.

5.3.1.2. Leader-Follower Methods
Leader-Follower systems are the most common methodology used in decentralized swarm based systems for coordination. In these, one robot in the system acts as the leader, and the actions of all other robots in the system (the followers) either mimic or are based off the actions of the leader [75].

Leader-follower based systems have been utilized readily in manufacturing settings where transportation of large objects is of key concern [76]. A common application in literature of this problem is that of transporting an object too large for one robot to carry from an initial to target location. In [77], a decentralized controller is developed in which a leader is given the path desired to be traversed, and two follower robots estimate the path they should take based on the movement of the object they are carrying. The desired path of the followers is estimated using velocity controlled actuators that create a virtual pull or push to distinguish the direction of the boxes movement. Applications such as these are also found in [78] which does not utilize any force/torque sensors for box movement detection, and [79] in which the follower robots have some control over the pose of the object by the use of two extendable arms.
In [80], the leader-follower controller is applied to this same object moving scenario by modelling the follower robots as 3-D castors. In this, each follower robot acts independently as a castor that can freely rotate about its joint with the object. If the leader pushes the object in a direction the robot cannot readily translate in, just like a castor, the robot rotates to be able to move in that direction and then translates with the other robots.

The leader-follower coordination strategy can also be applied to multiple mobile robots moving in a specified formation [81]. In this, if the leader robot is capable of moving, it tells the followers to traverse in the same motion. If it is not capable of moving, the leader tells the robots to reverse their last motion. For this coordination methodology, all robots are required to remain in formation for all movements. Local perception of the other robots in the system is necessary for the communications between robots to work, and to ensure that the movement of the followers is in the direction desired by the leader.

In [82], a decentralized methodology for the alignment and synchronous rotation of a group of robots is detailed. In this, once the leader robot has decided on a specific pose, followers use the attitude information of neighbouring robots to determine their desired movement until all robots are in the same alignment. As well, the desired angular velocity for rotation can be passed from the leader to the followers using a distributed adaptive controller.
5.3.2. Multiple Task Situations
For applications in which more than one type of task is required to complete the overall goal, task allocation and coordination methodologies are more complex. Robots are faced with not only identifying who and where to do the task, but what the task should be. As a result, task allocation systems are required which determine which robot is best suited for each task so as to ensure optimal efficiency in the system.

5.3.2.1. Consensus Based Systems
Consensus Based Systems (CBS) are a method of distributing different tasks to mobile robots using a form of agreement among the robots [83]. CBS usually deal with multi-robot systems where the type of task allocated to each robot is the same, but the location of the task is different. For example, many robots may be exploring a new area. Each robot is exploring (the task is the same), however each robot is exploring a different region in the new area.

In [84], a centralized task allocation method is used for the coordination control of a group of decentralized pallet movers in a manufacturing warehouse. In this, each robot in the system submits a bid for the task. The bid consists of the length of time it will take for that robot to complete the task. Then, the bids are evaluated by the centralized station, and it is awarded to the robot with the best bid. Although in this case the task allocation is centralized, the robots themselves are still decentralized as the execution of tasks is still controlled solely by the individual robots.
In [85], a more sophisticated approach to consensus based task allocation occurs where the robots negotiate to decide the next action of the system. In this application, multiple mobile robots are searching for a single lost target. By each robot in the system developing a probability density function (PDF) of the target’s state, and fusing it with the PDFs of the other robots, they negotiate anonymously to determine the next best action of the system.

Ma et al detail a behaviour based method of auctioning tasks in [86]. First, the robots in the system compete for the role of auctioneer. Once one wins the role, all other robots in the system default to the bidder status and bid on frontiers to explore that are available from the auctioneer. When a frontier is won by a robot, it explores the respective area and then returns to get another task. After a successful exploration round, the bidders in the system compete for the role of auctioneer based on the amount of area explored, and their situation in the system. The process is then repeated again continually reassigning roles and exploring new frontiers until all required area has been explored.

5.3.2.2. **Cooperative Behaviours**

Cooperative Behaviours is a way of determining the overall goal of the system, and breaking it up into the different sub-tasks required for the completion of the overall goal [87]. In this, each different task a robot is expected to perform is termed a behaviour [88]. Over the course of a deployment, a robot can move through several different behaviours depending on the needs of the system [89]. The end result of this coordination methodology is the completion of the overall goal through the natural completion of a
series of local goals. Different strategies have been developed for determining the necessary behaviours, and allocating them amongst robots in the system.

In [89], centralized cooperative behaviour dissemination is detailed using a tele-operated, centralized command centre. Although this method is not decentralized, many of the principles surrounding its operation parallel those of a decentralized system. In this paper the application of tele-operated robot soccer is discussed. Here, each robot is assigned a role by the tele-operator and from that role has the opportunity to function according to a series of behaviours associated with that role. For example, the role of attack has the behaviours pass, chase and shoot. The robot decides which behaviour it will assume according to the distance between the robot and the ball, and the robot and the opponent’s goal. In this methodology, although the roles are disseminated in a centralized manner, each robot still decides its behaviour in a decentralized fashion according to its local sensory information.

Sheng et al. in [90] outline a method of cooperation that utilizes different behaviours in a consensus based task allocation methodology for a decentralized system. For the application of area exploration, each robot can be in one of three behaviours: sensing and mapping, bidding or travelling. In this methodology, a robot consistently cycles through the three behaviours in the sequence listed above. During the bidding phase a robot bids on exploring a new frontier cell by calculating its expected information gain versus the cost to obtain it. If a robot wins a new frontier cell it travels to the new frontier cell and
begins the cycle again from the sensing stage. If a robot does not win the bid, it continues sensing in its current frontier cell until it wins a bid.

In [91], a biomimetic design for behaviour based coordination is shown in which the multi-robot system is modelled as the human immune system for a simulated multi-robot soccer application. The human immune system can be broken down into 4 categories of decision making interactions: body level, organ level, tissue level, and the cellular level. At the body level an appropriate strategy to oppose the competitor is determined, and thus a group behaviour is selected. This behaviour is further broken down at the organ level in which the individual actions of the robots are determined and the behaviour that best completes the overall goal is selected. Each robot selects its behaviour using a synthesis immunity network algorithm which analyses the stimulus of the opponent and the antibody total and density of the MRS for defeating them.

5.4. Coordination Issues
From the algorithms investigated in the previous two sections it is apparent that there are issues in decentralized coordination of multi-robot systems that still need to be addressed. Certain and efficient task allocation methodologies are required that ensure the completion of the overall goal. Since there is no central processor in decentralized systems, the dissemination of sensory information can present a major problem for multi-robot collaboration and decision making. In this section, apparent issues in decentralized coordination and task allocation will be discussed, and proposed areas of further study in these topics will be addressed.
5.4.1. System Stability
One common issue among all coordination architectures is the issue of system stability. The stability of a system in this context refers to the ability to function with temporary lapses in communication between robots and thus with a lack of information [92]. When these lapses occur, possible collisions within the workspace may occur, or another robot will repeat the same task as the lost robot, introducing redundancy into the system [93]. Central to the stability of the system is the capability of the communications network to handle the quantity of information transmitted via its connections. Several algorithms have been developed to determine that the network is input-to-state stable where the robot will be capable of achieving the state transmitted to it [94]. As well, the stability of the system must account for noise and external disturbances on the information transmitted. Although filtering can remove some of the noise from the system, it cannot remove all of it, nor the effects of external disturbances. As a result, more investigation is warranted in determining how to make the decentralized communication networks more stable.

5.4.2. Communications Capabilities
The ability for all robots to transmit the required information for decision making over the given communication network is of paramount importance to the type of methodology that can be developed [95]. As the communication abilities of MRS are limited, decentralized coordination methodologies are limited by the amount of information a robot can share with the other members of its system. Different methodologies have been developed around the basis of limited communication, where
information is only communicated to neighbouring robots within a certain proximity [96]. As a result, a global image of the workspace for each robot cannot be attained, and complete coordination of the system is not possible. Therefore communication networks that can handle transmitting greater quantities of information over larger distances warrant investigation for these types of applications.

5.4.3. Scalability
Scalability of the number of robots in a decentralized system is a key point of research. Since the decentralized system lacks a central command centre, the system is naturally scalable to more or less robots as each is its own controller and can integrate into the network [70]. However, current control methodologies are only scalable within certain regions as the communication network requirements for a system depend on the quantity and frequency of information transmission [97]. As a result, no comprehensive method has been established that can work on both a small number (2-3) and a large number (50-100) of robots, and thus warrants further investigation.

5.4.4. Robustness of Algorithm
The ability for the coordination methodology to work under all worst case scenarios is fundamental to the successful completion of the required task [98]. As temporary lapses in communication can occur between robots as well as incorrect measurements of robot locations or states, the coordination methodology must encompass a strategy to overcome such issues. As a result, the algorithm of each robot’s individual controller must be robust enough to function with or without the necessary information, and the overall
coordination algorithm fast enough to detect errors in the system (i.e. missing robot) and reallocate tasks such that the overall goal is not affected [99]. Research is warranted into the investigation of controllers that are not affected by communication glitches for appropriate task allocation.

5.4.5. Uncertainty

Current task allocation methods do not always account for verification of whether a task has actually been completed as prescribed. As a result, during the task allocation phase a robot may be assigned a task that it is not capable of executing, despite the fact that its bid or status may appear as though it could [100]. In real applications, task allocation mechanisms are not always sufficient to ensure the completion of the overall goal when subdivided into tasks as a result of the uncertainty in the system. Often the coordination system receives a ‘task received’ confirmation bit when a robot has accepted the task assigned [101]. However, there is no task completed confirmation noted in the literature, the robot either queues to wait for another task or bids on tasks at an auction. As a result, there is no method to confirm that the overall goal is attainable during task allocation. Thus, investigation is warranted into the determination of successful completion of tasks and their allocations.

5.4.6. Time Delays

In a decentralized system, processing time is decreased from that of a centralized system as each robot needs only to determine its own task, and not those of all the robots in the system as a centralized command centre would. However, for situations in which sensor
fusion from many robots is required to make the next coordination decision, a lot of computational time is required [102]. As a result, coordination decisions that may have been valid at the time of measurement acquisition may no longer be valid by the time the decision has been made and executed. As well, while a robot bids for the ability to complete a task, a perception delay exists between the image of the workspace the robot is bidding under, and the workspace the robot will complete its task in [90]. As a result, investigation is warranted into the methods of minimizing communication delays so that decisions can be made accurately.

5.4.7. Accuracy of Sensory Information
In the evaluation of a robot’s ability to perform a required task, sensory information is required to analyse the state of the system, and the robot’s place within it [103]. Errors from sensory measurements could result in a misallocation of tasks for a specific robot, and result in an increase in time required for the system to reach the overall goal. As well, if the sensor data from an inaccurate robot is fused with another, this will compound the error to the system level where the potential to skew all task allocations is present. The analysis of a cost-function to determine the quality of sensing has been proposed to determine the trade-off in performance between sensing and communication [104]. Such a methodology to determine the benefits of merging sensory data during communication could lead to better coordination between robots, as an analysis to determine the most accurate information could take place. Therefore, a method to validate sensor information before fusing is warranted to ensure no major errors influence the coordination system.
5.4.8. Global View
For multi-robot systems in which a global view of the system is needed for optimal task allocation, decentralized systems are sub-par. Since all robots have a local view of the workspace only, coordinating tasks optimally over the entire system, instead of over a particular segment of the workspace is difficult [75]. Even with robots sharing their information with the robots they are within proximity of, it is improbable that one robot will acquire the data of every robot in the system and have a complete global view [96]. As well, general broadcast methods in which all robots’ information is continuously shared over the entire workspace are only relevant to small-scale and small area applications [74]. Further research is warranted to determine an optimal method of giving each robot a global view of the entire system.

5.5. Concluding Remarks
Coordination is an important component of MRS. Central to issues in coordination is the communication abilities of the robots within the system. For systems in which a global-view is possible, task allocation can occur in an optimal manner. Since each robot can see the entire system and how its task fits into the overall goal, it allows for a more accurate spread of tasks. As well, uncertainty is less of a factor with a global view as other robots will be able to tell if the task has been completed. For decentralized systems a global view is often unattainable and therefore much research into developing methodologies that can segment the overall goal into divisions that can be completed entirely independently, or that allow for a sufficiently detailed local view, are required.
6. Localization and Coordination

As can be seen from the above literature review, localization and coordination are important components in the functionality of any multi-robot system. These two components are so integral to the system architecture, and to the functionality of each other, that errors in one area affect the other to the point where errors can compound and cause the system to not achieve its desired goal.

Localization and Coordination are parallel tasks that need to be performed for optimal system performance. Localization is necessary so that the location of all robots in the system is known, and thus accurate coordination of the robots’ movements can be determined [54]. In cases where accurate localization does not exist, errors in movement and planning can occur and collisions between robots and other entities within the workspace are possible. For example in coordination, if a robot is believed to be near a certain task and thus is assigned it, but it is not near that task, time will be lost waiting for the robot to move the greater distance to the specific task before completing it. As well, when dealing with collaborative localization, if a stable coordination system is not in place, data may not be properly shared among the robots and the localization will not be optimized [45].

To develop a multi-robot system that will achieve global tasks optimally, a robust coordination system and an accurate localization methodology are required. In decentralized systems, the optimal fusing of these two components is more readily
apparent than in centralized systems where a global view of the entire system is readily attainable. As a result, further investigation into the interactions between these system components in decentralized systems is warranted to develop a robust and accurate method of coordinating and localizing the robots in the system.

7. Research Proposal
As a culmination of the above literature review the selection of one topic from each of the issues addressed in localization and coordination will be addressed in a high-level manner for decentralized systems. This methodology will address both issues using a single methodology and application that encompasses both problems.

The issues selected to be addressed in this proposal are the optimal number of robots from the localization issues and scalability from the coordination section. Both of these issues had less than ten research papers deliberately devoted to addressing the topic and thus have the potential for a novel contribution in future work. As well, both issues are similar in nature and have the potential to contribute positively to both localization and coordination methodologies.

7.1. Application Selection
The application selected to address these issues was determined to be Urban Search and Rescue (USAR) using multi-robot systems. This application is a relatively new area for investigation in decentralized MRS as most applications have been devoted primarily to the transportation of large objects [105], area exploration and mapping [90], and
perimeter surveillance [94]. USAR poses unique challenges in decentralized MRS as the robots are spread over large distances requiring a more robust coordination system and accurate localization.

7.2. Motivation
Search and Rescue (SAR) is a challenging operation that is currently completed by humans. However, in many environments where searching is necessary, humans are not able to get there or it is too dangerous to send them [106]. As well a search mission can often be a tiresome and physically taxing event where the use of a MRS is more durable and will provide a greater efficiency in successfully attaining the lost target [107]. MRS provide the opportunity to execute more efficient and time effective searches due to increased automation.

Similar to the method in which humans search for a missing person, MRS methodologies cannot always determine the exact number of robots required to find the target at deployment. As the search area grows and shrinks, the number of robots required to search the area in a time optimal manner cannot be prescribed. In human executed SAR missions, the number of people designated to search will change over time to account for the changing area and possible target motion.

For a successful search using multiple robots, a coherent coordination method is required. The USAR workspace is a large area that can encompass several kilometres, and thus the likelihood of having all robots in communication with each other is not probable.
Communication methodologies which only require peer-to-peer communication are beneficial for such applications. However, a coordination methodology that is capable of segmenting between peer-to-peer communications for coordination and whole system communication to signify the target has been found are required.

Therefore, the overall objective of the proposed research is to develop an on-line autonomous multi-robot coordination methodology for determining the optimal number of robots to localize accurately and search for a moving target allowing for a dynamic number of robots in the system over time.

7.3. Problem Statement
First, let us clarify the extent of this application. SAR applications require two main tasks to take place, the first to locate the target being searched for, and the second to physically acquire the target. In this future work, neither the searching for nor the rescuing of the target is analysed, as a result search theory and rescue methodologies will not be examined. Solely the use of localization and coordination of the mobile robots in the system for these applications will be analysed.

The focus of this future work is in determining the optimal number of robots to deploy for a specific USAR case, and developing a methodology that is scalable. In this, the methodology determined will be able to be used on small numbers of robots (2-3) and large numbers (20-30) and be able to dynamically change the number of robots in the
system while on-line. As a result, the controls methodology proposed will always be applicable to the optimal number of robots for a given application.

The problem scenario can then be described as follows. An Alzheimer’s patient leaves a treatment facility at a specific time. Once it is noted that the patient is missing a team of mobile robots is assembled at the location of disappearance and prepare for deployment. It is assumed that many robots are available, and thus as many as are required are available for use. Information on the search area is limited, such as topographic maps in which locations of buildings and streets are available. Potential hazards such as cars, pedestrians and other obstacles are not known and need to be avoided on detection. Since the search area is not bounded, it is possible that the initial number of robots deployed will not be sufficient to maintain the communications network, or accurately localize and locate the target and thus the number of robots may need to be increased or decreased. This work focuses on the coordination and localization aspect of the MRS which comprises the following:

**Optimal Number of Robots**

The Optimal Number of Robots (ONR) is a function of two parameters, search area and localization accuracy. Since the search area is unbounded, it is only possible to make an estimate of the ONR to search the area upon deployment. As the robots progress through the environment it is possible that more or less robots will be required to search the area in a time optimal fashion. Given target predication information, such as distance travelled
before robot deployment and a potential direction of travel, the ONR and configuration for initial deployment can be determined. The ONR should take into account the theoretical bounds of the search area, the abilities of the robots, the maximum distance of communication, and the amount of information required to make accurate decisions. The ONR for localization is a function of performance time and computational cost. As the number of robots increases the demands on the communication system are increased. The ONR for localization must take into account sensor processing times, time delays in communication, and the quantity of information required for accuracy and be able to balance the need for accuracy versus the cost in performance.

**Communication Verification**

To ensure that the system is always scalable to the ONR, the communication architecture needs to be such that each robot does not require a global view of the system. For cooperative localization to take place each robot needs to be constantly connected with at least one other robot in the system to generate a flow of information. While a global view is not necessary, a local view of surrounding robots will increase the localization accuracy and decision making of each individual robot. As well, to allow for the ONR optimization to occur, a local view of the number of robots in each area and their uses is required so that the optimal number can be utilized at all times. When a robot is added to, or removed from the system the communication network should adapt such that no loss in information occurs. To ensure that once the target is located the robots stop searching, all robots in the system should be connected over the communication network. Cost analysis
in terms of performance time to determine the ONR to constantly network with versus the total number in the system must be determined. As well, to ensure each robot is performing a useful task and is able to reassign if necessary, the communication architecture must be continually verified to ensure that no robot extends past the maximum communication range from another robot in the system.

**Task Allocation**

Once the ONR is determined and the communication system verified, task allocation in terms of area’s to be searched must be determined. A method to evaluate the most eligible robot for each task must be developed and an assignment system set-up. The assignment system must be dynamic such that it can readily reassign tasks if the robot is no longer the most eligible, if a robot has been added to or removed from the assignment systems span, or if the task is no longer necessary.

**Low-level motion planning**

For all assigned tasks to be executed in a systematic, and time efficient manner accurate low-level motion planning is required. In this, the robots need to perform adequate mapping, path planning and obstacle avoidance such that more high-level tasks can be completed. An efficient method of path-planning based on communication limitations, location of task required for completion, and obstacles in the environment must be developed. Motion planning will also take into account the presumed motions of the target from a separate search theory module.
7.4. Proposed Methodology
The following four methods comprise the overall methodology to address this problem.

7.4.1. Communications and Coordination
Let us first note that this MRS will be decentralized. USAR missions encompass large areas, making it improbable that a centralized control centre can be used as the communications distance is too great. Due to the nature of decentralized communication systems, each robot must be capable of decision making, and networking with surrounding robots for group decision making.

One possible way to address the communication and coordination of the MRS is by using an approach similar to that of a linked list. Linked lists store each list entry as a node which uses specifically allocated pointers to refer to the previous and next nodes in the system. As a result, without having each item stored in a sequential manner the list can be traversed in a sequential manner. This theory can be applied to a decentralized MRS where each robot is seen as a node in the system. Each robot will connect to two other different robots such that a string of communication is apparent across the system. Checks will be performed for every four of five node segments to ensure that a loop has not been created to detach that group of robots from the overall system. This way, robots can function with solely the robots around them, while still affecting the movement of the entire group. As well, once the target has been found, the notification can be passed across the entire system to all robots to stop searching.
Due to the nature of a linked list, the previous and next robots in the chain can be changed to rescale the system. Rescaling will occur when either another robot has been added to or removed from the system or when it is more appropriate to be connected with a different set of robots due to task similarity or proximity. If a robot is found to no longer be in communication with either its previous or next robot it will perform a series of tasks to determine whether it is at the end of the “linked list” of robots, or if it has extended past its communication bounds. If it is found to be past its communication bounds, it will retrace its steps until the communication is re-established and then the robots will then resume their tasks.

7.4.2. Determination of Optimal Number of Robots
The ONR required for the system will be developed two-fold. First, the ONR will be determined for collaborative localization, in which the optimal number will likely be a subset of the total number of robots in the system. The most important factor in determining this is to have the sensor information for each robot reach steady-state and be accurately filtered for outliers before collaborating with the robots surrounding the one being localized [11]. Once the sensor information has been filtered for noise, by combining the sensor measurements of the robots any variance in measurement overtime will be attenuated. The optimal number will be determined by maximizing the number of robots and minimizing the rate of uncertainty according to an empirically determined cost function, where the rate of uncertainty reduction is equivalent to:

\[
\frac{\text{change in pose from individual localization}}{\text{change in pose from global localization}} \times \frac{\text{time for group localization to settle}}{\text{time for individual localization to settle}}
\]
This cost function must be empirically determined once the robots are chosen for this specific application, and the sensing and localization capabilities of the individual robots are determined. Only if the result of this cost function reveals that there is a benefit to using collaborative localization will it be used.

Second, the initial ONR for the search mission will be determined based on information provided about the target. Using the location of disappearance as the base point and target prediction information, an initial number of robots will be determined based on the size of the area the target could be located in. Accounting for communication constraints, the rate at which a robot can search an area and the amount of space to be covered, the ONR will be able to be determined by weighting these three criteria equally and factoring it by the physical limitations of the robot. As the target moves and time elapses, the area which needs to be explored grows radially from the location of disappearance, and as the area grows larger more robots may need to be deployed to cover the area thoroughly. Therefore, from the initial ONR, the number in the system will be able to change dynamically by robots realizing that the area is too great for them to cover with their individual constraints, and sending a request back through the chain of robots to that which is close to the deployment location to request backup.

7.4.3. Task Allocation
For the above mentioned design, a simple task allocation method is required to ensure the robots are optimally searching the given area. Since each robot in this design has only one possible behaviour, “search”, robots solely need to determine which location on the
frontier of the search area they are going to investigate. This can be done using an auction based system like that detailed in [86], where robots bid against those in their communication range to win the right to explore the frontier at auction. The difference for this methodology is that the robot will bid against the closest 1-2 robots on either side of it in the “linked-list” structure. Since each robot is required to be within a limited communication range, all robots outside of these bounds will be too far from the frontier at auction to place a good bid.

Tasks will be able to be reassigned if a robot sends out a ‘task incomplete’ message instead of a ‘task complete’ message to its network of bidders. At this time the robot will then begin an open auction for the task it could not complete. If a robot is removed from the system, it must exit by the same protocol as not completing a task. As well, if a robot is added to the system, it will be initially assigned the task that it was noted a robot was required for, and then will enter the normal communication architecture and bidding protocol for more tasks.

7.4.4. Low-level Motion Planning
To ensure all tasks are performed optimally, low-level motion planning needs to be robust. The low-level planning is completed independently by the robot and does not require communication with any other robots. Since the robot does not have a complete map of the environment, or potentially an out-of-date map, the robot must extract key features from its environment and add details to its map. As it discerns obstacles in its way, the robot must determine a detour around the obstacle that will still allow it to
complete its task. Much work has been done in obstacle avoidance and path-planning which is not the focus of this future work, therefore incorporation of a previously designed methodology for both will be utilized. This method however will need to be modified to take into account the communication limitations of the system. As well, path-planning will need to take into account the presumed motions of the target, from a separate search theory module.

8. Recommendations for Future Work
As stated in the purpose of this thesis, a problem definition and preliminary methodology to address localization and coordination issues for a specific application have been detailed for future work in graduate school. Three main points in this proposal will be the focus of future work:

1. The simulation in Matlab or equivalent software of the proposed “linked-list” structure for decentralized communications. Investigations into its validity and scalability are necessary to ensure the proposed methodology addresses the problem definition accurately.

2. Verification and or modification of the rate of uncertainty reduction formula to ensure it increases the accuracy of cooperative localization.

3. The simulation in Matlab or equivalent software of the proposed determination of the optimal number of robots for initial deployment based on known target information, and the ability to utilize the optimal number of robots for localization.
As well, overall validation of the entire methodology needs to be performed upon completion of the validation of the three individual subsections. Overall validation will consist of completing simulations and experiments to determine the functionality and potential areas for improvement. Possible improvements to this methodology include incorporating search theory into the methodology so that an external search algorithm does not need to be incorporated.

9. Conclusions
In this thesis a problem definition with motivation and research objectives was outlined for future work in localization and coordination in decentralized MRS. Through an in-depth literature review of topics related to localization and coordination in both centralized and decentralized MRS, 18 issues that warranted further investigation were identified as potential areas for future work. Of these 18 topics, 2 were selected for future work (optimal number of robots and scalability) and a problem definition with motivation and research objectives detailed. In this future work a methodology to develop an on-line autonomous multi-robot coordination methodology for determining the optimal number of robots to localize accurately and search for a moving target allowing for a dynamic number of robots in the system over time is proposed. This methodology uses a linked-list type structure for the communications architecture that allows for an increase or decrease in the number of robots in the system over time. A further investigation into the functionality of the proposed methodology is warranted through simulation and experiments in graduate studies.
10. References


