Development of an Artificial Intelligence System for the Instruction and Control of Cooperating Mobile Robots

Praneel Chand

DISSERTATION.COM

Boca Raton

Development of an Artificial Intelligence System for the Instruction and Control of Cooperating Mobile Robots

Dissertation.com
Boca Raton, Florida
USA • 2012

ISBN-10: 1-61233-950-6
ISBN-13: 978-1-61233-950-4

Abstract

This thesis focuses on the development of an artificial intelligence system for a heterogeneous ensemble of mobile robots. Many robots in the ensemble may have limited processing, communication, sensing, and/or actuation capabilities. This means that each robot may not be able to execute all tasks that are input to the system. A hierarchical system is proposed to permit robots with superior processing and communication abilities to assign tasks and coordinate the less computationally able robots. The limited processing robots may also utilise the resources of superior robots during task execution. Effective task allocation and coordination should result in efficient execution of a global task. Many existing approaches to robot task allocation assume expert knowledge for task specification. This is not ideal if a non-expert human user wants to modify the task requirements.

A novel reduced human user input task allocation and feedback coordination technique for limited capability mobile robots is developed and implemented. Unlike existing approaches, the presented method focuses on expressing tasks and robots in terms of processing, communication, sensing, and actuation physical resources. This has the potential to allow non-expert human users to specify tasks to the team of robots. Fuzzy inference systems are utilised to simplify detailed robot information for comparison with simple human user inputs that represent task resource requirements. Like many existing task allocation methods, a greedy algorithm is employed to select robots. This can result in suboptimal task allocation. In addition to this, the non-expert user's task specifications might be erroneous in some instances. Hence, a feedback coordination component monitors robot performance during task execution.

In this thesis, a customised multi-robot mapping and exploration task is utilised as a model task to test the effectiveness of the developed task allocation and feedback coordination strategy. Extensive simulation experiments with various robot team configurations are executed in environments of varying sizes and obstacle densities to assess the performance of the technique. Task allocation is able to identify suitable robots and is robust to selection weight variation. The task allocation process is subjective to fuzzy membership function parameters which may vary for different

users. Feedback coordination is robust to variation in weights and thresholds for failure detection. This permits the correction of suboptimal allocations arising from greedy task allocation, incorrect initial task specifications or unexpected failures. By being robust within the tested limits, weights and thresholds can be intuitively selected. However, other parameters such as ideal achievement data can be difficult to accurately characterise in some instances.

A hierarchical hybrid deliberative-reactive navigation system for memory constrained heterogeneous robots to navigate obstructed environments is developed. Deliberative control is developed using a modified version of the A* algorithm and a rectangular occupancy grid map. A novel two-tiered path planner executes on limited memory mobile robots utilising the memory of a computationally powerful robot to enable navigation beyond localised regions of a large environment. Reactive control is developed using a modified dynamic window approach and a polar histogram technique to remove the need for periodic path planning.

A range of simulation experiments in different sized environments is conducted to assess the performance of the two-tiered path planning strategy. The path planner is able to achieve superior or comparable execution times to non-memory constrained path planning when small sized local maps are employed in large global environments. Performance of hybrid deliberative-reactive navigation is assessed in a range of simulated environments and is also validated on a real robot. The developed reactive control system outperforms the dynamic window method.

Acknowledgements

I wish to express my sincere gratitude to the many people who have helped me during this project. First, I would like to thank my supervisor Professor Dale Carnegie for his invaluable advice and encouragement. I am also very grateful for his time and effort in reviewing papers and thesis chapters.

A number of past graduate students are deserving of thanks for fruitful discussions, assistance and support. In particular, I would like to thank Dr. Christopher Lee-Johnson for providing feedback, contributing ides and collaborating on a conference publication. Other students who have assisted me are Jason Edwards, Luke Cawley, David Williamson and Thomas Roehr. I also appreciate the technical assistance provided by Scott Forbes and Bruce Rhodes.

I am also grateful to my mum for proof reading draft chapters of this thesis and continuously pushing me to get this thesis submitted as quickly as possible. Mohammed Faizal's assistance in compiling the thesis chapters into a single document is also appreciated. I am also grateful to the University of the South Pacific for funding to attend the oral examination.

Finally, I wish to thank the New Zealand Vice-Chancellors Committee (NZVCC) for awarding me a Commonwealth PhD Scholarship to undertake the research presented in this thesis.

Table of Contents

List of Figures

List of Tables

1 Introduction

Cooperative robotic behaviour independent of human intervention is an active area of mobile robotic research. Ideally, a human should only provide the initial command to a team of robots that then decide for themselves how to execute the given task.

There are several advantages to cooperative behaviour in multi-robot systems. By working in parallel, multiple robots can increase efficiency and reduce the time required to complete a task. Reliability is increased by introducing redundancy when using a team of robots, while cost can be reduced due to the use of smaller simplistic machine designs. Application specific design and manufacturing costs can be reduced by fabricating semi-generic robots. New complex tasks can be introduced to a team of robots which are difficult for a single robot to achieve.

Multi-robot systems can be homogeneous or heterogeneous. Homogeneous systems consist of robots with identical hardware and software elements. This provides good robustness to individual robot failure. However, the robots are required to be generalists that can perform any type of task given to team. It can be expensive to manufacture a team of generalists. Hence, many conventional homogeneous systems are limited to simplistic robot designs that employ detailed human user inputs for control.

Similar to homogeneous systems, heterogeneous systems can be robust to individual robot failure. But, heterogeneous systems comprise robots with non-identical hardware and software elements. Hence, the thesis presented here is that a heterogeneous ensemble of mobile robots can be hierarchically organised with task feedback control, which significantly reduces the need for human user input.

Three broad categories of multi-robot system applications are transportation, sensing, and foraging. Object transportation involves multiple robots transporting objects from one location to another and has been exhibited in robot soccer teams [1-3] as well as in object pushing [4, 5] and object lifting and carrying [6, 7]. Cooperative sensing develops a group robotic system for localisation, map building, and exploration [8-

11]. In foraging, groups of robots must locate and move objects scattered in an environment to a storage location [12-14].

A variety of mobile robots are currently under development at Victoria University of Wellington (VUW). Amongst these is a pair of functionally equivalent tricycle robots for investigating cooperative behaviour such as object transportation or sensing [15]. Another two robots, Rubble-bot [16] and Tank [17], are being developed as part of an urban search and rescue (USAR) multi-robot application [18].

The VUW USAR hierarchical heterogeneous multi-robot system has three categories of robots: grandmothers, mothers, and daughters. At the top of the hierarchy, the grandmothers are physically the largest and most computationally powerful. Grandmother robots are generally employed to manage the operation of a group task. They achieve this by monitoring and coordinating lower tiered robots (mothers and daughters). Mothers and daughters are smaller in size and less computationally powerful. They are also limited in their sensing and actuation abilities. The smaller size of the mother and daughter robots enables them to be deployed for searching the environment as worker robots.

Coordinating a team of mobile robots such as the VUW USAR system usually involves implementing task allocation and coordination mechanisms. Task allocation mechanisms address the question: "which robot should execute which task?" [19] Coordination mechanisms enable the actions performed by each robot to take into consideration the actions of the other robots in the team resulting in coherent team operation [20]. Recently research in multi-robot systems has also addressed coalition formation, the organising of multiple robots into temporary subgroups to accomplish an assigned task that would otherwise be impossible to complete [13, 21].

In certain multi-robot applications, such as exploration (section 2.9), predefined task allocation and coordination may not always work as desired. This is due to the inability to model all aspects of a robot's interactions with the environment prior to task execution. Task allocation may also fail if tasks are incorrectly specified. Robots with limited capabilities also present the challenge of using resources effectively to achieve the objectives of the group task.

Allocating tasks to robots in a team like the VUW USAR system requires a strategy that takes into account the physical capabilities (i.e. resources) of the different robots. Generally, the resources present on a robot may be classified into four broad categories: processing, communication, sensing and actuation.

Most of the existing task allocation methods require expert knowledge to specify tasks to a team of robots. None of the methods reviewed in section 2.7 attempt to specify tasks in terms of the four broad physical capability categories. Specifying tasks in terms of these physical capability categories may have the potential to allow non-expert users to intuitively select task requirements.

After initial task allocation, robots may not perform as desired due to the inability to fully model all interactions with the environment accurately. Additionally, existing task allocation algorithms (section 2.7) employ heuristic greedy methods to select robots which can be suboptimal. It may also be possible for a user to inaccurately specify tasks when using the four broad physical capability categories. These problems need to be mitigated by employing a feedback mechanism that monitors task execution. Task execution can be classified into four broad categories: planning, communication, sensing and actuation. Hence, a feedback mechanism may be designed in terms of these four categories to detect and correct abnormal performance. Consequently, a group task should be executed with increased efficiency.

Using limited capability robots also presents challenges in task execution. In exploration tasks, robots are required to navigate beyond localised regions of an environment. Memory constrained robots in a heterogeneous system require a hybrid of deliberative and reactive control to achieve this. Deliberative control should be able to provide a path to travel beyond the localised region of the environment. A limited memory robot may be able to utilise the resources of computationally powerful robots to achieve this. Reactive control must facilitate collision avoidance and modify the path of travel when obstacles are encountered during movement.

1.1 Objectives

In this thesis, the aim is to develop an artificial intelligence system to instruct and control a heterogeneous ensemble of mobile robots. Motivated by the VUW USAR hierarchical system that is under development, the robots will have a variety of processing, communication, sensing and actuation resources. Many of the robots will have limited processing, sensing, and actuation capabilities.

One of the specific objectives is to develop a task allocation strategy based on physical robot capabilities. Tasks and robots will need to be specified in terms of the four broad physical capabilities (processing, communication, sensing and actuation). Specifying tasks in terms of the four major physical capabilities should allow non-expert human users to use the task allocation strategy.

Existing task allocation methods employ heuristic greedy techniques which can often be suboptimal. Developing an optimal mapping of tasks to robots is NP-hard [22]. Therefore, another major objective is to develop a feedback coordination strategy that monitors robots during task execution. Task execution performance will be characterised in the broad categories of planning, communication, sensing and actuation. By detecting and correcting failures, the feedback system should facilitate improved group task execution.

A conceptual diagram of the task allocation and feedback coordination mechanism (also motivated by the VUW USAR system) is shown in Figure 1.1. There are three levels of control. At the highest level (level A) a remote base station computer is used to specify the group task (management and worker tasks) and robots. Depending on the management task requirements and robot capabilities, the remote computer identifies manager robot(s) (level B). The manager robots are delegated the responsibilities of global data maintenance, worker task devolution and performance monitoring. After manager task devolution, the remote computer is no longer required by the robot team since task management is essentially transferred to the manager robot(s).

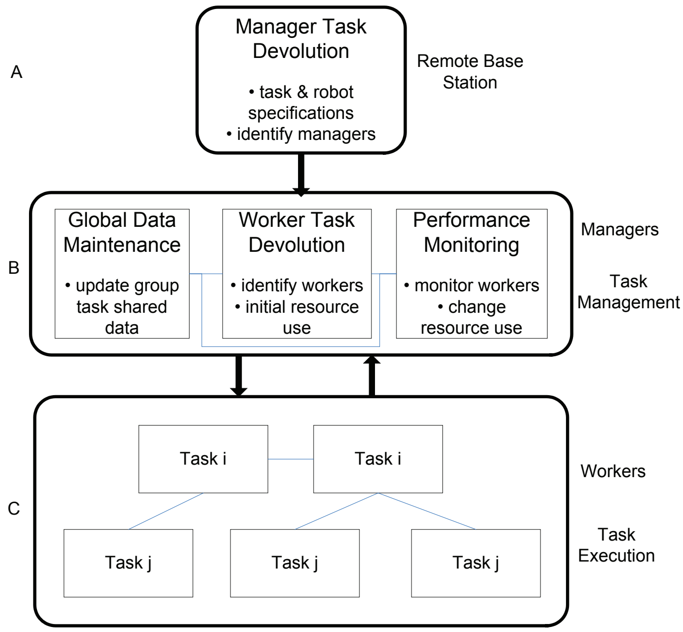

Figure 1.1: Overview of the multi-robot task allocation and coordination mechanism.

At the third level of control (level C), worker robots are responsible for executing the objectives of the group task. Worker robots are selected by the manager robot(s) during execution of a worker task devolution process. Depending on the nature of worker tasks to be allocated, the worker robots are assigned a position in a predefined hierarchy. Worker robots executing some tasks (e.g. Task *i*) could be supervising robots executing other tasks (e.g. Task *j*). Following the worker task devolution process, the worker robots perform their tasks and the manager robots monitor and direct their performance using a feedback coordination mechanism.

To evaluate the developed task allocation and feedback coordination strategies, a suitable multi-robot task needs to be implemented. A customised multi-robot map-building and exploration task is developed for this objective.

In some situations, the limited memory worker robots may be required to perform global path planning (deliberative control) to navigate beyond localised regions of the global world. This can be problematic if the limited memory robots are unable to store the entire map in their local memory. The methods reviewed in section 2.5 cannot be applied to the multi-robot application presented in this thesis. Thus another objective is to explore a new approach to global path planning for limited memory robots.

To successfully navigate obstructed environments, limited memory heterogeneous robotics requires a hybrid of deliberative and reactive control. Hence, a navigation system that combines the benefits of reactive and deliberative control for heterogeneous mobile robots is also developed in this thesis.

1.2 Thesis Outline

- Chapter 2 – A review of relevant literature is presented. Topics of interest in single robot and multiple robot control, such as control architectures, navigation systems, task allocation and coordination techniques, and fault-tolerance are reviewed. A review of multi-robot map building and exploration strategies is also included.

- Chapter 3 – The hybrid generic navigation system employed by the heterogeneous mobile robots is presented. Its design is based on the A* algorithm, a polar histogram and a modified dynamic window approach. Simulation experiments with three heterogeneous robots in a range of environments are conducted. Initial hardware experiments demonstrate the navigation system working in the real world.

- Chapter 4 – A two-tiered path planning technique to permit global path using limited (processing and memory) capability mobile robots is presented. Using a two-tiered A* algorithm that executes entirely on the limited capability robots, a set of local maps describing the global map is searched for a global path. Planning time, data communication and path length are evaluated for various combinations of local and global maps.

- Chapter 5 – Details of the proposed task allocation and feedback coordination technique for limited capability mobile robots are presented. The task allocation component employs Fuzzy Inference Systems (FISs) to simplify human user input at the task specification stage. FISs are also employed in the primary (manager) and secondary (worker) task devolution processes. Feedback coordination executes periodically to detect and correct three forms of robot failure: poor performance, partial failure and complete failure. An exploration task (defined in chapter 6) is employed as a specific example to demonstrate the technique.

- Chapter 6 – The customised multi-robot map building and exploration task is detailed. A global environment is divided into local environments for limited capability mobile robots to explore. Planner and explorer tasks are executed by the limited capability robots to complete the exploration of a global world. Explorer robots utilise the navigation system presented in chapter 3 and planner robots plan global paths using the technique presented in chapter 4. Exploration of global worlds with relatively flat terrain containing sections of boggy terrain is considered.

- Chapter 7 – Experimental results of utilising the task allocation mechanism for the customised multi-robot map building and exploration task are presented. The influence of weight variation on ranking and selecting candidate robots is evaluated for five sets of eight robots.

- Chapter 8 – Results obtained from executing the multi-robot mapping and exploration task without any feedback is compared with task execution employing feedback coordination. Each type of feedback (task score, poor performance, partial failure and complete failure) is tuned and a complete system with tuned parameters is also evaluated.

- Chapter 9 – A summary of the contributions and publications arising from this research is presented as well as a discussion of future work.