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Robot Teams and Robot Team Players

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1. Introduction

Multi-robot systems are generally organized around the concept of a team, from teams of mobile robots for outdoor tasks such as surveillance to teams of smaller robot systems for competitions such as RoboCup (Balch & Parker, 2002; Schultz & Parker, 2002). Variants of this theme include small numbers of cooperating robots for transport tasks, such as two robots carrying an extended payload, which is the robot equivalent of a two-man team. In the majority of research the team structure is limited to a single team. In this chapter, we propose to explore a multi-team model for multi-robot systems, whereby multiple subsets of robots are drawn from a larger pool to form multiple teams. Each team has an assigned task that is to be distributed among the members of the team.

In the conventional model for robot teams, a task is broken into sub-tasks and each sub-task is allocated to members of the team through a negotiation process; individual robots can signup for one or more sub-tasks based on their ability to perform the sub-tasks. The set of robots which sign-up are essentially the team associated with the task. A limitation of this model is that it doesn't support the concept of multiple teams of robots, in which each team has a collective identity associated with a task it is to perform that is separate from the identity of other teams. However, multiple teams are a successful approach used in business and industry to organize work (Jelphs & Dickinson, 2008). The benefit of multiple teams is that work can be carried out in parallel, improving efficiency. Further, it is possible to reallocate robots between teams, a practice often used in business and industry to ensure that tasks are completed on time.

Introducing a multi-team framework in multi-robot systems can offer the same benefits. Moreover, in the conventional multi-robot team, robots can locally cooperate, effectively forming a sub-team. This is generally perceived as cooperation but not necessarily team based cooperation. However, the concept of forming and re-forming sub-teams may be useful in this context as well. Therefore, a model emerges in which a pool of robots provides a resource for creating multiple teams, each of which essentially can be seen as a pool of resources in its own right for creating further sub-teams when needed.

The chapter is organised as follows. The following section outlines the requirements for multiple robots working in multiple teams. The third section of the chapter proposes a model for multiple robots working in multiple teams, which we abbreviate as the MRMT model.The fourth section discusses the architecture in more detail, specifically the concepts of roles and targets and the communication requirements. The fifth section provides two case studies, motivated by space applications, to describe how the model can work in practice. The final section provides a summary and conclusions.

2. Requirements for multiple robots working in multiple teams

The term 'multi-robot systems' can be used to refer to a wide range of robotics systems incorporating more than one robot, including swarms of many robot systems and smaller numbers of robots in robot teams for competitions such as Robocup (Balch & Parker, 2002). The term is used in this chapter to refer to homogeneous or heterogeneous teams of mobile robot systems, including, for example, robot teams in the Middle Sized league of RoboCup and medium sized robots for surveillance operations in both open unstructured landscapes and structured outdoor and indoor environments. Such systems typically incorporate wireless Ethernet as the basis for communication, vision based sensing, an on-board computer, possibly a laptop, and hence the ability to support a significant level of autonomy as well as robot-robot and human-robot cooperation.

A set of two or more robot systems can be incorporated into a robot team to perform some task. The task can be broken out into subtasks, which can then be allocated to individuals members of the robot team (Choudhury et al., 2009; Parker, 1998). There are four issues concerned with the allocation of tasks to robots and the subsequent performance of the robot team in completing the tasks.

First, the allocation of tasks can be categorised based on whether the robot team is homogeneous or heterogeneous. In the former case, since the robots are all equally capable of performing any task the main issue is the distribution of the robots between the different tasks (e.g. (McLurkin & Yamins, 2005)). In the second case, since the robots are different, possibly overlapping in their capability, the key challenge is to match each task to a robot in the team capable of performing the task (e.g. (Mataric et al., 2003)). A number of strategies are available for such task allocation, including both centralised and distributed strategies and taking into account the capabilities of the robots, typically their sensing capabilities (e.g. (Estlin et al., 2005; Tsalatsanis et al., 2009)). Among the strategies include bidding strategies based on a market economy model whereby each robot bids for and is allocated a task based on comparing its bid with that of other robots (e.g. (Zlot et al., 2002)).

Second, during the performance of the task a robot may suffer partial (e.g. a sensor fails) or total failure which prevents it completing the task it has been assigned. The task must in this case be reallocated to another robot. A number of successful behaviour-based strategies have been developed for this purpose, whereby the other robots in the team recognise the failure and take over the task (Mataric et al., 2003; Parker, 1998). This work is explored largely in the context of fault tolerance.

Third, the behaviour of the robots needs to be coordinated in order to ensure the successful completion of the task. For example, in the ALLIANCE architecture the coordination operates to ensure that all tasks assigned to the team are completed (Parker, 1998). The coordination is through explicit communication, whereby each robot broadcasts its current state to the other robots, which can in turn determine whether a task is being completed successfully or should be reallocated. Communication has associated overheads, and algorithms have been explored which trade-off communication requirements (e.g. (Balch & Arkin, 1998; McLurkin & Yamins, 2005)).

Fourth, robot teams incorporate a number of interface types, the most common being the interface between the individual robots in a team, employing explicit communication via a wireless network to share task-related information. However, in some cases this communication is not direct robot-to-robot but via a server or base station (e.g. (Roussos et al., 2007)). In addition to these, the robot team may also be interfaced with one or more

human operators to which the robots report task information that can be used to support task coordination (e.g. (Sugiyama et al., 2008)).

The adopted control architecture for many robot systems, either alone or working in a team is a hybrid comprising deliberative and behavioural components with the balance between the two determined by the task performed and the scale and number of robot systems (Balch & Parker, 2002; Bekey, 2005; Schultz & Parker, 2002). A multi-robot team also creates challenges in command and control, whether top-down, bottom-up, or a combination of these; and challenges and opportunities for human-robot interaction. These must be reflected in the capabilities incorporated in the robot architecture itself and in the global commands that need to be translated into actions for individual robots.

The above issues set requirements for the creation of robot architectures to support robots working in teams. The conventional architectures for the robots in a team do not actually support team working for two reasons. First, the conventional robot architectures work largely on the principle that a robot is first and foremost an individual and only secondly has the potential to be a member of a robot team. In this context, team working is designed in as effectively an afterthought. If robots are expected to be team players, however, then team working should be designed in from the ground up. This can be realised by ensuring that the architecture supports robot-robot cooperation in its command and control interfaces and explicitly treats the robot as a team player.

Second, the conventional approach to multi-robot teams assumes a single-team single-level approach. Specifically, a pool of robots is assumed which is essentially configured into a team without an explicit representation of a "team" within the multi-robot team. In other words, the robots have no notion that they are members of a team. In addition, there is no scope for a team of robots to organise into sub-teams. In cases where a subset of robots within a team needs to coordinate, the subset is treated as an exceptional circumstance rather than a natural feature of a more explicit model of team working.

In summary, therefore, a more useful architecture for team working will treat an individual robot as a team player, which means essentially that the robot knows it is a team player, and will incorporate an explicit recursive model of team working whereby a pool of robots can form into a set of teams and a team can form into sub-teams. In this context also tasks and roles are not only assigned to individual robots but also to teams.

3. The MRMT model

Having established the requirements for multi-robot multi-team working, we propose in this section to outline a model for the same. In order to present the model, we first need to establish some assumptions and terminology which will be used to define and explain the model. The following sub-section explains the concepts of macroscopic and microscopic commands, explicit and implicit communication, and roles and targets. The first is familiar from swarm robotics (Varghese & McKee, 2008), the second from cooperative robotics (Bouloubasis & McKee, 2005; Lam et al., 2003) and the third are definitions that we are introducing in order to articulate the model.

3.1 Command, communication and task assumptions

In multi-robot multi-team working we wish to draw the distinctions between commands which are issued to a team of robots as against commands which are issued to individual robots. This distinction is reflected in the distinction between macroscopic and microscopic

commands (Varghese & McKee, 2009). Macroscopic (group) commands are issued to a team of robots and define a task or action that the team needs to perform as a group. Examples include commanding the team to pack more closely together or to move forward in a specified direction as a group. Microscopic (individual) commands are issued to individual robots, specifying for the robot a task or action that it needs to perform independent of the other robots in the team. Each robot can convert macroscopic commands to microscopic commands, reflecting its individual perspective on the group task. For example, a team of robots commanded as a group to fetch an object will each have been allocated specific grasp points on the object; each robot is required to interpret the fetch command in terms of its allocated grasp point.

In addition to interpreting group and individual commands, the robots in a team will need to share information with each other, and depending on the task this communication can be mediated explicitly or implicitly, which are terms from familiar to robotics. Explicit communication is a mode of communication in which the robots share information with each other via a wireless communications network. For example, the individual robots in a robot team performing a fetch operation will alert other team members when they have grasped their respective interfaces and therefore are ready to move. Implicit communication is a mode of communication in which the robots sense the action of other robots through the latter's action on the same target. For example, if one of a team of robots holding an object moves off, the other robots will sense the action that the move has on their respective grasp interfaces (implicit communication) and can react immediately (tight coupling) by moving off as well.

We propose, in addition, to draw a distinction between the roles that a robot performs in a team and the targets on which the roles are performed. Roles are associated with tasks and targets are associated with the objects to which the tasks are directed. An example of a role is to carry an object, while the object to be carried is an example of a target. Tasks assigned to a team can be classified on the basis of roles and targets as follows:

- Single Role
  - Single Target
  - Multiple Target
- Multiple Role
  - Single Target
  - Multiple Target

The extent to which implicit and explicit communication and also macroscopic and microscopic control should be exploited in each of the above categories is summarised in Table 1.

	Single Target	**Multiple Target**
Single Role	Macroscopic	Macroscopic & Microscopic
	Implicit	Explicit & Implicit
Multiple Role	Macroscopic & Microscopic	Microscopic
	Explicit & Implicit	Explicit

Table 1. Roles and Targets

In summary, single target scenarios tend to provide more scope for implicit communication and more macroscopic control, whereas multiple target scenarios tend to provide more

scope for explicit communication and more microscopic control. In contrast, single role scenarios tend to provide more scope for implicit communication and more macroscopic control whereas multiple role scenarios tend to provide more scope for explicit communication and more microscopic control.

3.2 Components of the MRMT model

The Multi Robot Multi Team (MRMT) model that we are proposing comprises five components as well as a design for the lifecycle of a task under the model. The latter is described in section 4. The five aspects are (a) the concept of a universal robot set, from which robots are drawn to form one or more team, (b) teams, robots and their capabilities, (c) tasks, roles and targets, (d) role management and (e) command, control and communication. The definition of each of these aspects is provided in detail below and the key components of the architecture and their dependencies are summarised in figure 1.

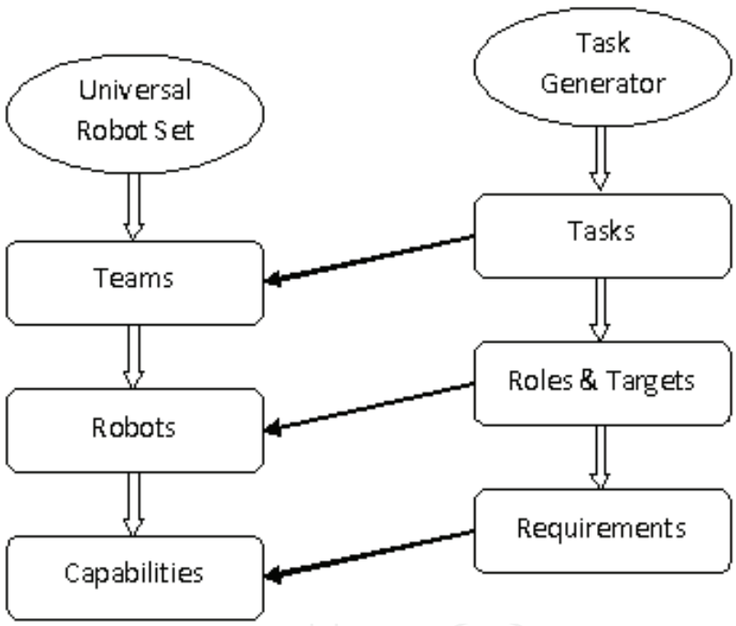

Fig. 1. Overview of the proposed MRMT architecture

a. Universal Robot Set (URS)
   - A pool of robots, referred to as the universal robot set (URS) is assumed from which robots can be drawn to form one or more robot teams.
   - Subsets of robots can be drawn from the universal set to form robot teams. A robot team may comprise zero, one, two or more robots. The first case represents the requirement for a team to perform a task but the robots may not need to be allocated immediately.
   - If multiple robot teams are drawn simultaneously from the universal set they are expected to be mutually exclusive; however it is possible for a robot to be a member of multiple robot teams simultaneously.

b. Teams, robots, capabilities
   - Robot teams are comprised of robots which possess mobility, manipulation, sensing, computing and instrumentation modules that determine their capabilities.

- In a modular framework a robot can swap in or out modules, and hence the selection of a robot to be a member of a team should take into account its potential configurations.
- The capabilities of a robot are determined also by its cognitive, deliberative and behavioural intelligence, which can also be swapped in or out to suit different roles.
- The set of capabilities that are collectively possessed by a robot team must satisfy the requirements of the task that the team is required to perform.

c. Tasks, roles, targets
- A task specifies the work that a robot team is to perform, specifically the goal to be achieved and the termination conditions to be satisfied.
- Tasks have associated implementation schemas. The schema sets out the roles that are required for the task, the targets of these roles, the plans for completing the task; and the requirements for the robotic systems to perform the roles including sensing, actuation, instrumentation, and cognitive, behavioural and deliberative intelligence components.
- Tasks are assigned to robot teams and roles and targets are assigned to robots within the team.
- The robots within the robot team must possess the capabilities required to satisfy the roles to which they are assigned.

d. Role Management
- Each robot possesses a Role Manager which has the responsibility for managing the allocation of roles to the robot and the robot's operation according to the role(s) it has been assigned.
- The Role Manager is responsible for either accepting an assigned role (top-down allocation) or negotiating on behalf of the robot to be assigned a role (bottom-up negotiation).
- The Role Manger incorporates mechanisms to ensure the appropriate interaction and scheduling of multiple roles, if multiple roles are assigned to a robot.
- Each robot possesses a Download Manager, a Configuration Manager, and a Task Manager.
- The Role Manager liaises with a Download Manager to ensure that the software required to support the role is downloaded and installed.
- The Role Manager liaises with a Configuration Manager to ensure that the modules appropriate to the roles are installed.
- The Role Manager liaises with the Task Manager to ensure that the robot executes the subtask associated with the role that has been allocated to the robot.

e. Command, Control and Communication
- The method a task schema proposes for performing a task places requirements on robot to robot command, control and communication. These are specified in the task schema and embodied in the software that implements the method.
- These requirements are stated in terms of
  - macroscopic and microscopic command & control
  - implicit and explicit communication
- In order to support these requirements the command structures for robot control need to be stated as group-type commands and each robot, in fulfilling the roles

and targets it has been assigned in a robot team, must possess a command, control and communication system that interprets these commands with respect to the individual robot's operations.

4. The lifecycle of a task

The previous section described the aspects and components of the MRMT model. This section illustrates the application of the model. To support the application of the model we propose a lifecycle for a task. This is described in the following sub-section. We then give examples to illustrate the application of the lifecycle for the four combinations of roles and targets from Table 1.

4.1 The design of the lifecycle

We propose a design for the lifecycle of a task in the MRMT model that comprises seven steps, from the inception of the task to its satisfactory completion and subsequent disbanding of the robot team as follows.

Step 1. *Generate the task to be performed.* The task may be generated manually or automatically, on the fly in response to real-time events or part of a predefined work schedule. The responsibility for the generation of tasks can be considered to be a role that could be carried out centrally or assigned to a robot in a robot team.

Step 2. *Assess the requirements for the task and determine a corresponding task schema.* The requirements can be used to index a schema library. A number of schemas may be available for completing the task. The selected schema may also incorporate rules for scaling it to meet the size and scope of the task.

Step 3. *Create a robot team and allocate the task and schema to the team.* A team object is created to represent the team that is required for the task. The task and the schema are then registered with the team object.

Step 4. *Populate the team with robots and assign roles and targets.* The allocation of robots to the robot team can follow a top-down centralised approach where roles are assigned to robots and the robots are therefore assigned to the team, a bottom-up negotiated approach where each of the robots negotiates for its position in the team, or a combination of these. In all cases the services offered by individual modules and robots (current and potential configurations of modules) must be considered. The responsibility for the creation of teams to perform a task can be considered to be a role. The role can be performed centrally or allocated to one or more of the robots in a team.

Step 5. *Install the appropriate robot configurations to support the assigned roles.* The modules (e.g. instruments) that are required by each robot to perform its allocated role on associated target are installed. The software to support the cognitive, deliberative and behavioural requirements for the task is downloaded, if required, and installed.

Step 6. *Perform the task until satisfactorily completed.* The task is performed according to the overall task plan and the plans associated with each role, as set out in the task schema. The task is completed when the goal has been achieved to the satisfaction of the individual robots and the robot team, which is also set out in the task schema.

Step 7. *Disband the robot team.* The set of robots are removed from the team and the team bject is removed.

4.2 Demonstration of the lifecycle

In section 3.1 we proposed classifying roles and targets into four categories, namely (a) Single Role, Single Target, (b) Single Role, Multiple Targets, (c) Multiple Roles, Single Targetand (d) Multiple Roles, Multiple Targets. We now demonstrate the application of the lifecycle model for example tasks relevant to space applications that fall under each of these categories.

4.2.1 Single role, single target

We select as an example, multiple robots cooperating to carry an object. One role is required, namely a carrier role. The target is the object to be carried and sub-targets are the grasp interfaces on the object to be carried. The carriers are responsible for collectively picking up the object, carrying the object to a destination and depositing or assembling the object. The robots will assess their resources and locations relative to the object to be carried and negotiate with each other for grasp interfaces. Each robot will approach and grasp its assigned grasp interfaces, avoiding obstacles and interference with other robots.

The robots will need to synchronise so that they lift the object together. This can exploit both explicit and implicit communication. The robots will need to coordinate during traversal, using primarily implicit communication, to ensure that the object to be transported is not dropped. The robots will need to synchronise to ensure that the object is set down or assembled safely. Each robot will need to ensure that it has the resources to perform its role and to evaluate satisfactory completion of its role.

The capabilities required by each robot include the identification and localization of target and sub-targets, planning and navigation functions, manipulation for object pick-up and transport, and grippers for the grasp interfaces. The robots will also require sensing and evaluation capabilities for task and sub-task completion.

4.2.2 Single role, multiple target

We select as an example, sample acquisition from multiple science sites. The task requires a single role, namely sample acquisition. The targets are a set of sites from which samples are to be taken; there are no sub-targets. The robots are responsible for navigating to an assigned target, taking a sample and returning the sample to a Lander. The robots will need to localize the target, generate a plan and navigate to the target following this plan. At the target the robots will deploy the sampling instrument, take the sample and stow it in a sample container. The robot will then be required to generate a plan and navigate back to the Lander and transfer the sample.

The robots will need to coordinate on the allocation of samples, taking account of their resources and locations with respect to the set of samples. A robot may be assigned a number of targets, which will require it to generate a plan to visit each of the targets before returning to the Lander. The robots will need to avoid interference with each other and avoid obstacles.

Each robot will need to ensure that it has the resources to perform its role and to evaluate satisfactory completion of its role. The robots must synchronise to ensure that the multiplesample acquisition task is completed successfully. If one or more targets have not been visited the robots will need to negotiate to assign the targets and acquire samples.

4.2.3 Multiple roles, single target

We select as an example, site preparation for construction of a human habitat. The roles include diggers, movers, and breakers. The target is a designated area that is to be leveled in

preparation for infrastructure building. The robots will be working on sub-targets within this area, avoiding interference with each other. The diggers are responsible for digging and moving soil. The movers are responsible for moving small sized rocks. The breakers are responsible for breaking medium sized rocks into small sized rocks. It is assumed that the site has been selected such that it contains no large sized rocks and minimal numbers of medium sized rocks.

Each role, namely digging, moving and breaking will have associated sub-target types. Digging will include areas from which soil is to be removed and areas in which it is to be deposited. Moving will include the identities of small sized rocks to be moved and locations to which they are to be deposited. Breaking will include the identities of medium sized rocks to be broken apart. The robots filling each role type need to assess their locations and resources and negotiate (explicit communication) to assign each other sub-targets.

The robots will need to identify their respective sub-targets from the environment, navigate to these, perform the corresponding operations on the sub-targets and repeat for all sub targets until the site preparation task has been completed. The robots will also need to identify new sub-targets. For example, when a medium sized rock has been broken a new set of small sized rocks are created, which become new sub-targets for the movers. The movers can identify the new sub-targets through implicit communication (i.e., observation of the environment) or explicit communication (i.e., the breakers inform the movers). The diggers need to identify if new sub-targets that need levelling and new sub-targets that need filling.

The robots will need to coordinate. For example, small sized rocks can be used to fill a dip in the terrain prior to depositing soil. Therefore, the movers and diggers need to coordinate to ensure that this constraint is satisfied. In addition, the robots will need to avoid interference with each other and avoid obstacles. Each robot will need to ensure that it has the resources to perform its role and to evaluate satisfactory completion of its role. The robots must synchronise to ensure that the terrain is levelled before agreeing that the task has been satisfactorily completed.

4.2.4 Multiple roles, multiple targets

We select as an example, transportation of an object across unstructured terrain. The scenario includes three robot teams with associated roles, namely carriers, clearers, and scouters. The targets are an object that is to be transported (the carriers team), a path that is to be cleared (the clearers team), and open terrain through which a path is to be scouted (the scouters team). Sub-targets are respectively grasp points on the object to be transported, rocks that are to be removed from the path, and areas to be explored. The carriers are responsible for picking up an object to be transported, carrying it along a path and setting it down or assembling it at a destination. The clearers are responsible for clearing rocks from the path. The scouters are responsible for discovering a path to the site where the transported object is to be relocated.

The robots will need to identify their respective sub-targets from the environment, navigate to these, and perform the corresponding operations on the sub-targets until the object has been successfully transported to the destination. The requirements of the carrier team are similar to those described in the example above of multiple robots cooperating to carry an object. The requirements for the clearers team are similar to those for the movers team described in the example above of site preparation for construction of a human habitat. The scouters will need to collectively identify new sub-targets to explore in order to find a path to the destination. They will need to evaluate the suitability of the sub-targets for traversal and clearance.

The scouters will need to coordinate with each other to select a suitable path through the explored sub-targets. The scouters will need to communicate the selection to the clearers and also to the carriers. The clearers need to coordinate with the scouters and the carriers to confirm the path. Each robot will need to ensure that it has the resources to perform its role and to evaluate satisfactory completion of its role. The robots must synchronise to ensure that the task has been satisfactorily completed.

5. Case studies

In this section two extended scenarios are presented to illustrate the application of the MRMT model. The scenarios are labelled here as expedition robotics and transportation robotics. The expedition robotics scenario emphasises diversity of robot-robot cooperation with a specific focus on exploration, whereas the transportation robotics scenario emphasises cooperation between robot teams, as an extension of cooperation between robots in a single team.

5.1 Expedition robotics

This scenario comprises two robotic systems, a Carrier (Heavy-Duty UAV) Robot and a general purpose Runabout Robot. The Carrier Robot provides a transport vehicle for robots, robot spares and science instruments, while the Runabout provides a dexterous and highly mobile assistant to the Carrier. The following are the considerations of the scenario with respect to the proposed MRMT model.

5.1.1 Universal robot set

- The Carrier, the Runabout, and robots on the Carrier (e.g. mini-robots, micro-robots; small teams, swarms; surface, air, underground robots; and robots custom-built from modules).

5.1.2 Teams, robots, capabilities

- The Carrier Robot offers the following:
  - A charging station for the Runabout.
  - A charging station for the Runabout.
  - Crane hoist for lifting/deploying robots and instruments from Storage; can be stowed during long-distance traverse.
  - Storage Rack for instruments and robot spares.
  - A computational platform complementing the Runabout's onboard processing capabilities.
  - A heterogeneous pool of micro and mini robot systems with wheeled and legged mobility.
  - A Build and Change out station for assembling robot systems and hot-swapping robotic modules.
- The Runabout offers the following:
  - A high-dexterity mobility platform.
  - A mobile assistant to deploy science instruments from the Carrier.
  - A scouting capability to support navigation to science sites.
  - Ability to survey a science site in cooperation with the Carrier.

5.1.3 Tasks, roles, target

- Science Deployment Tasks
  - The Runabout carries an instrument pack from the Carrier to a selected location where it is deployed.
  - The Runabout carries one or more robots to selected deployment sites.
- Science Tasks
  - Sample acquisition task can be performed by the Runabout and/or Carrier-supplied robots and instruments.
  - Site surveys employing the Runabout and/or Carrier-supplied robots and instruments.
- These tasks can be generated locally, i.e. at the site by the robot systems (i.e. autonomously) or through cooperation between the Carrier and the Runabout working together to identify science targets. In the latter, the Runabout may fulfil the role of a roving eye for the Carrier.
- The task generation role can be located on the Carrier, using its powerful onboard computing capacity and/or located on the Runabout.

5.1.4 Role management

- The Carrier is assumed to house a server on which the task schema library is housed and the software modules to support the range of roles applicable to the tasks. The software is downloaded as required.
- The Carrier must support the configuration of the Runabout and other robot systems to support the roles required for the task.

5.1.5 Command, control, communication

- Most of the tasks will require explicit communication, since it is assumed that the Carrier houses assembly mechanisms for configuring robots and there is little requirement for tightly coupled cooperation such as for object transport.
- Much of the cooperation will be in terms of managing the loading and off-loading of robots and instruments between the Carrier and the Runabout with the help of the Crane Hoist.
- The Carrier and/or Runabout can issue group commands to robot teams.

5.2 Transportation robotics

This scenario comprises multiple robot teams, incorporating cooperation between robots within a team and between robot teams. Three robot teams are proposed including (a) a mover robot team, charged with cooperatively carrying an extended payload incorporating multiple grasp interfaces, (b) a clearing robot team, charged with clearing a path of obstacles for the mover robot team and (c) a scouting robot team, charged with scouting a path to a target site and hence guiding the clearing robot team and the mover robot team. The following are the considerations of the scenario with respect to the proposed MRMT model.

5.2.1 Universal robot set

- A heterogeneous set of robot systems to support lifting, clearing, exploring.

5.2.2 Teams, robots, capabilities

- Ability to lift objects, good mobility, custom purpose grippers/manipulators.
- Vision sensing for localisation, navigation and identifying objects to be cleared from the path.
- Planning and navigation software capability for autonomy.
- Information can be passed between the teams (team-based communication required).
- Robots can move between teams as resources become available and the subtasks become doable.
- In one scenario the task starts with all robots assigned to the scouting team; then as the task progresses some of these are reallocated to the clearer team, and then some of both of these to the mover team.

5.2.3 Tasks, roles, target

- Tasks include cooperative pickup, transport, assembly, clearance and scouting/ mapping.
- Roles include moving, clearing, scouting and guiding.

5.2.4 Role management

- The task script is pre-defined; a number of scripts can be assumed for the task, requiring selection and download.
- Role allocation is required, since different robots may perform different roles, and possibly a single robot may perform multiple roles simultaneously.
- Robots may be reassigned between teams.

5.2.5 Command, control, communication

- The mover team will require implicit communication.
- Synchronisation of the robots for initiation and completion of the task requires explicit communication.
- Explicit communication is required between the members of the scouter team.
- Guidance and command & control may be directed from the guide robots to clearers and movers.
- Macroscopic/microscopic command and conversion will be required.
- Inter-team communication will be explicit.

5.3 Summary

The two case studies, Expedition and Transportation Robotics, illustrate how the proposed MRMT model can be exploited in multi-robot multi-team working. The second scenario, in particular, illustrates the way in which the model supports multiple teams, including collaboration between teams and sharing of robots between teams. This builds on the idea that an individual robot is inherently a team player.

6. Conclusions

Conventional robot architectures applied to team robot systems treat the robots as individual systems and only then overlay a team-based perspective. This does not offer the flexibility of teams being able to organise themselves recursively into finer sub-teams and

indeed leaves the whole idea of a team implicit. In this chapter, we have proposed a model, the Multi- Robot Multi-Team (MRMT) model, for multiple robots working in multiple teams. We have defined aspects and components to the model and presented a design for the lifecycle of a task. We have subsequently illustrated the application of the model in a set of four example applications and two extended scenarios using space robotics as the application domain. We propose, in conclusion, that the MRMT model offers a more flexible framework for robot teams since the individual robots are effectively designed from the ground up as team players.

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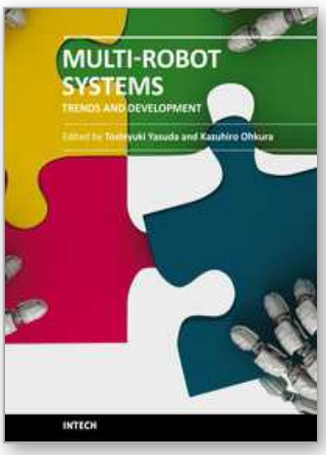

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