International Journal of Advance Research in Science and Engineering
Vol. No.6, Issue No. 08, August 2017
www.ijarse.com
IJARSE
ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

A STUDY ON MULTIROBOT COMMUNICATION

Thilagavathy R[1], Sumithra Devi K.A[2]

[1]*Assistant Professor, Dept.of ECE, GSSSIETW, Mysuru, Karnataka, (India)*

[2] *Principal, GSSSIETW, Mysuru, Karnataka, (India)*

ABSTRACT

Co-ordination, coupled with communication, is very important for any multi-robot system to successfully accomplish the task. Co-ordination and communication can multiply the capabilities and effectiveness of a group of robots. Having made great progress in the development of the basic problems concerning single-robot control, many researchers shifted their focus to the study of multi-robot coordination. This paper presents a systematic survey and analysis of the existing literature on coordination, especially in multiple mobile robot systems (MMRSs). A series of related problems have been reviewed, which include a communication mechanism, a planning strategy and a decision-making structure. A brief conclusion are given at the end of the paper.

Keywords: *Communication, Coordination, Decision Making, Mobile robot systems, Planning*

I. INTRODUCTION

Communication comes in many forms and involves the use of signals (e.g., sound, look, motion) and every animal, from the smallest insect to humans, uses some type of communication since the ability to share information is an important survival tool. Although they have different lifestyles than humans, other animals use communication for many of the same reasons such as getting food, staying safe, finding a mate, and protecting territory. In multi-robot systems (MRS) the objective of communication is very similar: usually, in order to accomplish a given task (e.g., finding an object), robots must share information (e.g., about what they are sensing).Multi-robot systems (MRSs) are an important part of robotics research [1].

One of the major challenges for MRSs is to design appropriate coordination strategies between the robots that enable them to perform operations efficiently in terms of time and working space. Most of today’s robots fall into one of three primary categories – the manipulation robotic system, the mobile robotic system and the data acquisition and control robotic system. The manipulation robot system is the most commonly used in the manufacturing industry. These systems are made up of many of the robot arms with 4-6 axes and varying degrees of freedom. They can perform several different functions, including welding, material handling and material removal applications.

The mobile robotic system is a bit different. This system consists of an automated platform that moves items from one place to another. While these robot systems are used heavily in manufacturing for carrying tools and spare parts, they are also used in the agricultural industry for transporting products. These can also be used by several different industries because of their ability to swim and fly, as well as move along the ground. Data acquisition and control robotic systems are used to gather, process and transmit data for a variety of signals. They are also

used in software for engineering and business. Many of the mobile robotic systems can use signals from these systems. The area of MRS involves mobile robots that can move in the physical world and must interact with each other physically [2].

So far, a number of papers have been published regarding the research review, taxonomy and survey analysis for MRS. Dudek et al. [3] presented a taxonomy that classifies MASs according to communication, computational capacity and certain other capabilities. They also presented additional results concerning the MAS to illustrate the usefulness of the taxonomy and demonstrate that a collective can be more powerful than a single unit of the collective. Cao et al. [2] gave a critical survey of the cooperative mobile robotics literature up to the mid-1990s. They synthesized five research axes that were: group architecture, resource conflict, origin of cooperation, learning and geometric problems. They also discussed the constraints arising from technological limitations and possible lacunae in existing works. Stone and Veloso [4] presented four multi-agent scenarios: homogeneous non-communicating agents, heterogeneous non-communicating agents, homogeneous communicating agents and heterogeneous communicating agents. They illustrated the scenarios by using the pursuit domain and described existing works in the field. The techniques presented are biased towards machine learning approaches. Arai et al.

[5] identified seven primary research topics within the MRS: biological inspirations, communication, architectures, localization / mapping / exploration, object transport and manipulation, motion coordination, and reconfigurable robots. They also discussed a number of special issue articles and suggested several additional research issues. Farinelli et al. [6] presented a survey of works up to the early 2000s in the area of cooperation and coordination in MRS. Moreover, they proposed a taxonomy for classification focused on coordination that is characterized by two groups of dimensions: coordination dimensions and system dimensions. Other works on the review of the MRS include [7] [8] [9] [10] [11].

The remainder of the paper is organized as follows: Section 2 describes Robotic systems compared single-robot systems with multi-robot systems; Section 3 presents four types of communication mechanism: explicit, implicit, state and goal; Section 4 describes two multi-robot environments: cooperative and competitive; Section 5 discusses two types of coordination; Section 6 discusses the problem of planning based on coordination, which includes task planning and motion planning; Section 7 presents two decision-making mechanisms: centralized and decentralized; the paper is concluded with a discussion in 8.

II. ROBOTIC SYSTEMS

A single-robot system contains only one individual robot that is able to model itself, the environment and their interaction [4]. Several individual robots are well known, such as RHINO [12], ASIMO [13], MER-A [14], Big Dog [15], NAO [16] and PR2 [17]. The robot in a single-robot system is often designed to deal with a task on its own account. Such robots are usually integrated with multiple sensors, which themselves need a complex mechanism and an advanced intelligent control system. Although a single-robot system give have a relatively strong performance, some tasks may be inherently too complex or even impossible for it to perform, such as spatially separate tasks. For example, Dudek et al. [3] gave an example of a missile launch task that requires some sort of synchronization: there are two keys separated by a large distance in space that need to be activated simultaneously. Hence, an inherent restriction to the single-robot system is that it is spatially limited.

The field of cooperation and coordination of multi-robot systems has been object of considerable research efforts in the last years. The basic idea is that multi-robot systems can perform tasks more efficiently than a single robot or can accomplish tasks not executable by a single one. Moreover, multi-robot systems have advantages like increasing tolerance to possible vehicle fault [18][19][20], providing flexibility [21] to the task execution or taking advantages of distributed sensing and actuation.

A MRS can be homogeneous or heterogeneous. In homogeneous robot teams, the capabilities of the individual robots are identical (physical structures do not need to be the same). In heterogeneous robot teams, the capabilities of robots are different, whereby robots can be specialized for specific tasks. Some works considering the use of heterogeneous robot teams include [22] [23] [20] [24] [25] [26]. In general, heterogeneous systems are more complex than homogeneous systems because the task planning becomes more difficult.

III. COMMUNICATION

3.1 Need for communication

There are many scenarios where we desire communication in the context of multi robot systems. First there is need to co-ordinate actions between different robots so that the task can be accomplished without any conflicts. Second the robots could exchange knowledge about situations they are in, for example a map of a room one robot has explored but others haven't. Third robots can share sensory evidence to enhance, de-noisify or reveal things about the world. A very basic example would be when robots are heterogeneous and have different kinds of sensors. Communication is desirable in the building of group goals. In case of a robocup team, there is a global, constant goal of winning the match. However, sub-goals that influence the current movements and near future tactics of the team members can and should change rapidly to be able to cope with the opponent. Such goals need to be communicated. Communication increases the group cohesion [27]

3.2 Communication, a broad definition

In the context of multi robot systems, the definition of communication is very broad due to the fact that a lot of robots are simple agents. We define Communication as the transfer of information between one robot and another. The problem with this broad definition is that it includes all kinds of unintentional forms of communication. For a more precise definition, it is required that the conveying of information have some form of intentionality on both the sides.

3.3 Types of Communications

A simple classification of communication used in the field of multi robot systems is as follows:

3.3.1 Implicit Communication

Implicit communication is communicating through change in the environment, also known as stigmery. Robots can leave marks and trails that can convey information to other robots that will recognize these changes in the environment. Such actions can be compared to human actions like children chalking arrows on the sidewalk or ants leaving scent trails.

3.3.2 Explicit Communication

This type of communication is purposely transmitting and receiving communication via some sort of protocol or language as a medium. Explicit communication is always intentional and the robots are completely aware of it. Examples of such communication are nothing but alarm calls or humans speaking language to one another. A communication device is required for such communication to serve as a medium, for instance radio or wireless Ethernet. In comparison, explicit communication is less robust than implicit communication as communication needs to be transmitted and received in a separate process.

3.3.3 State Communication

In state communication, the robots should be able to observe the behavior of other robots. An example would be body language. It can be applied to robotics for instance in a light following task, where robots follow each other towards a light source. Note that for such communication a robot must be able to recognize other robots and know what their actions mean.

3.3.4 Goal Communication

This type of communication involves the transmission and reception of specific goal-oriented information. Implementation of it on mobile robots requires data to be encoded, transmitted, received and decoded. Goal communication differs from state communication in that the sender deliberately sends or broadcasts the information. A natural example of this type of communication is found in the behavior of honeybees.

IV. MULTI-ROBOT ENVIRONMENT: COOPERATIVE VERSUS COMPETITIVE

To get coordination among the robots, we can usefully consider the different aspects of coordination that is the cooperation and the competition. Popenoe [28] defined collective behavior as follows: collective behavior is behavior that occurs in response to a common influence or stimulus in relatively spontaneous, unpredictable, unstructured and unstable situations. The collective behavior includes cooperative behavior and competitive behavior. In other words, multi-robot environments can be cooperative or competitive [29]. Cooperation refers to a situation whereby multiple robots need to interact together in order to complete a task while increasing the total utility of the system. Alternatively, cooperation is the interaction between the robots, which work towards a common interest or reward [30]. The cooperative robots have a joint goal, which gives rise to various sub-goals.

V. COORDINATION: STATIC VERSUS DYNAMIC

Multi-robot coordination is the core task of MRSs. The overall system performance can be directly affected by the quality of coordination and control. Coordination can be static or dynamic. Static coordination (also known as deliberative coordination [8] or offline coordination [7]) generally refers to the adoption of a convention prior to engaging in the task. For example, some rules in traffic control problems include “keep right”, “stop at intersection” and “keep sufficient space between yourself and the robot in front of you” [31]. Dynamic coordination (also known as reactive coordination [8] or online coordination [7]) occurs during the execution of a task, and is generally based on the analysis and synthesis of information. The information can be obtained through the means of communication.

Dynamic coordination can also be divided into two categories: explicit coordination and implicit coordination. The first is realized by looking at the external behavior of the other agents, without any robot transmitting whatever information. The second is realized by sending voluntarily explicit coordination messages to the other agents. A fully distributed architecture based on explicit broadcast communication and active perception, that considers the cooperative side of coordination among heterogeneous mobile robots, with attention to fault tolerance, has been proposed in [22], where the cooperation is obtained by observing other robot’s activity, recognizing the action of a certain robot, and making use of broadcast communication. Another architecture has been proposed in [15], built on a multiple physical robot system, with emphasis on cooperation, where the coordination via implicit communication is exploited only to perform low-level coordination, as following, collision avoidance, and the so-called modest cooperation, letting the higher-level cooperation to the explicit communication. Efficient cooperation among two robots has been obtained in [18] by a communication system based on an explicit negotiation protocol performed when an action partner is selected in order to reach a collective decision.

VI. PLANNING: TASK PLANNING AND MOTION PLANNING

The task of coming up with a sequence of actions that will achieve a goal is called ‘planning’ [29]. In MRS, planning can be used to coordinate robots in accomplishing the team mission. Multi-robot planning is usually divided into two aspects: task planning and motion planning. Task planning is primarily designed to solve the problem of which robot should execute which task. This involves task decomposition and task allocation. Motion planning is primarily designed to generate the path of each robot. In addition, a robot should take into account the paths of others in order to avoid any collision, congestion or deadlock that may come along. There is a key characteristic of robotics problems: uncertainty, which arises from the partial observability of the environment and from the stochastic (or unmoulded) effects of the robot's actions [29]. This is why the benchmarking of robotics research is inherently difficult (especially for MRSs).

6.1 Task Planning

Multi-robot task planning (MRTP) includes two aspects: task decomposition and task allocation. So far, the research on task planning for MRSs has been mainly concentrated on the task allocation problem, with relatively little on the task decomposition problem. In fact, task decomposition is an important research topic because the effect of task allocation could be directly influenced by it. Multi-robot task decomposition (MRTD) mainly refers to how the team mission to be completed is decomposed into several single subtasks that can be completed by a robot independently, according to the characteristics, requirements and resource allocation of the team mission itself [32]. Stone and Veloso [33] achieved collaboration between agents through the introduction of formations, which decompose the task space defining a set of roles with associated behaviors. Botelho and Alami [34] presented a decentralized system to describe and perform task planning, decomposition and allocation in multirobot environments called the M+ protocol.

This work was developed from an early European project called MARTHA [35]. Zlot and Stentz [36] focused on complex tasks that can be decomposed into multiple inter-related subtasks. They addressed the task decomposition problem by generalizing tasks to task trees within a peerto-peer trading market. Tang and Parker [37] considered that, in typical approaches to multi-robot team working, the decomposition of the team’s task into subtasks is defined by the human designer in advance of the robot team’s performance, and that this pattern also outlines the available multi-robot task solutions in advance of the mission. As such, they described a methodology for automatically synthesizing task solutions for heterogeneous multi-robot teams. Other relevant works on MRTD include [38].

In our previous work, we considered task allocation and also took task decomposition into account. In [39] [40], we first decomposed the whole multi-robot exploration mission into several subtasks (i.e., the exploration of several unknown regions), which can be identified by topologizing the grid map of the environment. Next, we discussed how to assign the subtasks to each individual robot in a reasonable manner. Multi-robot task allocation (MRTA) can be considered as an instance of the well-known optimal assignment problem, whereby the general form of this problem can be expressed as follows: There are a number of agents and a number of tasks. Any agent can be assigned to perform any task, incurring some cost that may vary depending on the agent-task assignment. It is required to perform all tasks by assigning exactly one agent to each task in such a way that the total cost of the assignment is minimized. Moreover, the task allocation for heterogeneous and homogeneous systems may be different. In heterogeneous systems, task allocation may be determined by each robot’s individual capabilities. However, in homogeneous systems robots have no preference for roles, and they may then need to differentiate into different roles at design-time, or dynamically at run-time [40]. Parker [41] introduced the concept of task coverage, which measures the ability of a given team member to achieve a given task. This parameter can be used as an index to organize a robot team from the available pool of heterogeneous robots in order to perform a mission. The task coverage reaches the maximum value in homogeneous teams and decreases as teams become more heterogeneous.

6.2 Motion Planning

In robotics, the motion planning problem involves producing a continuous robot motion from one configuration to another in a configuration space while avoiding collision with obstacles. Motion planning is eminently necessary for mobile robots since, by definition, a robot accomplishes tasks by moving in the real world [42].

Multi-robot motion planning (MRMP) should consider not only any obstacles (whether static or dynamic) in the environment, but also any possible interference between robots. This is because, when robots in a team are used to perform independent tasks in a shared workspace, each one will become a mobile obstacle for the others. Therefore, the motion planning of each individual robot in the team should take into account the movement of others. One well-studied example of MRMP is the multirobot space sharing problem (see Section 4). A multi-robot environment must definitely be dynamic, in which robot motion planning is inherently difficult. Even for a simple case in two dimensions, the problem is NP-hard and not solvable in polynomial time [43]. Among existing MRMP methods, the environment for an autonomous mobile robot is usually represented by an occupancy grid map, and the robot is reduced to a point in a two-dimensional plane (i.e., the workspace). Next, the motion is represented as a path in the workspace space.

Most of the existing approaches to MRMP are expanded from the results of a single-robot system. Three major families of approaches are the cell decomposition, potential field and roadmap approaches. They all reduce the continuous motion planning problem to a discrete graph search problem by identifying some canonical states and paths within the free space. The cell decomposition approach decomposes the free space into a finite number of contiguous regions, called cells.

The potential field approach generates a path by combining repulsion from obstacles with attraction to a goal. This approach is extensively used in the multi-robot formation control problem. The roadmap approach reduces the robot’s free space to a set of one-dimensional curves connecting a set of nodes, called a roadmap. A typical roadmap approach is a Voronoi diagram, which specifies the set of all points equidistant from two or more closest obstacles. Following the Voronoi diagram may not give the shortest path, but the resulting paths tend to maximize clearance [29]. The Voronoi diagram is often applied to the problem of robotic exploration.

Another roadmap approach is the probabilistic roadmap (PRM) [44], which has been widely used for robot arms in engineering and manufacturing. This method randomly generates a large number of collision-free configurations and achieves motion planning by connecting some of them. Several studies address multirobot coordination based on PRM, but focus on manipulator arms [45] [46].

VII. DECISION-MAKING: CENTRALIZED VERSUS DECENTRALIZED

Decision-making can be regarded as a cognitive process resulting in the selection of a course of action among several alternative scenarios. Every decision-making process produces a final choice. In MRS, the decision making guided by planning can be centralized or decentralized in accordance with the group architecture of the robots. There is a central control agent in centralized architectures that has the global information about the environment as well as all information about the robots, and which can communicate with all the robots to share them. The central control agent could be a computer or a robot. The advantage of the centralized architecture is that the central control agent has a global view of the world, whereby the globally optimal plans can be produced. Nevertheless, this architecture: 1) is typical for a small number of robots and ineffectual for large teams with more robots; 2) is not robust in relation to dynamic environments or failures in communications and other uncertainties;

3) produces a highly vulnerable system, and if the central control agent malfunctions a new agent must be available or else the entire team is disabled.

Decentralized architectures can be further divided into two categories: distributed architectures and hierarchical architectures. There is no central control agent in distributed architectures, such that all the robots are equal with respect to control and are completely autonomous in the decision-making process. In hierarchical architectures, there exist one or more local central control agents which organize robots into clusters. The hierarchical architecture is a hybrid architecture, intermediate between a centralized architecture and a distributed architecture. In contrast to a centralized architecture, a decentralized architecture can better respond to unknown or changing environments, and usually has better reliability, flexibility, adaptability and robustness. Nevertheless, the solutions they reach are often suboptimal.

VIII. CONCLUSION

In this paper, we surveyed the key research problems in the field of MMRS, focusing on those approaches involving multi-robot coordination. We started by surveying the potential advantages of Robotics systems in contrast to single-robot systems. Afterwards, we discussed two multi-robot environments, namely cooperative and competitive environments. Next, we discussed multi-robot coordination in two respects, including static and dynamic, and communication as a means of coordination. Following this, we discussed multi-robot planning problem, including task planning and motion planning, which is inseparable from multi-robot coordination. Finally, we identified two decision-making architectures including centralized and decentralized approaches.

REFERENCES

[1] Micael S. Couceiro, Rui P. Rocha, Nuno M. F. Ferreira, Patricia A. Vargas, Darwinian Robotic Swarms for Exploration with Minimal Communication, 2013 IEEE Congress on Evolutionary Computation , 127-134, June 20-23, 2013.

[2] Y. Uny Cao, Alex S. Fukunaga, and Andrew B. Kahng. Cooperative mobile robotics: Antecedents and directions. Autonomous Robots, 4(1):7-27, 1997.

[3] Gregory Dudek, Michael R. M. Jenkin, Evangelos Milios, and David Wilkes. A taxonomy for multiagent robotics. Autonomous Robots, 3(4):375-397, 1996.

[4] Peter Stone and Manuela Veloso. Multiagent systems: A survey from a machine learning perspective. Autonomous Robots, 8(3):345-383, 2000.

[5] Tamio Arai, Enrico Pagello, and Lynne E. Parker. Editorial: Advances in multi-robot systems. IEEE Transactions on Robotics and Automation, 18(5):655661, 2002.

[6] Alessandro Farinelli, Luca Iocchi, and Daniele Nardi. Multi-robot systems: A classification focused on coordination. IEEE Transactions on Systems, Man, and Cybernetics, Part B: Cybernetics, 34(5):2015-2028, 2004.

[7] Eduardo Todt, Gustavo Raush, and Raúl Suárez. Analysis and classification of multiple robot coordination methods. In Proceedings of ICRA'00, pages 3158-3163, San Francisco, CA, USA, April 2000.

[8] Luca Iocchi, Daniele Nardi, and Massimiliano Salerno. Reactivity and deliberation: a survey on multi-robot systems. Lecture Notes in Computer Science, 2103:9-32, 2001.

[9] Brian P. Gerkey and Maja J. Matarić. A formal analysis and taxonomy of task allocation in multirobot systems.

[10] Jun Ota. Multi-agent robot systems as distributed autonomous systems. Advanced Engineering Informatics, 20(1):59-70, 2006.

[11] Lynne E. Parker. Distributed intelligence: Overview of the field and its application in multi-robot systems. Journal of Physical Agents, special issue on multi-robot systems, 2(2):5-14, 2008.

[12] Joachim Buhmann, Wolfram Burgard, Armin B. Cremers, Dieter Fox, Thomas Hofmann, Frank E. Schneider, Jiannis Strikos, and Sebastian Thrun. The mobile robot RHINO. AI Magazine, 16(2):31-38, 1995.

[13] Yoshiaki Sakagami, Ryujin Watanabe, Chiaki Aoyama, Shinichi Matsunaga, Nobuo Higaki, and Kikuo Fujimura. The intelligent ASIMO: system overview and integration. In Proceedings of IROS'02, pages 2478-2483, Lausanne, Switzerland, September 2002.

[14] http://marsrover.nasa.gov/home/index.html

[15] Marc Raibert, Kevin Blankespoor, Gabriel Nelson, Rob Playter, and the BigDog Team. BigDog, the rough-terrain quadruped robot. In Proceedings of the 17th World Congress of the International Federation of Automatic Control, pages 10822-10825, Seoul, Korea, July 2008.

[16] David Gouaillier, Vincent Hugel, Pierre Blazevic, Chris Kilner, Jérôme Monceaux, Pascal Lafourcade, Brice Marnier, Julien Serre, and Bruno Maisonnier. Mechatronic design of NAO humanoid. In Proceedings of ICRA'09, pages 769-774, Kobe, Japan, May 2009.

[17] Jonathan Bohren, Radu Bogdan Rusu, E. Gil Jones, Eitan Marder-Eppstein, Caroline Pantofaru, Melonee Wise, Lorenz Mösenlechner, Wim Meeussen, and Stefan Holzer. Towards autonomous robotic butlers: Lessons learned with the PR2. In Proceedings of ICRA'11, pages 5568-5575, Shanghai, China, May 2011.

[18] Dieter Fox, Wolfram Burgard, Hannes Kruppa, and Sebastian Thrun. A probabilistic approach to collaborative multi-robot localization. Autonomous Robots, 8(3):325-344, 2000.

[19] Stergios I. Roumeliotis and George A. Bekey. Distributed multirobot localization. IEEE Transactions on Robotics and Automation, 18(5):781-795, 2002.

[20] Raj Madhavan, Kingsley Fregene, and Lynne E. Parker. Distributed heterogeneous outdoor multirobot localization. In Proceedings of ICRA'02, pages 374-381, Washington, DC, USA, May 2002.

[21] Amanda Prorok, Alexander Bahr, and Alcherio Martinoli. Low-cost collaborative localization for large-scale multi-robot systems. In Proceedings of ICRA'12, pages 4236-4241, Saint Paul, MN, USA, May 2012.

[22] Lynne E. Parker. ALLIANCE: An architecture for fault tolerant, cooperative control of heterogeneous mobile robots. In Proceedings of IROS'94, pages 776-783, Munich, Germany, September 1994.

[23] Brian P. Gerkey and Maja J Matarić. Murdoch: Publish/subscribe task allocation for heterogeneous agents.

[24] Antonio Bicchi, Antonio Danesi, Gianluca Dini, Silvio Porta, Lucia Pallottino, Ida Savino, and Riccardo Schiavi. Heterogeneous wireless multirobot system. IEEE Robotics and Automation Magazine, 15(1):6270, March 2008.

[25] Yuanteng Pei and Matt W. Mutka. Steiner traveler: Relay deployment for remote sensing in heterogeneous multi-robot exploration. In Proceedings of ICRA'12, pages 1551-1556, Saint Paul, MN, USA, May 2012.

[26] Paula García, Pilar Caamaño, Richard J. Duro, and Francisco Bellas. Scalable task assignment for heterogeneous multi-robot teams. International Journal of Advanced Robotic Systems, 10(105):1-10, February 2013.

[27] Amit Keswani, Chemakura Baba Kumar Reddy, Girish Dhameja, Moqtar Ahmed Syed, Vinod devarajan, Navroop Singh, "Multi robot communication".

[28] David Popenoe. Sociology (11th Edition). Prentice Hall, 1999.

[29] Stuart J. Russell and Peter Norvig. Artificial Intelligence: A Modern Approach (2nd Edition). Prentice Hall, 2002.

[30] D. P. Barnes and J. O. Gray. Behaviour synthesis for co-operant mobile robot control. In Proceedings of Control'91, pages 1135-1140, Edinburgh, UK, March 1991.

[31] Shin Kato, Sakae Nishiyama, and Jun'ichi Takeno. Coordinating mobile robots by applying traffic rules. In Proceedings of IROS'92, pages 1535-1541, Raleigh, NC, USA, July 1992.

[32] Jianping Chen, Yimin Yang, and Liang Wei. Research on the approach of task decomposition in soccer robot system. In Proceedings of ICDMA'10, pages 284-289, Changsha, China, December 2010.

[33] Peter Stone and Manuela Veloso. Task decomposition, dynamic role assignment, and low-bandwidth communication for real-time strategic teamwork. Artificial Intelligence, 110(2):241-273, June 1999.

[34] Silvia C. Botelho and Rachid Alami. M+: A scheme for multi-robot cooperation through negotiated task allocation and achievement. In Proceedings of ICRA'99, pages 1234-1239, Detroit, MI, USA, May 1999.

[35] Rachid Alami, Sara Fleury, Matthieu Herrb, Félix Ingrand, and Frédéric Robert. Multi-robot cooperation in the MARTHA project. IEEE Robotics and Automation Magazine, 5(1):36-47, March 1998.

[36] Robert Zlot and Anthony Stentz. Complex task allocation for multiple robots. In Proceedings of ICRA'05, pages 1515-1522, Barcelona, Spain, April 2005.

[37] Fang Tang and Lynne E. Parker. Asymtre: Automated synthesis of multi-robot task solutions through software reconfiguration. In Proceedings of ICRA'05, pages 1501-1508, Barcelona, Spain, April 2005.

[38] Shimon Whiteson, Nate Kohl, Risto Miikkulainen, and Peter Stone. Evolving keepaway soccer players through task decomposition. Machine Learning, 59(1):5-30, May 2005.

[39] Zhi Yan, Nicolas Jouandeau, and Arab Ali Cherif. Sampling-based multi-robot exploration. In Proceedings of ISR/ROBOTIK 2010, pages 44-49, Munich, Germany, June 2010.

[40] Zhi Yan, Nicolas Jouandeau, and Arab Ali Cherif. Multi-robot decentralized exploration using a tradebased approach. In Proceedings of ICINCO'11, pages 99-105, Noordwijkerhout, The Netherlands, July 2011.

[41] Lynne E. Parker. Heterogeneous Multi-Robot Cooperation. PhD thesis, Massachusetts Institute of Technology, February 1994.

[42] Jean-Claude Latombe. Robot Motion Planning. Kluwer Academic Publishers, 1991.

[43] Yi Guo and Lynne E. Parker. A distributed and optimal motion planning approach for multiple mobile robots. In Proceedings of ICRA'02, pages 2612-2619, Washington, DC, USA, May 2002.

[44] Lydia E. Kavraki, Mihail N. Kolountzakis, and JeanClaude Latombe. Analysis of probabilistic roadmaps for path planning. In Proceedings of ICRA'96, pages 3020-3025, Minneapolis, MN, USA, April 1996.

[45] Gildardo Sánchez and Jean-Claude Latombe. Using a PRM planner to compare centralized and decoupled planning for multi-robot systems. In Proceedings of ICRA'02, pages 2112-2119, Washington, DC, USA, May 2002.

[46] Mitul Saha and Pekka Isto. Multi-robot motion planning by incremental coordination. In Proceedings of IROS'06, pages 5960-5963, Beijing, China, October 2006.