Special Issue on Multirobot Systems

BY MANUELA M. VELOSO
Guest Editor

DANIELE NARDI
Guest Editor

The research area of multirobot systems consists of the study of algorithms for perception, cognition, and actuation of systems composed of multiple robots. Until the early 1990s, mobile robotics focused mainly on the challenges of developing a single robot capable of robustly handling the physical environment. Industrial applications included multiple robots, but in a preprogrammed sense of replication. In the early to mid-1990s, there was a bloom of multiple robot systems inspired by the overall intelligent behavior of large biological insect communities, such as ants. Furthermore, the field of distributed artificial intelligence was also in great development. Multirobot research then expanded at a fast pace, in particular through the concrete RoboCup robot soccer initiative, which drew a broad and large community of multirobot researchers.

Multirobot systems are now a large well-established area of research that has reached a high level of maturity.

Multiple robots may achieve both more robust and more effective behavior by accomplishing coordinated tasks that are not possible for single robots. Groups of homogeneous and heterogeneous robots have a great potential for application in complex domains that may require the intelligent use and merge of diverse capabilities. The design, implementation, and evaluation of robots organized as teams pose a variety of scientific and technical challenges. A multirobot system can be considered as a multiagent system (MAS), but the techniques for coordination and cooperation in an MAS are often not well suited to deal with the uncertainty and model incompleteness that are typical of robotics. Hence, in this issue, we specifically focus on contributions to systems of multiple physically implemented robots.

Applications of multirobot systems span a broad spectrum of areas, including human-unreachable environments, such as space, underwater, and rescue; challenging domains, such as construction and teams of unmanned aerial vehicles; and adversarial domains, such as robot soccer. Various specific tasks are addressed, e.g., foraging and coverage of a given area, multitarget observation, object pushing and transportation, exploration and flocking. We expect that the complexity and the nature of tasks will continue to increase. The advances in robot soccer, as a complex, adversarial, highly dynamic and unpredicatable task demonstrate good evidence of progress.

The field of multirobot systems is now a large well established area of research that reached a high level of maturity. The research includes a variety of engineering and scientific aspects of robotics. This special issue is far from exhaustive, but it aims at presenting research in major areas, such as: 1) Cooperation Models; 2) Cooperative Sensing, Localization and Exploration, and 3) Control and Adaptation. We thank the authors and reviewers for their contributions.

Cooperation Models

A central issue in the design of multirobot systems is how cooperation is achieved within a team of robots. Cooperation approaches developed for multiagent systems do not directly apply to agents that are physical robots. Robots face perceptual, actuation, and communication challenges, including constraints in communication, limited perception capabilities, interaction with other robots and

Digital Object Identifier: 10.1109/JPROC.2006.877080

human operators, and complex agent structures for team formation. Furthermore, proposed approaches may be hard to experimentally evaluate due to the requirement of extensive use of fragile robot hardware.

The paper entitled "Market-Based Multirobot Coordination: A Survey and Analysis," by Dias *et al.*, surveys market-based approaches that allow for both centralized and distributed coordination. This family of approaches provides a coordination mechanism that inherits the efficacy and flexibility of a market economy and exploits these benefits to enable robust and efficient multirobot coordination in dynamic environments. The paper describes the philosophy, implementation, and results of the market-based approaches, and explores their ability to satisfy the many requirements for a successful coordination mechanism.

A different token-based coordination approach is presented in "Assignment of Dynamically Perceived Tasks by Token Passing in Multirobot Systems," by Farinelli *et al*. The assignment of the tasks to be accomplished by the members of a team of robots is done through token passing with the goal of substantially reducing the overhead of broadcast communication, while maintaining a suitable system performance. The paper addresses the dynamic perception of tasks during mission execution. In fact, in applications involving multirobot systems, tasks to be assigned cannot be inserted into the system in a centralized fashion, but are perceived by each entity during mission execution. The approach is evaluated by means of experiments both in a simulated environment and on real robots.

"Building Multirobot Coalitions Through Automated Task Solutions Synthesis," by Parker and Tang, describes a technique for automatically synthesizing task solutions for heterogeneous multirobot teams. The problem of forming teams of robots is faced in a context where the overall team behavior can be achieved by dynamically obtaining complex behaviors based on the individual behavior structure of each of the robots. Consequently, the robot team can synthesize new task solutions that use fundamentally different combinations of robot behaviors for different team compositions. Moreover, a general mechanism for sharing sensory information across networked robots is provided, so that more capable robots can assist less capable robots in accomplishing their objectives. The approach, named ASyMTRe (Automated Synthesis of Multirobot Task solutions through software Reconfiguration), is validated on two different teaming scenarios: altruistic cooperation involving multirobot transportation and coalescent cooperation involving multirobot box pushing.

The last paper in this group-entitled "Decentralized Cooperative Aerial Surveillance Using Fixed-Wing Miniature UAVs," by Beard *et al.*—addresses multirobot cooperation for applications that require aerial surveillance. After arguing that there is a critical need for automating aerial surveillance using teams of unmanned air vehicles (UAVs), the authors address a task that is common to many cooperative aerial surveillance applications: coordination of multiple UAVs to arrange their trajectories so that they sequentially fly over a given location (which could be moving) at fixed intervals in time. The paper presents an overview of the cooperative control techniques and shows how to use those techniques to develop a decentralized solution to the cooperative fly-by scenario. The approach is demonstrated via high-fidelity simulation as well as flight tests using miniature UAVs.

Cooperative Sensing, Localization, and Exploration

Mobile robots face the challenge of mapping and determining their position in an environment, based on perceptual information. While a single robot has access only to its local sensory data, a robot in a multirobot system can gather information from the other teammate robots. Sensing, localization, and exploration therefore become cooperative tasks involving the sharing and processing of distributed information.

The paper "Distributed Multirobot Exploration and Mapping," by Fox *et al.*, presents an approach to efficient exploration of unknown environments by multiple robots. The paper extends techniques of single-robot exploration and map building to large teams of robots. The extension involves two aspects: 1) a novel approach to multirobot map merging under global uncertainty about the robots' relative locations and 2) the fact that exploration strategies maximize the efficiency of exploration, based on shared maps. The proposed approach is developed as part of the CentiBots project, which aimed at fielding 100 robots in an indoor exploration and surveillance task.

"Building Segment-Based Maps without Pose Information," by Amigoni *et al.*, disregards the assumption that mobile robots can estimate the position from odometry readings. This is indeed the case when very simple robots are used to gather information from the environment. The authors propose a method to build a global geometrical map by integrating partial maps without using any odometry information. Building maps without odometry information increases the flexibility in data collection. Robots do not need to see each other during mapping, and data can be collected by a single robot or multiple robots in one or multiple mapping sessions. Experimental results show the effectiveness of the approach in different types of indoor environments.

The paper "Multirobot Simultaneous Localization and Mapping using Manifold Representations," by Howard *et al.*, addresses the issue of map representation for the problem of simultaneous localization and mapping in multirobot systems. The authors argue that standard two-dimensional representations are not suited for a consistent representation of environments that may be structured on multiple levels. Therefore, a manifold representation that overcomes this limitation is introduced, which allows for the representation of inconsistencies possibly arising in planar maps at loop closures. The paper addresses the manifold representation and its use in simultaneous localization and mapping. The advantages of the approach are demonstrated by experiments on a team of four robots.

"Cooperation Issues and Distributed Sensing for Multirobot Systems," by Pagello *et al.*, describes a multirobot system able to dynamically exchange the role of robots in the team and a distributed sensor system based on omnidirectional vision sensors. The distributed vision system allows the robots to cooperatively track moving objects and share the information about them. The information gathered from every robot is broadcast to all the other robots and every robot fuses its own measurements with the information received from the teammates. The proposed approach is developed and tested within the framework of the RoboCup soccer competitions, but the authors argue that it can be used in any application where a team of robots has to jointly track multiple objects.

The last paper in this group, entitled "Merging Occupancy Grid Maps from Multiple Robots," by Birk and Carpin, proposes a new approach to map merging, based on a grid representation of the map. The authors implemented and compared different algorithms, like multipoint hill climbing or simulated annealing, and applied them to the problem of map merging. In addition, they developed a new algorithm that generalizes and improves classical merging approaches. Their algorithm performs a random-walk based exploration in the space of possible merging parameters, i.e., rotations and translations, and its main novelty is adaptivity. This research is motivated by the goal to develop rescue robots, to be used both in the Robocup Rescue League and in real-world applications, where the robots must explore an unknown environment and find victims (or any other information interesting for a mission purpose).

Control and Adaptation

In this group of papers, we have included several papers covering various aspects concerned with how the multirobot system reacts and adapts to the environment. Robot control includes navigation and effective path planning in response to the environment. Adaptation in teams of robots can range over a wide spectrum of approaches, such as learning in a coevolutionary process, reasoning about the presence of humans in the team, and biologically inspired control and learning architectures.

The paper "Safe Multirobot Navigation within Dynamic Constraints," by Bruce and Veloso, introduces a refinement of the classical complete sense–plan–act loop for control of multiple robots. The work takes place within the context of highly dynamic environments with adversarial robots and the control goals include effective obstacle avoidance. Concrete navigation goals are achieved by a real-time randomized path planner, a bounded acceleration motion control system, and a randomized velocity-space search for collision avoidance of multiple moving robots. The randomized search approach for objective maximization and motion planning allows real-time or any-time performance. A cooperative safety algorithm respects robot dynamics limitations while preventing collisions with static or moving obstacles. The work has been validated in a very fast and dynamic robot soccer environment.

"Incremental Coevolution with Competitive and Cooperative Tasks in a Multirobot Environnment," by Uchibe and Asada, addresses coevolution as a method for simultaneously developing the control structures of multiple robots. The authors show how cooperative and competitive behaviors can emerge through coevolutionary processes. They look at various aspects of the process for coevolution, discussing a few strategies to improve the result of the evolutionary process. Their experiments show how robust behaviors can be obtained in a cooperative and competitive scenario, such as robot soccer.

The paper "Coordinated Multiagent Teams and Sliding Autonomy for Large-Scale Assembly," by Sellner *et al.*, focuses on the issue of adjustable autonomy in the context of control in multirobot systems. A human operator is included in the team and different cooperation strategies are considered, including full teleoperation, variable degrees of autonomy, and full autonomy. Moreover, the user interface is addressed in a context where the situation awareness by the human requires a simple check of the state of the robot and control of the behavior of the team. The paper argues in favor of approaches that are based on a mixed team with robots and a human operator.

The final paper, entitled "How AI and Multirobot Systems Research Will Accelerate Our Understanding of Social Animal Behavior" by Balch *et al.*, deals with bio-inspired robot control and adaptation. Nature has inspired a significant body of the past work on multirobot systems, and the authors look again to biology, and social animals in particular, to review the many ways robotics and biology have enabled one another. In particular, they argue that behavior-based models provide a concise language for expressing animal behavior, thus becoming an effective investigative tool for social animal research. Specifically, they present algorithms for tracking, recognizing, and learning models of social animal behavior, and experimental results on their application to the study of social insects. ■

ABOUT THE GUEST EDITORS

Manuela M. Veloso received the B.S. degree in electrical engineering and the M.Sc. degree in electrical and computer engineering from the Instituto Superior Técnico, Lisbon, Portugal, in 1980 and 1984, respectively, and the Ph.D. degree in computer science from Carnegie Mellon University, Pittsburgh, PA, in 1992.

She is Herbert A. Simon Professor of Computer Science at Carnegie Mellon University. She is the author of one book on planning by analogical reasoning and editor of several other books. She is also an author in over 100 journal articles and conference papers. She researches in the area of artificial intelligence with focus on planning, control learning, and execution for single and multirobot teams. Her algorithms address uncertain, dynamic, and adversarial environments. She has developed teams of robot soccer agents, which have successfully participated in several RoboCup competitions since 1997.

Prof. Veloso is a Fellow of the American Association of Artificial Intelligence. She is Vice President of the RoboCup International Federation. She was awarded an NSF Career Award in 1995 and the Allen Newell Medal for Excellence in Research in 1997. She was Program Cochair of 2005 National Conference on Artificial Intelligence and the Program Chair of the 2007 International Joint Conference on Artificial Intelligence.

Daniele Nardi received the Laurea degree in electronic engineering from Politecnico di Torino, Italy, in 1981 and the M.S. degree in computer and system engineering from Facoltà di Ingegneria, Università di Roma "La Sapienza," Italy, in 1984.

He is Professor of Computer Science at the Facoltà di Ingegneria, Università di Roma "La Sapienza." He is a member of Dipartimento di Informatica e Sistemistica, which he joined in 1986, becoming Professor in 2000. He is also chair of a research laboratory of intelligent systems for emergency and civil defense at Istituto Superiore Antincendi, of the Italian ministry of Internal Affairs. He was the coordinator of an Italian national effort which led to the design of a team that achieved the second place in the RoboCup midsize league. He is coeditor of several books and conference proceedings and author in about 100 journal articles, book chapters and conference papers. His current research interests are mainly in the field of artificial intelligence, in the area of knowledge representation and reasoning, and cognitive robotics.

Prof. Nardi received the IJCAI-91 Publisher's Prize for the paper "Tractable Concept Languages" and the Intelligenza Artificiale 1993 prize from the Italian Association for Artificial Intelligence (AIIA). He is a Trustee of the International RoboCup Federation.