Guest Editorial
Advances in Multirobot Systems

***Abstract*—As research progresses in distributed robotic systems, more and more aspects of multirobot systems are being explored. This Special Issue on Advances in Multirobot Systems provides a broad sampling of the research that is currently ongoing in the field of distributed mobile robot systems. To help categorize this research, we have identified seven primary research topics within multirobot systems: biological inspirations, communication, architectures, localization/mapping/exploration, object transport and manipulation, motion coordination, and reconfigurable robots. This editorial examines these research areas and discusses the Special Issue papers in this context. We conclude by identifying several additional open research issues in distributed mobile robotic systems.**

***Index Terms*—Cooperative robotics, distributed robotics, multirobot systems, survey.**

I. INTRODUCTION

THE FIELD of distributed robotics has its origins in the late 1980s, when several researchers began investigating issues in multiple mobile robot systems. Prior to this time, research had concentrated on either single robot systems or distributed problem-solving systems that did not involve robotic components. The topics of particular interest in this early distributed robotics work include the following.

- *Cellular (or reconfigurable) robot systems*, such as the work by Fukuda *et al.* [32] on the cellular robotic system (CEBOT), and the work on cyclic swarms by Beni [18].
- *Multirobot motion planning*, such as the work by Premvuti and Yuta [55] on traffic control, and the work on movement in formations by Arai *et al.* [2] and Wang [66].
- *Architectures for multirobot cooperation*, such as the work on ACTRESS by Asama *et al.* [12].

Since this early research in distributed mobile robotics, the field has grown dramatically, with a much wider variety of topics being addressed. Collections of research in this area include the edited volumes by Balch and Parker [15] and Schultz and Parker [59], as well as the series of proceedings from the Symposia on Distributed Autonomous Robotic Systems (DARS) [8]-[11], [40], [54]. Additionally, previous special journal issues have addressed the topic of multirobot systems; two of particular interest have been published by the journal *Autonomous Robots*—a special issue on robot colonies [4], and another on heterogeneous multirobot systems [14]. However, a significant amount of new research has been achieved since these previous special issues, and thus, this current Special Issue discusses many new developments in the field since these earlier publications.

Several new robotics application areas, such as underwater and space exploration, hazardous environments, service robotics in both public and private domains, the entertainment field, and so forth, can benefit from the use of multirobot systems. In these challenging application domains, multirobot systems can often deal with tasks that are difficult, if not impossible, to accomplish by an individual robot. A team of robots may provide redundancy and contribute cooperatively to solve the assigned task, or they may perform the assigned task in a more reliable, faster, or cheaper way beyond what is possible with single robots.

The field of cooperative autonomous mobile robotics is still new enough that no topic area within this domain can be considered mature. Some areas have been explored more extensively, however, and the community is beginning to understand how to develop and control certain aspects of multirobot teams. For example, the issue of balancing reactivity and social deliberation has been considered for both simulated and real multiagent systems in the collection of papers edited by Hannebauer *et al.* [33]. Rather than try to summarize the research papers in this Special Issue into a taxonomy of cooperative systems (see Dudek [29] and Cao [23] for previous related summaries), we instead organize this research by the principal topic areas that have generated significant levels of study, to the extent possible in a limited space. The seven principal topic areas of multirobot systems that we have identified are:

- biological inspirations;
- communication;
- architectures, task allocation, and control;
- localization, mapping, and exploration;
- object transport and manipulation;
- motion coordination;
- reconfigurable robots.

Many of the papers in this Special Issue address more than one of these foundational problems in multirobot systems. We, therefore, describe aspects of these papers as they apply to each of these key research areas. For context, we also discuss other key references and examples of prior research in each of these principal topic areas as we introduce this Special Issue. However, space does not allow an exhaustive treatment of each of these important research areas, and thus, we cannot thoroughly review all the previous literature pertinent to this subject. We conclude this editorial by suggesting additional research issues that have not yet been extensively studied, but appear to be of growing interest and need in distributed autonomous multirobot systems.

II. BIOLOGICAL INSPIRATIONS

Nearly all of the work in cooperative mobile robotics began after the introduction of the new robotics paradigm of behavior-based control [3], [20]. This behavior-based paradigm has had a strong influence on much of the cooperative mobile

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robotics research. Because the behavior-based paradigm for mobile robotics is rooted in biological inspirations, many cooperative robotics researchers have also found it instructive to examine the social characteristics of insects and animals, and to apply these findings to the design of multirobot systems.

The most common application of this knowledge is in the use of the simple local control rules of various biological societies, particularly ants, bees, and birds, to the development of similar behaviors in cooperative robot systems. Work in this vein has demonstrated the ability for multirobot teams to flock, disperse, aggregate, forage, and follow trails (e.g., [26], [28], and [44]). The application of the dynamics of ecosystems has also been applied to the development of multirobot teams that demonstrate emergent cooperation as a result of acting on selfish interests [46]. To some extent, cooperation in higher animals, such as wolf packs, has generated advances in cooperative control. Significant study in predator–prey systems has occurred, although primarily in simulation [17], [34]. An exception is the paper in this Special Issue, entitled “Multiagent Probabilistic Pursuit–Evasion Games with Unmanned Ground and Aerial Vehicles,” by Vidal *et al.*which implements a pursuit–evasion task on a physical team of aerial and ground vehicles. They evaluate various pursuit policies relating expected capture times to the speed and intelligence of the evaders and the sensing capabilities of the pursuers.

Competition in multirobot systems, such as that found in higher animals, including humans, is being studied in domains such as multirobot soccer. A previous special journal issue in *Artificial Intelligence* on RoboCup discusses many of the advances in this area; see [6] for a general overview of the field, and [5], [7], [49], [61], and [64] for some particular examples of this research. Another series of books appears yearly in the Lecture Notes in Artificial Intelligence series on the topic of multirobot soccer, beginning with [38]. Two papers in this Special Issue address multirobot control issues in the multirobot soccer domain. These papers are “Cooperative Probabilistic State Estimation for Vision-Based Autonomous Mobile Robots,” by Schmitt *et al.* and “CS Freiburg: Coordinating Robots for Successful Soccer Playing,” by Weigel *et al.*

Many areas of biological inspiration and their applicability to multirobot teams seem to be fairly well understood. More recently identified, less well understood, biological topics of relevance include the use of imitation in higher animals to learn new behaviors, and the physical interconnectivity demonstrated by insects, such as ants, to enable collective navigation over challenging terrains. One advance in this area is presented in the paper in this issue entitled “Hormone-Inspired Adaptive Communication and Distributed Control for CONRO Self-Reconfigurable Robots,” by Shen *et al.*This paper examines both the physical interconnectivity of modular robots, as well as biological inspirations for how to maintain communication and collaboration in a distributed multirobot network.

III. COMMUNICATION

The issue of communication in multirobot teams has been extensively studied since the inception of distributed robotics research. Distinctions between implicit and explicit communication are usually made, in which implicit communication occurs as a side effect of other actions, or “through the world” (see, for example, [51]), whereas explicit communication is a specific act designed solely to convey information to other robots on the team. Several researchers have studied the effect of communication on the performance of multirobot teams in a variety of tasks, and have concluded that communication provides certain benefits for particular types of tasks (e.g., [16], [43]). Additionally, these researchers have found that, in many cases, communication of even a small amount of information can lead to great benefits (e.g., [16]).

More recent work in multirobot communication has focused on representations of languages and the grounding of these representations in the physical world [35], [36]. Additionally, work has extended to achieving fault tolerance in multirobot communication, such as setting up and maintaining distributed communications networks [68] and ensuring reliability in multirobot communications [48]. An important related aspect of multirobot communication has been addressed in the paper by Shen *et al.* in this issue, entitled “Hormone-Inspired Adaptive Communication and Distributed Control for CONRO Self-Reconfigurable Robots,” which examines the use of adaptive communication in modular, reconfigurable robotics. The challenge in these systems is to maintain communication even when connections between robots may change dynamically and unexpectedly. This paper demonstrates one aspect of the recent progress that is being made in enabling multirobot teams to operate reliably, even amidst faulty communication environments.

Another paper in this Special Issue, entitled “Performance of a Distributed Robotic System using Shared Communications Channels,” by Rybski *et al.* explores communications issues of teams of miniature robots that must use very low-capacity radio frequency (RF) communications due to their small size. They approach this issue through the use of process scheduling to share the available communications resources.

IV. ARCHITECTURES, TASK ALLOCATION, AND CONTROL

A great deal of research in distributed robotics has focused on the development of architectures, task planning capabilities, and control. This research area addresses the issues of action selection, delegation of authority and control, the communication structure, heterogeneity versus homogeneity of robots, achieving coherence amidst local actions, resolution of conflicts, and other related issues. Each architecture that has been developed for multirobot teams tends to focus on providing a specific type of capability to the distributed robot team. Capabilities that have been of particular emphasis include task planning [1], fault tolerance [52], swarm control [], human design of mission plans [45], role assignment [22], [50], [62], and so forth.

The paper entitled “Performance of a Distributed Robotic System Using Shared Communications Channels,” by Rybski *et al.* presents a software architecture for the control of a set of miniature robots, called Scouts. The architecture for this system is constrained by the limited computational capabilities of the miniature robots, leading to a proxy-processing scheme enabling robots to use remote computers for their computing needs. They present a resource allocation system that dynamically assigns resources to each robot to maximize the utilization of resources, while also maintaining given behavior priorities. They present experimental results of their approach using their Scout robot team.

The architecture design challenge is also addressed in this Special Issue in the paper by Nakamura *et al.*entitled “Human-Supervised Multiple Mobile Robot System.” This paper presents a flexible command and monitoring structure that enables a human operator to work with a team of mobile robots. Four levels of control are defined, including the robot control level, the group level, the object control level, and the task control level. The effectiveness of their approach is illustrated in a transportation task using several mobile robots.

Another paper in this Special Issue, entitled “Emotion-Based Control of Cooperating Heterogeneous Mobile Robots,” by Murphy *et al.* presents a hybrid deliberative/reactive architecture that uses a computational model of emotions to modify active behaviors at the sensory-motor level and change the set of active behaviors at the schematic level. The emotion-based control enables the team to demonstrate the desired societal behavior without any centralized planning and with minimal communication. They illustrate their results on physical robots operating in public venues.

The task allocation issue is also addressed in the paper entitled “Sold!: Market Methods for Multirobot Control,” by Gerkey and Mataric. This paper presents an approach for dynamic task allocation using a resource-centric negotiation strategy to produce a distributed approximation to a global optimum of resource usage. They present validations of their approach in physical robot experiments in object pushing and in loosely-coupled task selection.

The paper by Miyata *et al.* entitled “Cooperative Transport by Multiple Mobile Robots in Unknown Static Environments Associated with Real-Time Task Assignment,” addresses the development of a task assignment architecture for multiple mobile robots. The architecture deals with multiple tasks that must be accomplished in real time, in applications that consist of a large number of tasks relative to the number of available robots. They present an approach that involves two real-time planners: a priority-based task-assignment planner and a motion planner. They illustrate their approach in a cooperative transport task in simulation.

Vidal *et al.* address multiagent control architectures for teams of ground and aerial vehicles in their paper entitled “Multiagent Probabilistic Pursuit–Evasion Games with Unmanned Ground and Aerial Vehicles.” The goal of their research is the integration of multiple autonomous heterogeneous robots into a coordinated system that is modular, scalable, fault tolerant, adaptive, and efficient. They present a hybrid hierarchical system architecture that segments the control of each agent into different layers of abstraction. These layers of abstraction allow interoperability in heterogeneous robot teams. They illustrate the effectiveness of this approach in a pursuit–evasion application.

The architecture, task allocation, and control issue is addressed by the paper entitled “CS Freiburg: Coordinating Robots for Successful Soccer Playing,” by Weigel *et al.* This paper presents a multiagent coordination architecture to enable robot teams to play RoboCup soccer. They use role assignments and an action-selection module based on extended behavior networks to enable robots to cooperate in this domain. They present results of their approach from their RoboCup soccer experiences.

V. LOCALIZATION, MAPPING, AND EXPLORATION

An extensive amount of research has been carried out in the area of localization, mapping, and exploration for single autonomous robots. Only fairly recently has much of this work been applied to multirobot teams. Almost all of the work has been aimed at two-dimensional (2-D) environments. Initially, most of this research took an existing algorithm developed for single robot mapping, localization, or exploration, and extended it to multiple robots. More recently, researchers have developed new algorithms that are fundamentally distributed. One example of this work is given in [31], which takes advantage of multiple robots to improve positioning accuracy beyond what is possible with single robots. Another example is a paper in this Special Issue entitled “Distributed Multirobot Localization,” by Roumeliotis and Bekey. This paper presents a decentralized Kalman filter-based approach to enable a group of mobile robots to simultaneously localize by sensing their teammates, and combining positioning information from all the team members. They illustrate the effectiveness of their approach through application on a team of three physical robots.

An additional paper in this Special Issue examines vision-based localization in multirobot teams. This paper, entitled “Cooperative Probabilistic State Estimation for Vision-Based Autonomous Mobile Robots,” by Schmitt *et al.* develops and analyzes a probabilistic, vision-based state estimation method that enables robot team members to estimate their joint positions in a known environment. Their approach also enables robot team members to track positions of autonomously moving objects. They illustrate their approach on physical robots in the multirobot soccer domain.

As is the case with single-robot approaches to localization, mapping, and exploration, research into the multirobot version can be described using the familiar categories based on the use of landmarks [25], scan matching [21], and/or graphs [56], and which use either range sensors (such as sonar or laser) or vision sensors. The paper entitled “LOST: Localization-Space Trails for Robot Teams,” by Vaughan *et al.* presents an algorithm enabling a robot team to navigate between places of interest in an initially unknown environment by using a trail of waypoint landmarks. They illustrate that their approach copes with accumulating odometry error, is robust to the failure of individual robots, and converges to the best route discovered by any robot on the team.

VI. OBJECT TRANSPORT AND MANIPULATION

Enabling multiple robots to cooperatively carry, push, or manipulate common objects has been a long standing, yet difficult, goal of multirobot systems. Many research projects have dealt with this topic area; fewer of these projects have been demonstrated on physical robot systems. This research area has a number of practical applications that make it of particular interest for study.

Numerous variations on this task area have been studied, including constrained and unconstrained motions, two-robot teams versus "swarm"-type teams, compliant versus noncompliant grasping mechanisms, cluttered versus uncluttered environments, global system models versus distributed models, and so forth. Perhaps the most demonstrated task involving cooperative transport is the pushing of objects by multirobot teams [57], [60]. This task seems inherently easier than the carry task, in which multiple robots must grip common objects and navigate to a destination in a coordinated fashion [37], [67]. A novel form of multirobot transportation that has been demonstrated is the use of ropes wrapped around objects to move them along desired trajectories [27].

A paper in this Special Issue, entitled "Cooperative Transport by Multiple Mobile Robots in Unknown Static Environments Associated with Real-Time Task Assignment," by Miyata *et al.* explores the cooperative transport task by multiple mobile robots in an unknown static environment. Their approach enables robot team members to displace objects that are interfering with the transport task, and to cooperatively push objects to a destination. They illustrate their results both in simulation and using a team of two physical robots.

The paper by Das *et al.* entitled "A Framework for Vision-Based Formation Control," presents a novel approach for cooperative manipulation that is based on formation control. Their approach enables robot teams to cooperatively manipulate obstacles by trapping them inside the multirobot formation. They demonstrate their results on a team of three physical robots.

VII. MOTION COORDINATION

Another popular topic of study in multirobot teams is that of motion coordination. Research themes in this domain that have been particularly well studied include multirobot path planning [30], [41], [63], [69], traffic control [55], formation generation [2], and formation keeping [13], [66]. Most of these issues are now fairly well understood, although demonstration of these techniques in physical multirobot teams (rather than in simulation) has been limited. More recent issues studied within the motion coordination context are target tracking [53], target search [39], and multirobot docking [47] behaviors. The motion coordination problem in the form of path planning for multiple robots is addressed in this Special Issue by Saptharishi *et al.* in the paper entitled "Distributed Surveillance and Reconnaissance Using Multiple Autonomous ATVs: CyberScout." In this paper, an approach is presented that performs path planning via checkpoint and dynamic priority assignment using statistical estimates of the environment's motion structure. Additionally, they explore the issue of vision-based surveillance to track multiple moving objects in a cluttered scene. The results of their approaches are illustrated using a variety of experiments.

With the increased interest in reconfigurable robotics, another important issue in motion coordination is the generation of cooperative gaits using modular robot systems. The paper in this issue by Shen *et al.*entitled "Hormone-Inspired Adaptive Communication and Distributed Control for CONRO Self-Reconfigurable Robots," addresses some issues in motion coordination for reconfigurable robots, illustrating the achievement of gaits that include the caterpillar move, a legged walk, and a rolling track.

Formation control has been a popular topic of multirobot systems for many years. The paper by Fredslund and Mataric in this Special Issue, entitled "A General Algorithm for Robot Formation Using Local Sensing and Minimal Communication," addresses the problem of achieving formation controls using only local sensing and interaction. Their key idea is to have each robot maintain another specific robot, called a *friend*, within its field of view, at a desired viewing angle. They illustrate the ability of this approach to produce a variety of formations, including diamond, triangle, arrowhead, wedge, and hexagon. Their results are illustrated through experiments on physical and simulated robot teams.

An advancement in the analysis of motion coordination in multirobot teams is the development of provable theorems that characterize the cooperative performance of team formations under certain conditions. The paper by Das *et al.* entitled "A Framework for Vision-Based Formation Control," examines motion control by developing a novel framework for controlling and coordinating a group of nonholonomic mobile robots. Their approach allows robot teams to accomplish diverse tasks such as scouting and reconnaissance, and distributed manipulation using vision-based formation control. They show how their approach guarantees stability and convergence in a wide range of tasks, and illustrate their results on a platform of three nonholonomic robots. An additional paper in this Special Issue by Ogren *et al.* entitled "A Control Lyapunov Function Approach to Multiagent Coordination," addresses the class of multirobot teams for which control Lyapunov functions can be found. Their results yield an abstract and theoretically sound coordination strategy for formation control in multirobot teams. Another paper in this Special Issue, entitled "Decentralized Control of Cooperative Robotic Vehicles: Theory and Application," by Feddema *et al.* describes how decentralized control theory can be used to analyze the motion coordination performance of multiple mobile robots. They illustrate the results of their theory through several examples of distribution motion coordination on physical robots performing applications such as perimeter security.

VIII. RECONFIGURABLE ROBOTICS

Even though some of the earliest research in distributed robotics focused on concepts for reconfigurable distributed systems [18], [32], relatively little work has proceeded in this area until the last few years. More recent work has resulted in a number of actual physical robot systems that are able to reconfigure. The motivation of this work is to achieve function from shape, allowing individual modules, or robots, to connect and reconnect in various ways to generate a desired shape to serve a needed function. These systems have the theoretical capability of showing great robustness, versatility, and even self-repair.

Most of the work in this area involves identical modules with interconnection mechanisms that allow either manual or automatic reconfiguration. These systems have been demonstrated to form into various navigation configurations, including a rolling track motion [70], an earthworm or snake motion [24], [70], and a spider or hexapod motion [24], [70]. Some systems employ a cube-type arrangement, with modules able to connect in various ways to form matrices or lattices for specific functions [19], [58], [65], [71]. An important example of this research is the paper in this Special Issue by Shen *et al.* entitled "Hormone-Inspired Adaptive Communication and Distributed Control for CONRO Self-Reconfigurable Robots." This paper presents a biologically inspired approach for adaptive communication in self-reconfigurable and dynamic networks, as well as physical module reconfiguration for accomplishing global effects such as locomotion. They demonstrate their results in the context of the CONRO modules that they have developed.

Research in this area is still very young, and most of the systems developed are not yet able to perform beyond laboratory experiments. While the potential of large numbers of robot modules has been demonstrated in simulation, it is still uncommon to have implementations involving more than a dozen or so physical modules. The practical application of these systems is yet to be demonstrated, although progress is being made in that direction. Clearly, this is a rich area for continuing advances in multirobot systems.

IX. Additional Open Issues in Distributed Autonomous Mobile Robotics

It is clear that since the inception of the field of distributed autonomous mobile robotics less than two decades ago, significant progress has been made on a number of important issues. The field has a good understanding of the biological parallels that can be drawn, the use of communication in multirobot teams, and the design of architectures for multirobot control. Considerable progress has been made in multirobot localization/mapping/exploration, cooperative object transport, and motion coordination. Recent progress is beginning to advance the areas of reconfigurable robotics and multirobot learning. Of course, all of these areas have not yet been fully studied. Several other research challenges still remain, including the following.

- How do we identify and quantify the fundamental advantages and characteristics of multirobot systems?
- How do we easily enable humans to control multirobot teams?
- Can we scale up to demonstrations involving more than a dozen or so robots?
- Is passive action recognition in multirobot teams possible?
- How can we enable physical multirobot systems to work under hard real-time constraints?
- How does the complexity of the task and of the environment affect the design of multirobot systems?

These and other issues in multirobot cooperation should keep the research community busy for many years to come.

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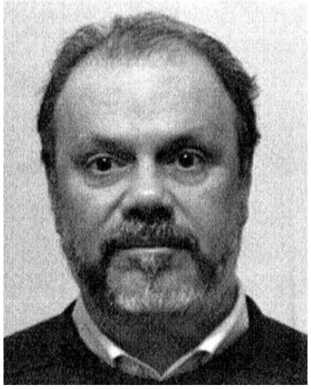

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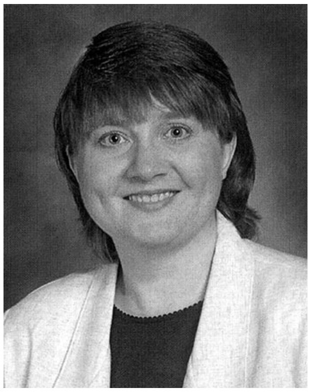

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