**PLENARY TALK**

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# Current research in multirobot systems

**Abstract** As research progresses in distributed robotic systems, more and more aspects of multirobot systems are being explored. This article describes advances in multirobot systems, and surveys the current state of the art. The focus is principally on research that has been demonstrated in physical robot implementations. I have identified eight primary research topics within multirobot systems – biological inspirations, communication, architectures, localization/mapping/exploration, object transport and manipulation, motion coordination, reconfigurable robots, and learning – and discuss the current state of research in these areas. As I describe each research area, I identify some key open issues in multirobot team research, and conclude by identifying several additional open research issues in distributed mobile robotic systems.

**Key words** Multirobot systems · Survey · Distributed robotics

## 1 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 those listed below.

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- *Cellular (or reconfigurable) robot systems*, such as the work by Fukuda and Nakagawa[1] on the cellular robotic system (CEBOT), and the work on cyclic swarms by Beni.[2]
- *Multirobot motion planning*, such as the work by Premvuti and Yuta[3] on traffic control, and the work on movement in formations by Arai et al.[4] and Wang.[5]
- *Architectures for multirobot cooperation*, such as the work on ACTRESS by Asama et al.[6]

Since this early research in distributed mobile robotics, the field has grown dramatically, with a much wider variety of topics being addressed. This article examines the current state of the art in autonomous multiple mobile robotic systems. The field of cooperative autonomous mobile robotics is still so new that no topic area within this domain can be considered to be 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. Thus, rather than summarize the research into a taxonomy of cooperative systems (see Dudek et al.[7] and Cao et al.[8] for previous related summaries), I organize this study by the principal topic areas that have generated significant levels of research, to the extent possible in a limited space. As I present the review, I identify key open research issues within each topic area. I conclude 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.

## 2 Biological inspirations

Nearly all the work in cooperative mobile robotics began after the introduction of the new robotics paradigm of behavior-based control.[9,10] This behavior-based paradigm has had a strong influence in much cooperative mobile robotics research. Because the behavior-based paradigm for mobile robotics is rooted in biological inspirations, many cooperative robotics researchers have also found it instruc-

tive 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 – in the development of similar behaviors in cooperative robot systems. Work in this vein has demonstrated the ability of multirobot teams to flock, disperse, aggregate, forage, and follow trails (e.g., Mataric,[11] Deneubourg et al.,[12] and Drogoul and Ferber[13]). 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.[14] To some extent, cooperation in higher animals, such as wolf packs, has generated advances in cooperative control. Significant study into predator–prey systems has occurred, although primarily in simulations.[15,16] Competition in multirobot systems, such as that found in higher animals, including humans, is beginning to be studied in domains such as multirobot soccer.[17,18]

These areas of biological inspiration and their applicability to multirobot teams seem to be fairly well understood. More recently identified, and 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 allow collective navigation over challenging terrains.

## 3 Communication

The issue of communication in multirobot teams has been studied extensively 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," 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 task.[19,20] These researchers have also found that in many cases, communication of even a small amount of information can lead to great benefit.[20]

More recent work in multirobot communication has focused on representations of languages and the grounding of these representations in the physical world.[21,22] This work has also extended to achieving fault-tolerance in multirobot communication, such as setting up and maintaining distributed communications networks[23] and ensuring reliability in multirobot communications.[24] While progress is being made in these more recent issues of communication, much work remains to be done in order to enable multirobot teams to operate reliably in faulty communication environments.

## 4 Architectures, task planning, 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, the delegation of authority and control, the communication structure, heterogeneity versus homogeneity in robots, achieving coherence in local actions, the 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 received particular attention include task planning,[25] fault tolerance,[26] swarm control,[27] the human design of mission plans,[28] and so forth.

A general research question in this vein is whether specialized architectures for each type of robot team and/or application domain are needed, or whether a more general architecture can be developed that can easily be tailored to fit a wider range of multirobot systems. Relatively little previous work has been aimed at unifying these architectures. Perhaps an all-encompassing architecture would be too unwieldy to implement in practical applications. It remains to be seen if a single general architecture for multirobot teams can be developed that is applicable to a much wider variety of domains than is currently possible with existing architectures.

## 5 Localization, mapping, and exploration

An extensive amount of research has been carried out in the areas of localization, mapping, and exploration for single autonomous robots, but only fairly recently has this been applied to multirobot teams. In addition, nearly all of this research has taken an existing algorithm developed for single-robot mapping, localization, or exploration, and extended it to multiple robots, as opposed to developing a new algorithm that is fundamentally distributed. One exception is some of the work in multirobot localization, which takes advantage of multiple robots to improve positioning accuracy beyond what is possible with single robots.[29,30]

As is the case with single-robot approaches to localization, mapping, and exploration, research into the multirobot version can be described using familiar categories based on the use of landmarks,[31] scan-matching,[32] and/or graphs,[33] and using either range sensors (such as sonar or laser) or vision sensors. While the single-robot version of this problem is fairly well understood, much work remains to be done on the multirobot version. For example, one question is about the effectiveness of multirobot teams over single-robot versions, and to what extent adding additional robots brings diminishing returns. This issue has begun to be studied, but much remains to be determined for the variety of approaches available for localization, mapping, and exploration.

## 10 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, none of these areas have yet been fully studied; we have identified key open research challenges for the areas described in the previous sections.

Several other research challenges still remain, including those listed below.

- How do we identify and quantify the fundamental advantages and characteristics of multirobot systems?
- How do we enable humans to control multirobot teams easily?
- Can we scale-up to demonstrations involving more than about 12 robots?
- Is passive action recognition possible in multirobot teams?
- 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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