PLENARY TALK

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Current research in multirobot systems

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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.

- Cellular (or reconfigurable) robot systems, such as the work by Fukuda and Nakagawa¹ 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 Yuta³ 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. 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-

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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 Ferber¹³). 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 networks²³ 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, fault tolerance, swarm control, the human design of mission plans, 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.

6 Object transport and manipulation

Enabling multiple robots to carry, push, or manipulate common objects cooperatively has been a long-standing, yet difficult, goal of multirobot systems. Many research projects have dealt with this topic area; few 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 non-compliant 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. This task seems inherently easier than the carry task, in which multiple robots must grip common objects and then navigate to a destination in a coordinated fashion. A novel form of multirobot transportation that has been demonstrated is the use of ropes wrapped around objects to move them along the desired trajectories.

Nearly all of the previous work in this area work involves robots moving across a flat surface. A challenging open issue is cooperative transport over uneven outdoor terrains.

7 Motion coordination

A 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,³⁹ traffic control,³ formation generation,⁴ and formation keeping.^{5,40} Most of these issues are now fairly well understood, although demonstrations of these techniques in physical multirobot teams (rather than in simulation) have been limited. More recent issues studied within the motion coordination context are target tracking,⁴¹ target search,⁴² and multirobot docking⁴³ behaviors.

Nearly all the previous work has been aimed at 2D domains, although some has been directed at 3D environments.³⁹ One of the most limiting characteristics of much of the existing path-planning work is the computational complexity of the approaches. Perhaps as computing processor speeds increase, the computational time will take care of itself. In the meantime, this characteristic is a limiting factor to the applicability of much of the path-planning research in dynamic, real-time robot teams.

8 Reconfigurable robotics

Even though some of the earliest research in distributed robotics focused on concepts for reconfigurable distributed systems, 1,2 relatively little further work had been done 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 for 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 shown to form into various navigation configurations, including a rolling track motion, 44 an earthworm or snake motion, 44,45 and a spider or hexapod motion. 44,45 Some systems employ a cube-type arrangement, with modules which are able to connect in various ways to form matrices or lattices for specific functions. 46-49

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

9 Learning

Many multirobot researchers believe that an approach with more potential for the development of cooperative control mechanisms is autonomous learning. While a considerable amount of work has been done in this area for multiagent learning, 50 somewhat less work has been accomplished to date in multirobot learning. The types of application that are typically studied for this area of multirobot learning vary considerably in their characteristics. Some of the applications include predator/prey, 15,16 box-pushing, 51 foraging, 27 multirobot soccer, 17,18,52 and cooperative target observation. 41

Particularly challenging domains for multirobot learning are those tasks that are *inherently* cooperative, i.e., tasks in which the utility of the action of one robot is dependent upon the current actions of the other team members. Inherently cooperative tasks cannot be decomposed into independent subtasks to be solved by a distributed robot team. Instead, the success of the team throughout its execution is measured by the combined actions of the robot team, rather than by individual robot actions. This type of task is a particular challenge in multirobot learning owing to the difficulty of assigning credit for the individual actions of the robot team members. Multirobot learning in general, and inherently cooperative task-learning in particular, are areas in which significant research into multirobot systems remains to be done.

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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