

in *Multi-Robot Systems: From Swarms to Intelligent Automata*,  
Volume II, A. Schultz, L. E. Parker, and F. Schneider (eds),  
Kluwer 2003: 205-215.

## THE EFFECT OF HETEROGENEITY IN TEAMS OF 100+ MOBILE ROBOTS

Lynne E. Parker  
*Department of Computer Science*  
*The University of Tennessee*  
*Knoxville, Tennessee USA*  
parker@cs.utk.edu

**Abstract** In mid-2002, a new project was begun as part of DARPA/IPTO's Software for Distributed Robotics (SDR) Program, aimed at the practical implementation of a team of 100+ heterogeneous mobile robots in an indoor surveillance and reconnaissance task. The overall project involves the collaboration of Science Applications International Corporation (the lead organization), the University of Tennessee, the University of Southern California, and Telcordia Technologies, Inc. This paper focuses on one aspect of this project – the impact of heterogeneity in the development of scalable cooperative control approaches enabling large numbers of robots to collaborate. The robots on this team are heterogeneous by design, particularly in their sensing capabilities, with the result that no single type of robot on this team would be able to accomplish the entire mission, even if that robot type were duplicated 100 times. This approach enables expensive sensors to be distributed across a few of the robots, rather than requiring all robots to share a similar sensor suite. The result is the expected ability to accomplish the task with a high degree of flexibility and fault tolerance, but with a more extensive requirement for heterogeneous cooperation. This paper, which describes a work in progress, discusses the impact of heterogeneity in developing cooperative sensing and control capabilities for teams of 100+ robots.

**Keywords:** Heterogeneous robots, Multi-Robot Teams, Distributed Sensing, Distributed Control

### 1. Introduction

The fundamental motivations of research in multi-robot systems are: 1) the ability to solve problems that are inherently distributed in space, time, or functionality, 2) the ability to solve problems faster through

the use of parallelism, and 3) the ability to increase solution robustness through the use of redundancy. In a significant proportion of multi-robot systems research, the benefits of parallelism, redundancy, and solutions distributed in space and time are obtained through the use of homogeneous robots, which are completely interchangeable. While a growing body of research is addressing the issues of heterogeneous robots (see, for example, Balch and Parker, 2002), this research typically involves a relatively small number of robots – perhaps on the order of a dozen or fewer robots. Even research in homogeneous robotics is rarely demonstrated on teams of more than ten to twenty robots<sup>1</sup>.

It is understandable why large robot team research typically focuses on homogeneous robots, since the interchangeability of robots dramatically simplifies the cooperative control problem. A natural correlation to the collective interactions of swarm insect societies also facilitates the use of interesting metaphors for multi-robot team control in homogeneous robot teams. However, future complex applications of large-scale robot teams may require the simultaneous use of multiple sensors, all of which cannot be designed into a single type of robot. Robots may need to be scaled to smaller sizes, which will limit their payload, or certain required sensors may be too expensive to duplicate across all 100+ robots on the team. This leads to the need to enable large numbers of heterogeneous robots to work together collaboratively to solve applications of interest.

Our research addresses this challenging problem by developing distributed sensing and control techniques that enable large numbers of heterogeneous robots to share capabilities to solve challenging problems. The overall project with which we are involved involves the close collaboration of researchers from Science Applications International Corporation (SAIC – the lead organization), the University of Tennessee, the University of Southern California, and Telcordia Technologies, Inc. Each organization is making key contributions in the areas of distributed mapping and localization, adjustable autonomy, heterogeneous robot cooperation, operator command and control, and ad hoc mobile networking. This paper discusses one aspect of this overall project – namely, the impact of heterogeneity in bringing about the practical cooperation of a heterogeneous team of 100+ physical robots. Section 2 describes the application that our heterogeneous team of robots must perform, along with the robots to be used in this research. Section 3 briefly describes the overall project, putting the heterogeneous control issues into context of the overall project. Section 4 describes the aspects of heterogeneity that are being studied and addressed in this project, using a specific example of heterogeneous robot sensor net deployment to illustrate the challenges involved. Section 5 provides a brief summary.

## 2. Application

The proof-of-principle application to which our heterogeneous robot team will be applied is an indoor surveillance and reconnaissance task defined by DARPA and the overall project team. This task requires a team of robots to autonomously map out a single floor of a previously unknown building, to search for targets or *items of interest*, and then to “protect” the items of interest by maintaining a mobile sensor net nearby. If “intruders” are detected near the items of interest, then the sensor net should monitor the locations of the intruders. Human operator(s) will monitor the robot team’s progress from an Operator Control Unit at the base station, which will be located near an entrance to the building. The building is large enough that the robot team must ensure that the communications network is maintained between the robot team members and the human operator(s). The robot team must continue this surveillance and reconnaissance task over a 24-hour period, maintaining their battery supplies at levels appropriate to continue the task, recharging as necessary. The robots can return to the base station periodically for fresh batteries or recharging. While the human operator(s) will be provided with the ability to command and control individual robots, the intent is for the robot team to autonomously make decisions as needed to ensure that the task is successfully completed.

The robot team that will be used for this application consists of robots pooled from SAIC, the University of Southern California, and the University of Tennessee (in cooperation with Oak Ridge National Laboratory). These robots include about 75 Amigobots (potentially with multiple sensor configurations), about 18 Pioneers (with multiple sensor configurations), about 4 ATRV-minis (with multiple sensor configurations), and about 4 Nomad-200 robots. The Amigobots are configured with a mobile wireless ad hoc communications card, an iPAQ computer with a microphone, and wheel encoders. At the time of this writing, evaluation is underway to determine the cost/benefit analysis of equipping some of the Amigobots with a CMUCam Vision Sensor (camera) mounted in a fixed position. The Pioneers are equipped with multiple sensor configurations, including different subsets of the following sensors: sonar, encoders, Sony pan/tilt/zoom (PTZ) color cameras, and SICK laser range scanners. The ATRV-minis are equipped with different subsets of the following sensors: sonar, SICK laser scanner, absolute orientation sensors, wheel encoders and PTZ color camera. The Nomads are equipped with different subsets of the following sensors: sonar, electronic compass, infrared, bump sensors, wheel encoders, camera, and single line laser range finder.

To simplify the inter-robot communications needs, all robots on the team will be equipped and/or retrofitted with a wireless mobile ad hoc networking communications capability provided by Telcordia Technologies, Inc. This networking technology will provide strength-of-signal information to the robots, as well as the protocols necessary to enable any subset of robots to continue communications even if separated from the operator base station.

Player/Stage (Gerkey et al., 2001; Vaughan, 2000) is being used as a simulator and networked robot server for development in this project. Player provides an interface to a set of device drivers for real robots and sensors, while Stage simulates a population of devices and makes them available through Player. This environment allows rapid prototyping of controllers for the different robots in our system.

Clearly, this team of robots was not designed specifically with our indoor surveillance and reconnaissance task in mind. Optimizing the appropriate multi-robot team for a given application is a separate exercise, and may not always be possible due to robot cost and availability considerations. Instead, this team of robots provides excellent opportunities to explore issues of heterogeneous multi-robot cooperation at a scale that have not previously been addressed. This team of robots also offers opportunities to integrate a wide variety of technologies into a single multi-robot system. Finally, this project offers the opportunity to create a testbed for testing a variety of strategies and approaches to heterogeneous multi-robot cooperation. With this final opportunity in mind, our ultimate goal in this project is not to create a single-point solution for the surveillance and reconnaissance task. Rather, we aim to create an infrastructure that enables extensive exploration of the challenging issue of large scale heterogeneous multi-robot cooperation.

### **3. Overall Project**

As has been previously described, the overall multi-robot team surveillance and reconnaissance project involves the collaboration of a number of key participants. The Operator Control Unit is being developed by SAIC and is made up of the ONESaF Testbed for operator command, control, and monitoring of the robot team during the application. Novel techniques for distributed localization and mapping are being developed by the University of Southern California based on the ideas in Howard et al., 2002. The University of Southern California is also providing technologies for adjustable autonomy (based on Tambe, 1997 and subsequent research), which can vary the amount of user interaction required during the application. Telcordia Technologies is providing the technology to

enable a scalable persistent on-the-move communications network to be created by dynamically allocating ad hoc collaborative network domains. This network auto-configuration combined with dynamic border routers will allow for highly mobile and survivable communications.

Our general strategy for demonstrating the surveillance and reconnaissance task is to have robots fulfill different roles depending upon their sensing and software capabilities. The robot roles defined for this task include LocalizerMapper, CommsSensorNet, CommsHelper, Interceptor, and DynamicTracker. The LocalizerMapper robots will first enter the building and cooperatively build a map of the environment. As they map, they will also detect the items of interest and mark their locations on the map. This map will then be used by the CommsHelper robots to deploy the CommsSensorNet robots throughout the environment, based upon preferred positioning to maintain a communications network and to set up a sensor network for detecting Intruders. The CommsSensorNet robots need this assistance from the CommsHelper robots because they are unable to localize on their own, and do not even have sensors for obstacle avoidance. Thus, our approach is to employ a “shepherding” group behavior, where the smarter CommsHelper robots autonomously teleoperate the CommsSensorNet robots into position as the group moves through the building. Multiple groups of CommsHelper robots and CommsSensorNet robots will be used to deploy the entire set of CommsSensorNet robots. Once the CommsSensorNet robots are deployed, they will use distributed acoustic sensing (plus perhaps video color tracking) to detect, roughly localize, and report the position of intruders moving near the items of interest. The Interceptor robot(s) will then move to intercept the intruder(s), converting to the DynamicTracker role to keep the intruder under observation and to report its position to the human operator. During the 24-hour application, the CommsHelper robots will again assist the CommsSensorNet robots as needed to help them make their way back to the base station for battery recharging when needed. Figure 1 shows the functional interaction of the robot behavior software modules to accomplish parts of this task.

The roles that can be fulfilled by a particular type of robot depend upon that robot’s sensing, effector, and software capabilities. Some robots will be able to fulfill more than one role, while other robots will only be able to contribute to a single role. The selection of robot roles will occur dynamically, depending upon the current state of the mission and the robot team.

While clearly this application would be easier to solve from a programming perspective if all the robot team members were homogeneous, well-equipped, and able to perform all tasks in the application (or at least



disjoint subsets of tasks required by the application), this project offers interesting opportunities to explore issues of heterogeneity in robot teams that will be relevant for a broad range of applications.

From a more general perspective, our goal is to develop a strategy that will enable robots to autonomously configure themselves into teams and sub-teams depending upon the current goals of the mission and the available robots and their resources. When dealing with heterogeneous robot teams with different sensing capabilities, developing this general reconfiguration capability is non-trivial. The following section discusses the issues of heterogeneity that we are addressing in this project.

#### 4. Heterogeneity in Multi-Robot Teams

Robot heterogeneity can be defined in terms of variety in physical capabilities or differences in behavioral performance. Some types of heterogeneity can be evaluated quantitatively, using metrics such as the social entropy metric described in Balch, 2000. Clearly, the required behavioral performance in a given application dictates certain constraints on the physical design of the robot team members. However, it is also clear that multiple choices may be made in designing a solution to a given application, based upon cost, robot availability, ease of software design, flexibility in robot use, and so forth. Designing an optimal robot team for a given application prior to deployment requires a significant amount of analysis and consideration of the tradeoffs in alternative strategies (see, for example, Parker, 1998 for a discussion of some of these issues). The idea of the optimal team design is to engineer the best robots for a particular application in advance, and then apply those robots to the application with a certain solution strategy in mind.

However, our research is not aimed at this *a priori*, pre-deployment design issue. Instead, we want to develop general techniques that enable any collection of heterogeneous robots to reorganize into subteams as needed depending upon the requirements of the application tasks and on the available robots and their resources. The assumption is that there is a sufficient mixture of robot capabilities available to solve the problem, although no attempt has been made to ensure that an “optimal” team is available. An additional assumption is that with a large team of heterogeneous robots, different combinations of robots will be able to solve certain tasks in different ways. The desired objective is to achieve a high degree of flexibility and fault tolerance in the team solution through the ability of the robots to autonomously reconfigure into subteams.

How might this autonomous subteaming occur? In a typical approach to heterogeneous robot team tasking, the application would be subdivi-

vided into subtasks, and team members would compete in some way (e.g., through motivations or through bidding) for performance of each subtask. The “winning” robots then proceed to execute their assigned subtasks. However, by having different possible solutions depending upon the particular subteam of robots working together, the typical sub-tasking approach is no longer feasible, since the required subtasks will vary depending upon the particular subteam of robots that “wins” the allocation. The task subdivision will vary because different robots are providing different sensing and cooperative control strategies to the team. The challenge, therefore, is providing the robots with a general strategy for self-organization based upon the current robot capabilities and the current application goal(s).

#### 4.1 Heterogeneity in Sensor Net Deployment

To further illustrate and motivate this objective, let us explore a specific example that arises in the surveillance and reconnaissance project we are addressing. One task within this application is the deployment of a sensor net within a single floor of a building. This task requires a large number of robots to be positioned within the building in order to “protect” the items of interest in the building by monitoring for intruders. The general information and capabilities needed to accomplish this task are the following:

- Knowledge of the map of the environment
- Knowledge of the location of the items of interest
- Ability to plan deployment positions
- Ability to select a robot’s specific deployment position
- Ability to locomote in the environment
- Ability to localize to the map
- Sensor capabilities for intruder detection
- Communications capabilities to report detected intruder(s)
- Software control for coordinating actions

Let us consider several different situations, which are outlined in Table 1. A single robot that possesses all the required knowledge and capabilities would be able to participate in the deployment task by coordinating the selected deployment positions with other robot team members. If a

Robot Team Composition	Cooperative Control Approach for Sensor Net Deployment
Homogeneous smart robots	Coordination of deployment positions
Mothership and daughter robots	Marsupial delivery into deployment positions
A few smart robots plus many “seeing” robots	“Follow the leader” shepherding
A few smart robots plus many “blind” robots	Autonomous teleoperated shepherding

*Table 1.* Example illustrating the effect of differing heterogeneity on required cooperative tasks in a single mission – the deployment of a robotic sensor net. The subtasks that must be accomplished differ depending upon the knowledge and capabilities of the specific team of robots being used.

relatively large number of such robots were available, then the deployment task is fairly straight-forward. However, what if no single type of robot on the team possesses all the required capabilities, or there are insufficient numbers of such robots to achieve the deployed sensor net? Does this mean that the deployment of the sensor net cannot be achieved? Certainly not, but it requires closer collaboration and cooperation among robots.

Consider the case when the sensor robots are very small and simple, with minimal ability to locomote or localize in the environment. A few larger, smarter robots with the ability to carry the simple sensor robots would be able to accomplish the task by moving the sensor robots to their deployment positions and dropping them off. This is the typical marsupial or “mothership and daughters” approach to collaboration, where the locomotion and localization capability is supplied by the mothership for the daughter robots.

Now consider the case where a few “smarter” robots possess knowledge of the map of the environment, knowledge of the items of interest, and the ability to plan deployment positions. However, in this case, not enough smarter robots exist to completely cover the required sensing area. Now assume that there are also a large number of simpler types of “seeing” robots that possess sensory capabilities for intruder detection and for tracking other robots, but no ability to localize to the map. In this case, the smarter robots can help by providing indirect localization information through the use of “follow-the-leader” techniques to lead the simpler seeing robots to the sensor net deployment positions. The important point to recognize is that “follow-the-leader” capabilities were not fundamental to the original sensor net deployment task. This

new capability became necessary to enable the smarter robots to provide relative localization abilities to the simpler robots.

In the case where the simpler robots are effectively “blind”, and unable to track other robots, the smarter robots could use autonomous teleoperation to teleoperate the blind robots into position. In this case, the smarter robots would also need the ability to sense the position of the blind robots and to send them commands to move them into the correct positions. (Once deployed, the simple blind robots could use techniques such as distributed acoustic sensing to track intruders through the environment and summon more capable Interceptor robots to move to the location of the intruders when they are detected.) Again, note that this ability for the detection of other robots and the ability to teleoperate them was not part of the original sensor net deployment task. These new sensing and software control capabilities were needed in order to “transfer” the knowledge or capabilities possessed by one robot to other robot team members.

This example shows that the specific interaction requirements of heterogeneous robot teams can vary dramatically depending upon the particular composition and mixture of capabilities of the available robots. Our objective is to develop general techniques that will enable robot team members to collaborate in a very flexible manner, by sharing sensing capabilities and knowledge to help the team as a whole achieve tasks that would be impossible to accomplish by any available single type of robot. These general techniques should enable the robot team members to autonomously collaborate and share resources using the techniques appropriate for the current goal of the mission and the currently available heterogeneous robots. Our current research is working toward these objectives.

## 5. Summary

This paper has outlined our project that will demonstrate a team of 100+ heterogeneous robots solving an indoor reconnaissance and surveillance task. The specific problem to be solved has been outlined, along with the robot team we are using in this research. The focus of this paper is on the impact of heterogeneity on the collaborative solution approach that the robot team must take. Our objective and ongoing research is to develop general techniques that will allow robots to autonomously make decisions on how to form subteams in order to solve the particular task at hand, given the available set of heterogeneous robots and their resources.

## Acknowledgments

The authors gratefully acknowledge the sponsors of this project – DARPA/IPTO’s Software for Intelligent Robotics Program, managed by Dr. Douglas Gage, and Science Applications International Corporation (SAIC). Additional support of Dr. Parker is provided by The University of Tennessee’s Center for Information Technology Research. Development of this research has been greatly facilitated by interactions and discussions with other members of the project team, including Nahid Sidke, John Spofford, Peter Drewes, Gaurav Sukhatme, Miland Tambe, Andrew Howard, Brian Gerkey, Ben Birch, Xiaoquan Fu, Balajee Kannan, and Chris Reardon.

## Notes

1. A notable exception is the related ongoing project funded under this same DARPA/SDR program, led by SRI International, which plans to demonstrate 100+ robots in two homogeneous sub-teams performing the same application discussed in this paper.

## References

- Balch, T. (2000). Hierarchic social entropy: An information theoretic measure of robot team diversity. *Autonomous Robots*, 8(3):209–238.
- Balch, T. and Parker, L. E., editors (2002). *Robot Teams: From Polymorphism to Diversity*. A K Peters.
- Gerkey, B. P., Vaughan, R. T., Sty, K., Howard, A., Sukhatme, G. S., and Mataric, M. J. (2001). Most valuable player: A robot device server for distributed control. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS '01)*, pages 1226–1231.
- Howard, A., Mataric, M. J., and Sukhatme, G. S. (2002). Localization for mobile robot teams using maximum likelihood estimation. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS '02)*, pages 434–459.
- Parker, L. E. (1998). Toward the automated synthesis of cooperative mobile robot teams. In *Proceedings of SPIE Mobile Robots XIII*, volume 3525, pages 82–93.
- Tambe, M. (1997). Towards flexible teamwork. *Journal of Artificial Intelligence Research*, 7:83–124.
- Vaughan, R. T. (2000). Stage: A multiple robot simulator. Technical Report IRIS-00-394, Institute for Robotics and Intelligent Systems, School of Engineering, University of Southern California.