CHAPTER 7

NETWORKED ROBOTS

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INTRODUCTION

Networked Robots refers to multiple robots operating together in coordination or cooperatively[1] with sensors, embedded computers, and human users. Cooperation entails more than one entity working toward a common goal while coordination implies a relationship between entities that ensures efficiency or harmony. Communication between entities is fundamental to both cooperation and coordination and hence the central role of the network. Embedded computers and sensors are now ubiquitous in homes and factories, and increasingly wireless ad-hoc networks or plug-and-play wired networks are becoming commonplace. Robots are functioning in environments while performing tasks that require them to coordinate with other robots, cooperate with humans, and act on information derived from multiple sensors. In many cases, these human users, robots and sensors are not collocated, and the coordination and communication happens through a network.

(a) (b) (c) (d)

Figure 7.1. (a) Small modules can automatically connect and communicate information to perform locomotion tasks; (b) Robot arms on mobile bases can cooperate to perform household chores; (c) Swarms of robots can be used to explore an unknown environment; and (d) Industrial robots can cooperate in welding operations.

Networked robots allow multiple robots and auxiliary entities to perform *tasks that are well beyond the abilities of a single robot*. Figure 7.1 shows many prototype concepts derived from academic laboratories and industry. In all these examples, independent robot or robotic modules can cooperate to perform tasks that a single robot (or module) cannot perform. Robots can automatically couple to perform locomotion tasks (also see Figure 7.2) and manipulation tasks that either a single robot cannot perform, or would require a special-purpose larger robot to perform. They can also coordinate to perform search and reconnaissance tasks

[1] "Working cooperatively" according to the Oxford English Dictionary is defined as mutual assistance in working toward a common goal : *every member has clearly defined tasks in a cooperative enterprise.*

exploiting the efficiency that is inherent in parallelism. They can also perform independent tasks that need to be coordinated (for example, fixturing and welding) in the manufacturing industry.

Networked robots also result in *improved efficiency*. Tasks like searching or mapping, in principle, are performed faster with an increase in the number of robots. A speed-up in manufacturing operations can be achieved by deploying multiple robots performing operations in parallel, but in a coordinated fashion.

Perhaps the biggest advantage to using the network to connect robots is the ability to connect and *harness physically-removed assets*. Mobile robots can react to information sensed by other mobile robots in the next room. Industrial robots can adapt their end-effectors to new parts being manufactured up-stream in the assembly line. Human users can use machines that are remotely located via the network. (See Fig. 7.3.)

The ability to network robots also enables fault-tolerance in design. If robots can in fact dynamically reconfigure themselves using the network, they are more tolerant to robot failures. This is seen in the Internet where multiple gateways, routers, and computers provide for a fault-tolerant system (although the Internet is not robust in other ways). Similarly, robots that can "plug" and "play" can be swapped in and out, automatically, to provide for a robust operating environment.

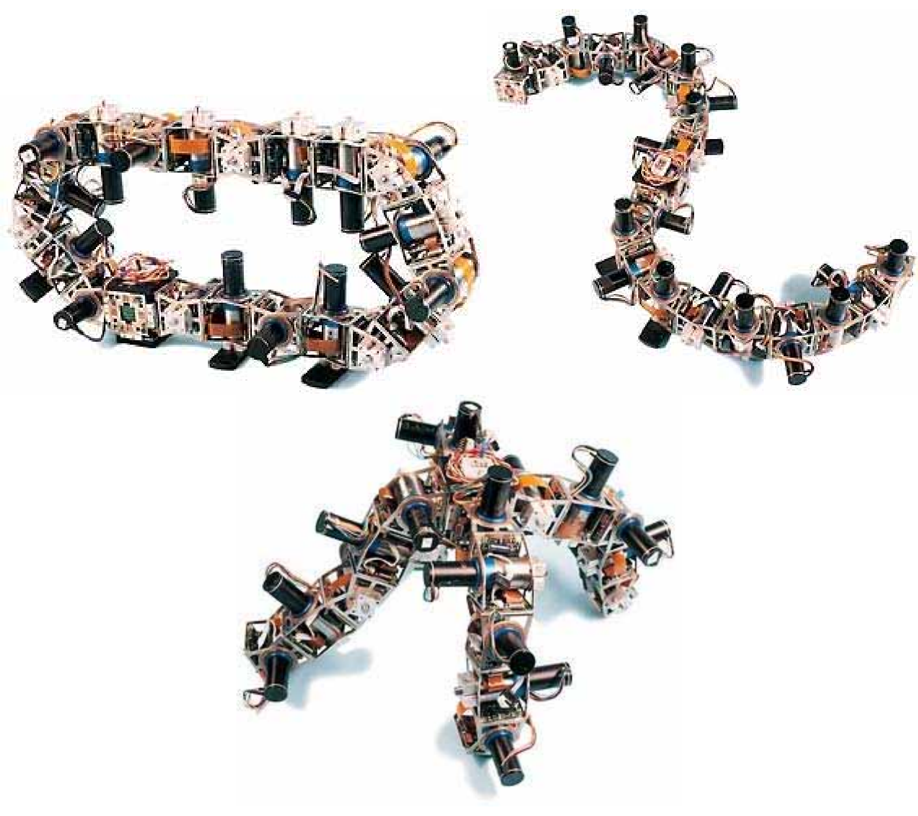

Figure 7.2. Robotic modules can be reconfigured to "morph" into different locomotion systems including a wheel-like rolling system (left), a snake-like undulatory locomotion system (right), a four-legged walking system (bottom).

Finally, networked robots have the potential to provide great synergy by bringing together components with complementary benefits and making the whole greater than the sum of the parts.

Applications for networked robots abound. The U.S. military routinely deploys unmanned vehicles that are reprogrammed remotely based on intelligence gathered by other unmanned vehicles, sometimes automatically. The deployment of satellites in space, often by astronauts in a shuttle with the shuttle robot arm, requires the coordination of complex instrumentation onboard the space shuttle, human operators on a ground station, the shuttle arm, and a human user on the shuttle. Home appliances now contain sensors and are becoming networked. As domestic and personal robots become more commonplace, it is natural to see these robots working with sensors and appliances in the house while cooperating with one or more human users.

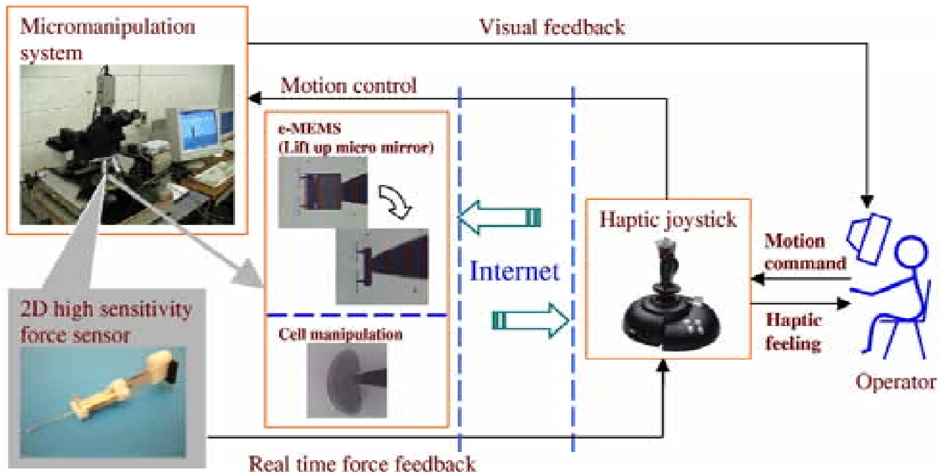

Figure 7.3. A human user communicating with remotely located expensive robots that can manipulate objects on the micro- or nanoscale. These robots can have multiple users without requiring collocation of the robots with the users.

SIGNIFICANCE AND POTENTIAL

The Network Robot Forum, established in Japan in 2003, estimates the Networked Robot industry to grow to over ¥19.8 trillion by 2013, approximately five times the industrial robot market for manufacturing applications. This growth is spread across many industries.

Sensor networks have been projected to grow dramatically in terms of commercialization and market value. Robot networks are analogous to sensor networks except that they allow sensors to have mobility and allow the geographical distribution of the sensors to be adapted based on the information acquired. There are significant efforts in CSIRO to exploit synergies between robot networks and sensor networks using networks of small vehicles (Figure 7.4).

Figure 7.4. A quad-rotor micro air vehicle with onboard cameras and inertial units and off-board processing (left), and a hybrid autonomous underwater vehicle (right).

Networks allow healthcare professionals to interact with their patients, other professionals, expensive diagnostic instruments, and in the future, surgical robots. Telemedicine is expected to provide a major growth impetus for remote networked robotic devices that will take the place of today's stand-alone medical devices.

The manufacturing industry is finding it easier to reconfigure existing infrastructure by networking new robots and sensors with existing robots via wireless networks. There is a noticeable trend towards robots interacting with each other and cooperating with humans.

Figure 7.5. Sony entertainment robots communicate and coordinate with each other in a game of soccer. The annual Robocup competition features teams from all over the world.

There are already many commercial products, notably in Japan, where robots can be programmed via, and communicate with, cellular phones. For example, the MARON robot developed by Fujitsu lets a human user dial up her robot and instruct it to conduct simple tasks including sending pictures back to the user via her cellular phone.

Nature provides the proof-of-concept of what is possible. There are numerous examples of simple animals executing simple behaviors, but communication with and sensing of nearest neighbors enable complex emergent behaviors that are fundamental to navigation, foraging, hunting, constructing nests, survival, and eventually growth. Biology has shown how simple decentralized behaviors in unidentified individuals (for example, insects and birds exhibiting swarming behaviors) can exhibit a wide array of seemingly intelligent group behaviors. Similarly networked robots can potentially communicate and cooperate with each other, and even though individual robots may not be sophisticated, it is possible for networked robots to provide a range of intelligent behaviors that are beyond the scope of intelligent robots. (See Fig. 7.5)

STATE-OF-THE-ART IN THEORY AND PRACTICE

There are already many impressive successful demonstrations of networked robots.

In the manufacturing industry, work cells are comprised of multiple robots, numerous sensors and controllers, automated guided vehicles and one or two human operators working in a supervisory role. However, in most of these cells, the networked robots operate in a structured environment with very little variation in configuration and/or operating conditions. There is a growing emphasis on networked robots in applications of field robotics, for example, in the mining industry. Like the manufacturing industry, operating conditions are often unpleasant, and the tasks are repetitive. However, these applications are less structured, and human operators play a more important role (Fig. 7.6).

Figure 7.6. Human operators can interact with remotely located manufacturing workcells with multiple robotic devices (left). A vision of mining and construction machines of the future (right) showing a similar network of autonomous vehicles controlled by human operators in a remote control station.

The U.S. military has a big Future Combat Systems initiative to develop network-centric approaches to deploying autonomous vehicles. While networked robots are already in operation, current approaches are limited to human users commanding a single vehicle or sensor system. However, it takes many human operators (between 2 to 10 depending on the complexity of the system) to deploy complex systems like unmanned aerial vehicles. A Predator UAV is operated from a tactical control station, which may be on an aircraft carrier, with a basic crew of 3–10 operators. The eventual goal is to enable a single human user to deploy networks of unmanned aerial, ground, surface, and underwater vehicles. (Fig. 7.7)

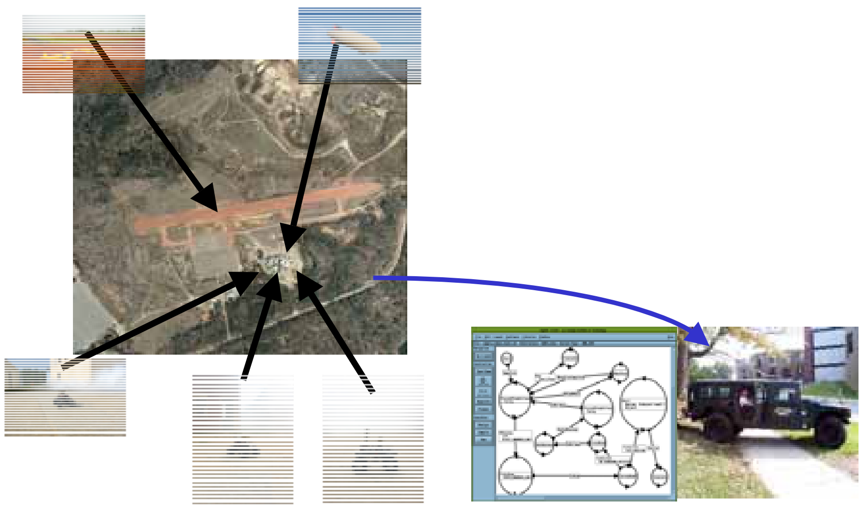

Figure 7.7. A single operator commanding a network of aerial and ground vehicles from a C2 vehicle in an urban environment for scouting and reconnaissance in a recent demonstration by University of Pennsylvania, Georgia Tech., and University of Southern California.

Mobile sensor networks are finding use in environmental studies and research projects in which robots are used to deploy sensors and measure environmental conditions. There are examples of measurements of salinity gradients in oceans, temperature and humidity variations in forests and chemical composition of air and water in different ecologies. The main benefit is to speed up the collection of data and increase efficiency. Mobile platforms allow the same sensor to collect data from multiple locations while communication allows the coordinated control and aggregation of information. (Fig. 7.8)

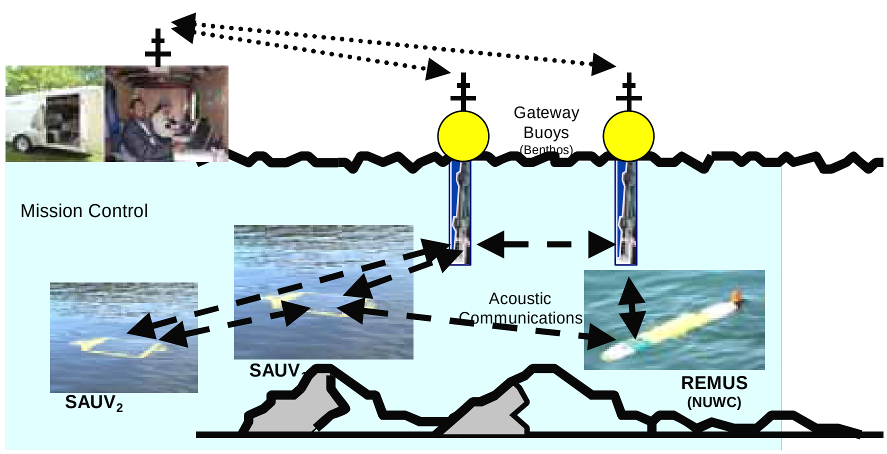

Figure 7.8. A network of buoys and underwater vehicles used for measuring oxygen content, salinity and cholorophil on the Hudson Bay (top) and the Neptune project (right) off the west coast of N. America.

The European Union has several EU-wide coordinated projects on collective intelligence or swarm intelligence. The *I-Swarm* project at Karlsruhe and the *swarm-bot* project at École Polytechnique Fédérale de Lausanne (EPFL) are examples of swarm intelligence.

The Laboratory for Analysis and Architecture of Systems (LAAS) has a strong group in robotics and artificial intelligence. This group has had a long history of basic and applied research in multi-robot systems. The most recent focus of this group is the COMET project, which integrates multiple unmanned vehicles for applications like terrain mapping and firefighting. (Fig. 7.10).

Figure 7.9. The Software for Distributed Robotics Project demonstrated the ability to deploy 70 robots to detect intruders in a unknown building (University of Tennessee, University of Southern California, and SAIC).

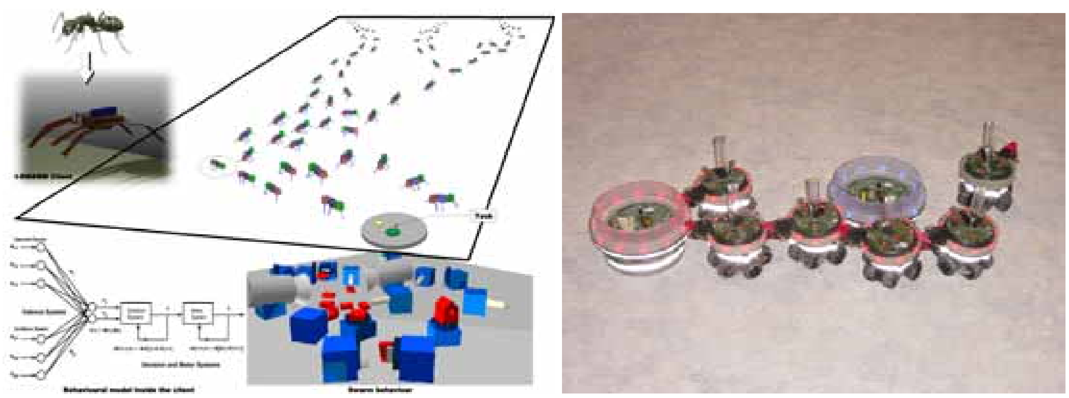

Figure 7.10. EU project on Swarm Intelligence: the I-Swarm project in Karlsruhe (left) and the *swarm-bot* project in EPFL with multiple robots forming physical connections for manipulation and locomotion (right).

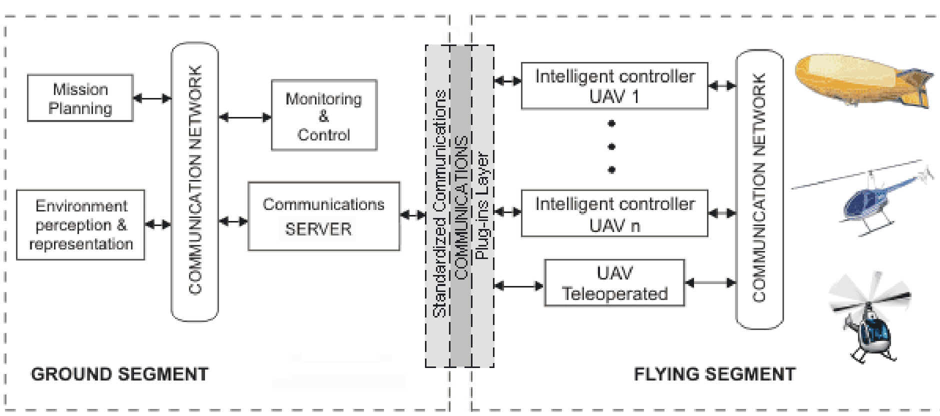

Figure 7.11. The COMETS project at INRIA (led by Rachid Alami) seeks to implement a distributed control system for cooperative detection and monitoring using heterogeneous UAVs with applications to firefighting, emergency response, traffic monitoring and terrain mapping.

SCIENTIFIC AND TECHNICAL CHALLENGES

While there are many successful embodiments of networked robots with applications to the manufacturing industry, defense industry, space exploration, domestic assistance, and civilian infrastructure, there are significant challenges that have to be overcome.

First, the problem of coordinating multiple autonomous units and making them cooperate creates problems at the intersection of communication, control and perception. Who should talk to whom and what information should be conveyed? How does each unit move in order to accomplish the task? How should the team members acquire information? How should the team aggregate information? These are all basic questions that need basic advances in control theory, perception and networking.

Second, because humans are part of the network (as in the case of the Internet), we have to devise an effective way for multiple humans to be embedded in the network and command/control/monitor the network without worrying about the specificity of individual robots in the network.

Third, today's networks tend to be static and responsive or reactive. They are static in the sense that sensors, computers or machines are networked together in a fixed topology. They are responsive or reactive in the sense that they respond to specific instructions provided by human users. Increasingly robot networks are becoming dynamic. When a robot moves, its neighbors change and its relationship to the environment changes. As a consequence, the information it acquires and the actions it executes must change. Not only is the network topology dynamic, but also the robot's behavior changes as the topology changes. It is very difficult to predict the performance of such dynamic robot networks. And yet, it is this analysis problem designers of robot networks must solve before deploying the robot network.

INTERNATIONAL COMPARISONS

Japan has many national R&D programs related to this area. The five-year Ubiquitous Networking Project established in 2003 has paved the way for a five-year Network Robots Project in 2004. The Network Robot Forum was established in 2003 and now has over a hundred prominent members from industry, academia and government.

While there are more mature efforts in Japan and Europe to develop better sensors and robot hardware to facilitate the development of robot networks, the U.S. has more impressive embodiments and imaginative applications of networked robots. Although it is hard to make such sweeping generalizations, U.S. arguably still maintains the lead in control and networking, while Europe and the U.S. may have an edge over Japan in perception. Japan has a bigger investment in network robots and has done a better job of creating national agendas that will impact the development of networked robots for service applications and eventually for domestic assistance and companionship.

Figure 7.12. The Australian Center for Field Robotics UAV fleet with 45 kg aircraft of 3 meter wing spans with reconfigurable sensor payloads.

Pioneering work on decentralization state estimation, localization, and tracking has been done by the Australian Center for Field Robotics at the University of Sydney in Australia. Indeed, their paradigm for decentralized data fusion and simultaneous localization and mapping has served as the foundation of many practical algorithms being used today. They also have exceptional strength in coordinated unpiloted aerial vehicles having demonstrated many impressive capabilities with multiple vehicles (Figure 7.12).

FUTURE CHALLENGES

There are many scientific challenges to realizing the vision for networked robots. The main overarching challenges are summarized here.

Technical challenges to scalability: We don’t have a methodology for creating self-organizing robot networks that are robust to labeling (or numbering), with completely decentralized controllers and estimators, and with provable emergent response. This requires basic research at the intersection of control, perception, and communication.

Performing physical tasks in the real world: Most of our present applications are emphasizing going from static sensor networks to mobile sensor networks and, as such, are able to acquire and process information. We are a long way from creating robust robot networks that can perform physical tasks in the real world.

Human interaction for network-centric control and monitoring: Advances over the last decade have provided human users the ability to interact with hundreds and thousands of computers on the Internet. It is necessary to develop similar network-centric approaches to interfacing, both for control and for monitoring.

Finally, a major challenge is to create robot networks that are proactive and anticipate our needs and commands rather than reacting (with delays) to human commands.

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