chapter fourteen

System of autonomous rovers and their applications

Ferat Sahin, Ben Horan, Saeid Nahavandi, Vikraman Raghavan, and Mo Jamshidi

Contents

14.1 System of autonomous rovers

In this chapter a system of autonomous rovers will be presented in the context of system of systems. In addition, a system of homogenous modular microrobots will be presented in the context of system of systems. The chapter starts with the introduction of the components and their roles in the system of autonomous rovers. Then, each system will be presented focusing on electrical, mechanical, and control characteristics and their capabilities in the system of autonomous rovers. Robust data aggregation and mine detection are then examined as applications of the system of autonomous rovers.

The system of autonomous rovers comprises four components: base robot, swarm robots, sensors and a threat. Figure 14.1 depicts the physical components of the system of rovers. The sensors represent a standalone system able to measure temperature and pressure and the ability to communicate with the Base Robot. The threat is spatially dynamic and it is assumed it is detectable by the chosen sensors.

In this particular scenario, the temperature local to a particular sensor or combination of sensors has been increased manually for ease and controllability of experimentation. Once the sensors have appropriately detected the

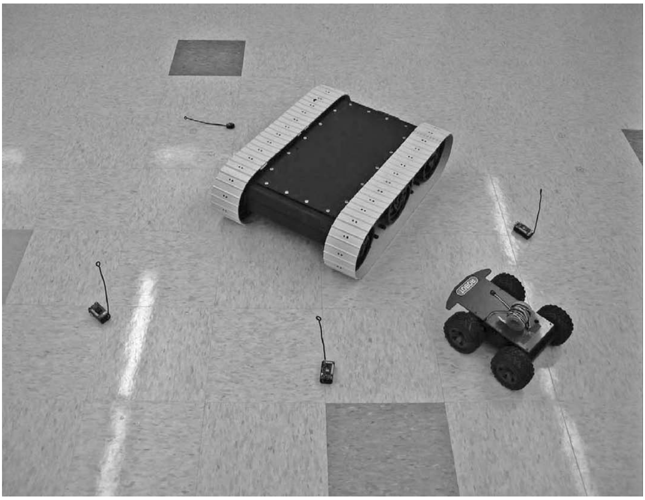


Figure 14.1 Components of the system of rovers: base robot, swarm robot, and sensors.

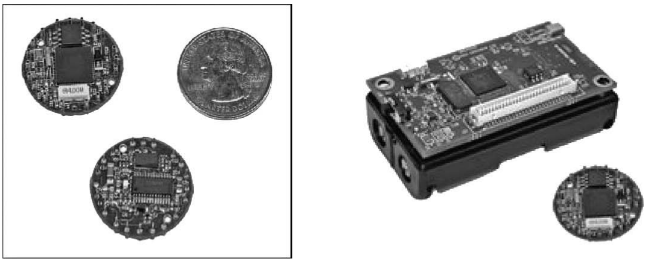


Figure 14.2 Stationary and mobile sensor platforms currently in use/development.

threat (temperature change), the base robot is informed of the event and subsequent location. The base robot then informs the swarm robot of the location of the threat. Upon receiving the threat information, the swarm robots navigate to the target location and use onboard sensory systems to validate the information obtained by the static sensors. Finally, the swarm rovers' sensor readings are communicated to the base robot for decision making based on its robust data aggregation algorithm. The base robot, swarm robot, and microrobots are discussed in the following sections. Sensor units are discussed here briefly, since we focus on autonomous rovers in this chapter.

14.1.1 Stationary sensors and sensor networks

For the stationary sensor platforms, we are currently using Crossbow's sensor motes (Mica 2 and Mica2Dot) that are equipped with processor-radio board and a multisensor board, shown in Figure 14.2. The processor-radio board consists of a 433-MHz multichannel transceiver and a low-power Atmel Atmega-128L 4-Mhz processor with 128 KB program flash memory. The multisensor board has the following sensors: temperature, humidity, barometric pressure, ambient light, 2-axis accelerometer (ADXL202), and a GPS receiver.

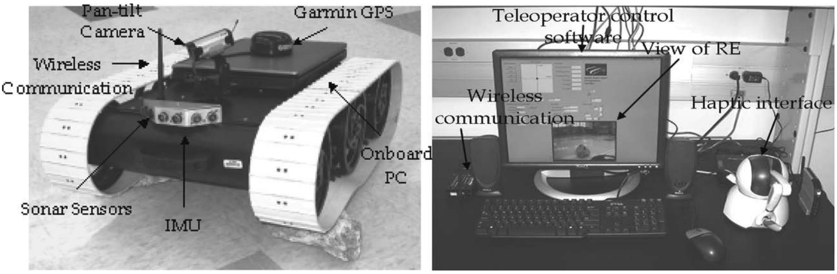
14.2 Haptically controlled base robot

The haptically teleoperated base robot plays an important role in the presented system of systems (SoS). The base robot provides onboard computational power, an advanced suite of sensors, and tracked locomotion for all-terrain navigation. Given the mechanical and load capabilities of the base robot, this system provides the capability for initial deployment of the sensor nodes to desired locations in order to appropriately monitor the target environment. The base robot also provides a communication link between each swarm robot, as well as providing a communication medium between the swarm robot and sensor network systems. The base robot utilizes its onboard processing power to transfer communication and commands between the swarm robot and sensor network systems. In the context of system of autonomous rovers and their applications, the base robot can be considered as a semistatic base station, which is responsible for autonomous handling of information between the swarm robots and sensor networks. This is of course, based on the assumption that the sensor nodes have previously been placed appropriately in the target environment. Facilitating intuitive navigation and deployment of sensor nodes, a human-in-the-loop approach was adopted. Intuitive haptic control methodologies [1] and application-specific augmentation have been developed [1,2] in order to improve teleoperator performance in the navigation to and deployment of sensor nodes.

14.2.1 Electrical and mechanical construction

The mobile platform developed in this work is an open-architecture articulated-track rover. The requirements of specific sensory, computation, communication and all-terrain capabilities necessitated the development of a custom platform for implementation in this system. The developed prototype is presented in Figure 14.3(a). The robot's tracked locomotion offers superior all-terrain capabilities, including the ability to traverse sand, mud, and shrubs and to climb rocks and stairs. The locomotion of this platform was chosen specifically to facilitate traversal of challenging real-world terrain. The haptic attributes of this teleoperation system therefore have the potential to improve the operator's control capabilities when attempting to navigate difficult real-world scenarios.

In order to facilitate task-relevant haptic augmentation, the robot is equipped with various sensory and control systems. The robot's onboard sensors include a GPS for absolute positioning in outdoor environments, wireless video for a view of the remote environment, ultrasonic range-finding for obstacle detection, 3-axis gyro for orientation, 3-axis accelerometer for motion capture, and encoders for monitoring the vehicle's velocity. The robot's computation is achieved through an on-board Windows-based laptop. This platform was designed specifically to meet the necessary requirements in this haptically teleoperated scenario. In order to reduce the required



(a) (b)

Figure 14.3 (a) Base robot and (b) haptic teleoperator control interface.

communication bandwidth between the mobile platform and teleoperator control station, the robot processes all of its sensory information locally. This reduces the amount of communicated data, sending only information directly pertaining to the appropriate haptic cues, thus contributing to improved real-time system responsiveness.

The teleoperator control station provides a medium for human-in-the-loop control of the remote robotic system. Many teleoperator interfaces currently used in real-world applications are controlled by a simple joystick-type device, while an onboard camera provides information from the remote environment. In order to implement the haptic human-robotic interaction, a commercial single-point haptic interface is utilized. This haptic device is a grounded, manipulator-style device offering 6-DOF motion input with 3-DOF force feedback. The implemented teleoperator control station is designed to facilitate bilateral haptic human-robot interaction in order to improve performance when navigating in a remote environment. The teleoperator can then receive application-specific information from the mobile robot using both the visual and haptic sensory modalities.

14.2.2 Haptic control: the haptic gravitational field (HGF)

Controllability is often as important as platform capabilities. The effectiveness of an immersive operator interface in providing the operator with the necessary mission-critical information can prove highly advantageous. Considering the scenario where the operator is required to command the base robot to a specific location in order to deploy the sensor nodes, the haptic gravitational field [2] is introduced in the aims of assisting the operator in such a task. As a basis for the HGF, the following assumptions are made:

1. The absolute location of the desired goal is known, including direction relative to the robot.
2. The environment is so unstructured that determination and evaluation of obstacles and safe navigational paths is not feasible by an autonomous robot, but better performed by the human operator.

In order to deploy the sensor nodes to the desired locations, the overall objective of the teleoperator is to safely navigate the remote mobile robot from a start location to the goal or target location. In order to travel to a known goal location, the HGF can utilize the robot's capabilities to provide haptic indication to the teleoperator of direction and distance to the desired location. The HGF is intended to provide the teleoperator with a force-based haptic indication of the current distance and direction to the goal location. This can prove extremely valuable to the teleoperator when the goal location is not clearly identifiable by visual information alone.

The HGF is demonstrated by Figure 14.4, where x_r, y_r is the current position of the robot, and x_g, y_g the position of the desired sensor deployment

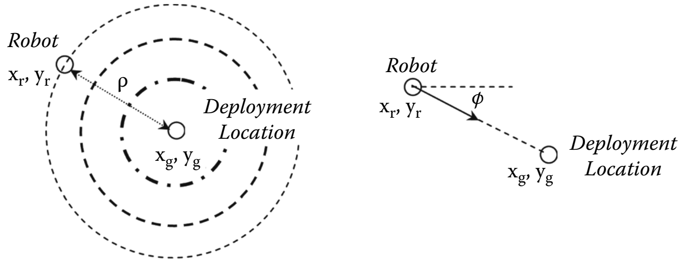


Figure 14.4 The haptic gravitational field (HGF) [2].

location, with respect to a world coordinate system. Given the current location of the rover and a known goal location, the magnitude of the haptic indicative force (ρ) resulting from the HGF is given by (14.1)

$$\rho = k_2 + k_3 \cdot \left(\sqrt{((y_g - y_r)^2 + (x_g - x_r)^2)} \right)^{-1} \tag{14.1}$$

where k_2 is the minimum possible haptic force, and k_3 is a constant of proportionality relating to the distance to the goal location. The direction to the goal location ϕ is given by (14.2)

$$\phi = \arctan((y_g - y_r) / (x_g - x_r)) \tag{14.2}$$

Given the current location of the robot (x_r, y_r) and a known goal position (x_g, y_g), the HGF results in the haptic force vector acting across an implemented haptic control surface [1]. The use of the HGF (including directionality) provides the teleoperator with a method to haptically determine the direction and distance to a goal location, when visual information may not be sufficient on its own. Furthermore, the HGF allows the teleoperator to concentrate their visual sense on local navigation of the challenging terrain, while inferring global navigation objectives from the haptic information.

14.2.3 *Operation in the system of autonomous rovers*

Having successfully placed the sensor nodes in the desired locations, the base robot assumes a semistatic and autonomous role within the system of autonomous rovers. This role involves receiving and processing information from the active sensor network and providing commands to the robotic swarm.

14.2.3.1 *Communication schemes*

The communication between sensor network and the base robot follows the star configuration (Figure 14.5). The sensor networks also utilize a centralized controller physically present within the base robot's onboard PC. Given this

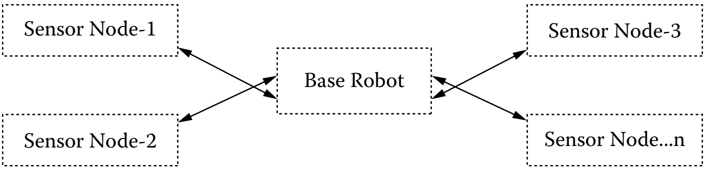


Figure 14.5 Base robot and sensor network communication—star configuration.

configuration, as the number of sensor nodes increases, the required communication channels only increase proportionally with the number of nodes.

14.2.3.2 Control schemes

As mentioned before, the base robot receives information regarding the detection of a possible threat from the sensor network. Given the prior knowledge of the location of any deployed sensor (x_n, y_n), the base robot receives sensory information pertaining to the monitored environment. If it is deduced that a threat is present, then the nature and location (GPS coordinates) of the threat location are communicated to the robotic swarm.

14.3 Swarm robots

The swarm robotic system comprises a set of identical robots which are relatively smaller in size, inexpensive, and hence less capable than the base robot. Each robot in the swarm has the same physical and functional characteristics. This section explains about the mechanical and functional characteristics of each of the robots in the swarm.

14.3.1 Mechanical construction and components

The robots use an off-the-shelf robotic mechanical platform. Four DC motors are coupled to the four wheels of the robot with appropriate gears. Control to the motors is provided with the help of an H-bridge servo controller. A field-programmable gate array (FPGA) board with a multiprocessor architecture is used as a controller. FPGA provides superior open architecture over conventional microcontrollers, which is desired for typical laboratory and field research.

A GPS receiver capable of sending data in National Marine Electronics Association (NMEA) 0183 format is part of the design. The receiver provides the navigation information to the robot. A magnetic compass that is used to complement the GPS information is also included in the design. Moreover, additional sensors for navigation and surveillance are included in the design. A radio modem is connected to provide connectivity to the rest of the system. A battery with appropriate A-h rating is essentially part of the system. The hardware block diagram is shown in Figure 14.6.

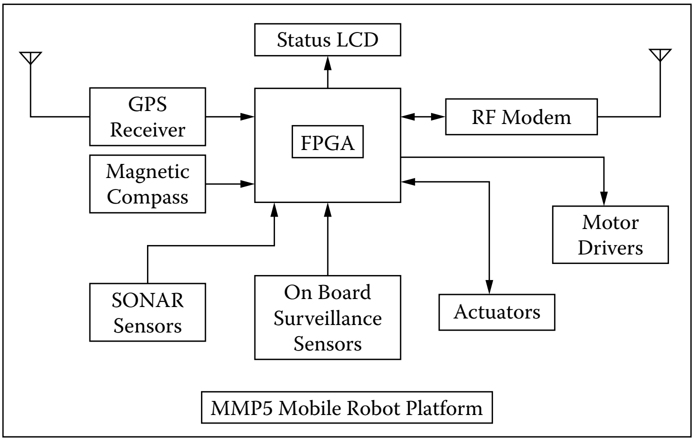


Figure 14.6 Architecture of the robot.

14.3.2 Navigation solution with GPS

14.3.2.1 The interface

GPS receivers calculate their position using the trilateration techniques. The basic position information includes the latitude, longitude, and their respective hemispheres. Based on those parameters, the receiver calculates dynamic parameters such as speed, magnetic orientation, etc. The receiver then formats all the parameters into sentences defined by the NMEA 0183 standard. The NMEA 0183 standard is an industrial standard for communication between marine electronics devices, and it widely used by GPS receivers. The most basic and powerful sentence of the NMEA 0183 standard is GPRMC, the recommended minimum specific GPS/transit data. The GPRMC sentence provides all the basic navigation information such as latitude, longitude, corresponding hemispheres, UTC fix, course over ground, speed over ground, and the mode in which the device works. Out of all the information, latitude, longitude, and corresponding hemispheres are the original data calculated by the receiver. Course over ground and speed over ground are calculated based on the rate of change of the read latitude and longitude data. For autonomous navigation the data necessarily needed are latitude, longitude, and hemisphere information. Also, we use course over ground information in our navigation algorithm.

The receivers communicate with a microcontroller/computer through a standard RS232 serial port or serial port–based USB interface. The sentences are transmitted in ASCII format through the interface. The NMEA 0183 specification suggests that the communication may be established at 4800 bps, 8 data bits, and no parity, which are the default connection parameters for all the receivers.

14.3.2.2 Understanding the parameters

With appropriate hardware and software interfaces the latitude, longitude, their hemispheres, and magnetic orientation data are parsed from the GPRMC sentence and converted from ASCII format to corresponding absolute number values. The data those are parsed and converted to in numeric format define the present location of the receiver/robot on the earth and its magnetic orientation. The destination latitude and longitude information is obtained from the user through an appropriate interface. The latitude and longitude distribution on the globe is basically two dimensional with four quadrants. The latitude and longitude intersect at right angle only at the intersection of equator and prime meridian. However, we can still consider that the latitude and longitude intersect at right angles at every point on the Earth, based on the assumption that the world looks flat to normal eyes and not elliptical. Moreover, the navigation algorithm discussed is iterative, which lets the robot recalculate its path until it reaches its destination. The iterative mechanism nullifies the error that is generated by assuming that the latitude and longitude intersect at right angles all over the Earth.

14.3.2.3 Calculating the heading angle

The present location and the destination location of the robot are mapped on a latitude-longitude layout with their respective (latitude, longitude) coordinates. With basic coordinate geometry concepts and trigonometric principles, the angle at which the robot should head to reach the destination from where it is at that point of time is calculated. Let us assume that a robot is to navigate from location A with (0 N, 0 E) as its (latitude, longitude) to location B with (3 N, 6 E) as its (latitude, longitude). Assuming that the latitude and longitude intersects at right angles,

1. Present location A and destination location B are connected with a straight line segment.
2. Applying the coordinate geometry distance formula, Δx and Δy are calculated.
3. $\theta = \tan^{-1} (\Delta y/\Delta x)$ is calculated.

In the above example, both the present and destination locations are on the first quadrant. If the present coordinate and end coordinate are in any other quadrant, the theta is correspondingly level shifted. The convention specified by NEMA for magnetic orientation is to have magnetic north as 0 or 360 degrees, south as 180 degrees, east as 90 degrees, and west as 270 degrees. After calculating the heading angle θ desired, the robot is aligned to head in the desired angle that leads it to the destination location. The actual magnetic orientation θ information extracted from the GPRMC sentence is used to verify if the robot has aligned to the desired heading angle θ.

14.3.3 Sensor fusion

It may be interesting to note that the magnetic orientation to a GPS receiver is a dynamic parameter. Dynamic parameters are calculated from the change of the latitude and longitude values calculated by the receiver. This suggests that the position data of the receiver, at each instant of time, are stored in a first-in first-out (FIFO) buffer array. The location history information is used to calculate the dynamic parameters. Once the buffer gets filled up with information, the buffer is replaced with newer location information. If the speed of the receiver is slower than the rate at which the buffer is replaced, the dynamic behavior of the receiver cannot be captured. Thus, the receiver has to be in continuous motion at a speed greater than the minimum speed required by the receiver to compute the magnetic orientation information and other dynamic parameters. Typical minimum speed that can be captured is about two miles per hour (mph). Practical robotic applications demand slow speed of less than two mph during certain maneuvers. Some common situations when the speed drops below two mph are when

1. Encountering obstacles
2. Evaluating threat
3. Waiting for a command
4. Executing a command

In these instances there is a possibility that the receiver on the robot fails to keep track of the dynamic behavior of the robot, including the orientation information. Also, during the cold start of the robot the receiver would not be able to provide magnetic orientation data and other dynamic parameters to the robot. However, the magnetic orientation data is necessary information for autonomous navigation. This forces us to complement the GPS receiver with another device that is capable of determining the magnetic orientation of the robot even when the robot is stationary. The simplest solution would be to use a dual-axis magnetic field sensor–based compass that can report the magnetic orientation information according to the NMEA 0183 specification. It may be interesting to note that the geographic north is different from magnetic north. Normal magnetic compasses work based on the Earth's magnetic field, and they would read North Pole where the Earth's magnetic north is present. But, due to the differences in the flow of metals inside the Earth's core, the magnetic north has been continuously drifting. Hence, the compass reading is not accurate. However, the GPS receiver calculates the orientation of the robot based on the way the latitude and longitude change, and it calculates the orientation with absolute north pole as reference. The error caused by the magnetic compass is calculated from the difference between the compass and GPS receiver readings. The error is compensated from the read magnetic orientation data. Thus GPS receiver and magnetic compass complement each other, forming a dynamic sensor fusion strategy.

14.4 Application: robust threat monitoring

14.4.1 Introduction

As eluded to in the preceding sections, this system was developed in order to perform threat monitoring of a target environment. Utilizing the distinct capabilities of the haptically controlled all-terrain base robot, the sensor network, and robotic swarms, the system of systems shown in Figure 14.7 aims to robustly monitor a target environment for potential threats. Sensors play the most fundamental and trivial role in any control system. Sensors basically measure a parameter of the system for further processing. The quantity and the quality of the measured data are then processed to understand the current state of the system. With the current state of the system known, there may be a need to take some corrective actions. This philosophy is fairly common in robotic systems.

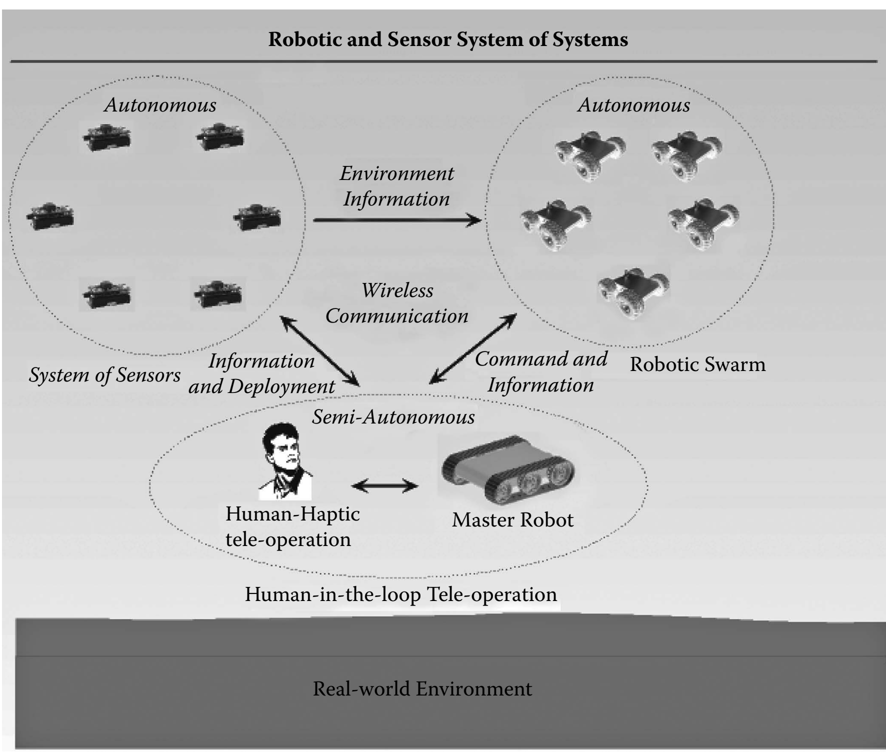


Figure 14.7 High-level system of systems architecture.

14.4.2 The scenario

To illustrate this philosophy in an SoS perspective, we introduce three individual systems that have already been explained in Sections 14.1, 14.2, and 14.3. A sensor network system is primarily used to find any exceptional condition that may prevail over the region of interest. The haptically controlled master robot acts as the central workhorse of the SoS, providing relatively exceptional physical strength, computational power, and communication node. Swarm of robots are characterized by their lower cost and relatively larger area of coverage [3,4].

14.5 Swarm of micromodular robots

In this section, we will present another set of robots in a similar application with a different hardware and software architecture. They are micromodular robots designed to study and emulate swarm intelligence techniques and applications [5,6,7]. These robots will be called GroundScouts throughout the section. In addition to the hardware and software components of the robots, the implementation of a robotic swarm as a system of systems and its application to mine detection problems will also be presented.

14.5.1 Electrical and mechanical construction

GroundScouts are cooperative autonomous robots designed to be both versatile and modular in hardware and software. The overall design was centered on modularity, creating a robot that could be easily altered to fit the conditions of almost any application. A picture of a GroundScout is shown below in Figure 14.8.

For modularity, GroundScouts are divided into several independent layers. The following subsections explore each layer.

14.5.1.1 Power layer

The power layer contains the circuitry needed for power of all the layers, including the motor drivers for the locomotion layer. The batteries are stored on the locomotion layer between the wheels.

14.5.1.2 Control layer

The control layer is composed of a Phillips 80C552 as the main controller for the entire robot. It is connected to all of the other layers via a hardware bus that runs up the back and the sides of the robot. This creates a mechanical and electrical means of connecting different layers of the robot. Currently, we are working on the second generation of GroundScouts, which has ARM processor and micro operating system.

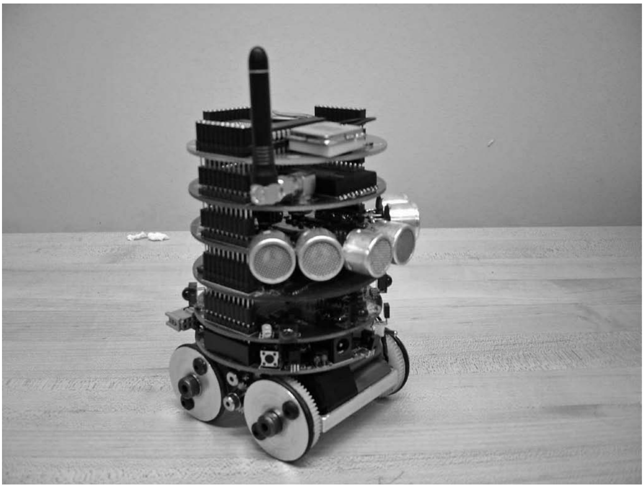


Figure 14.8 Front view of the GroundScouts.

14.5.1.3 Ultrasonic layer

The ultrasonic layer has three ultrasonic drivers, which can be arranged in two different configurations. In the first configuration, the sensors are 120 degrees offset from one another. In the second configuration, all three sensors are in the front of the robot with 60 degrees offset from one another.

14.5.1.4 Infrared layer

The infrared layer can be used for short-range communication from robot to robot along with trail following, meaning that the robot can be programmed to follow an IR signal.

14.5.1.5 Communication layer

The communication layer is composed of a PIC microcontroller and a wireless transceiver that is capable of transmitting serial data at ranges up to 300 feet. The modulation scheme that the transceiver uses is frequency-shift keying, meaning that all of the users are sharing the same medium. This created the need for an applied medium access control (MAC) protocol that was developed and described later.

14.5.1.6 GPS layer

The GPS layer was created to allow the robots to be sent off on autonomous missions and give them a way to get back to the master station by navigating based on GPS coordinates.

14.5.2 Communication scheme

Many different MAC protocols were studied in an attempt to find the one that was suitable for the robotic swarms. The protocols analyzed included frequency division multiple access (FDMA), code division multiple access (CDMA), time division multiple access (TDMA), and polling. The FDMA separates the users in the frequency domain. This is not suitable with the current hardware, since the transmit frequency of the transceivers cannot be changed. The CDMA gives each user a unique code. The message will only make sense to the user that has the code that the message was modulated with. The current hardware does not have the capability to implement a CDMA network, since the user has no control over the modulation and demodulation of the signal. Thus, we concluded that the TDMA was the most applicable method, since it is easy to implement a "collision-free" protocol and is suitable for the available hardware.

After implementing this protocol and analyzing it carefully, we discovered some inefficiencies in this type of network for robotic swarms. For example, the number of users on the network was fixed, creating a maximum number of users, and also creating unused slots if all of the users were not present. Thus, there was a need to develop an adaptive protocol that allowed the number of slots to change in accordance with the number of users on the network. This is referred to as adaptive TDMA [8–11].

The protocol works by creating a time slot at the beginning of each frame where users can request a transmit slot. The master grants each user a transmit slot. All of the other users on the network hear this and increment their transmit slot by one, creating a gap for the new user to enter. This also goes the other way. If no message is sent in a time slot, then the rest of the users on the network decide that the time slot is no longer in use, and they close it. The only contention is in the requesting time slot. This is handled by having the users generate a random number and wait that many frames before requesting another slot. Using the adaptive TDMA, swarms can organize their communication medium based on the number of robots in the swarm. By adaptively controlling the time slots, robots in a swarm can fully utilize the available transmission time. Next we discuss the swarm algorithm tested on the GroundScouts.

14.5.3 Swarm behavior: the ant colony-based swarm algorithm

The swarm behavior to be tested is ant colony behavior. The algorithm is designed based on short- and long-range recruitment behaviors of the ants when they are seeking food. The details of the algorithm can be found in [12,13]. The algorithm is applied to the mine-detection problem [6,7]. The resulting algorithm is presented in the diagram shown in Figure 14.9. The boxes represent the three different states that the robot can be in, while the diamonds represent the transitions that occur.

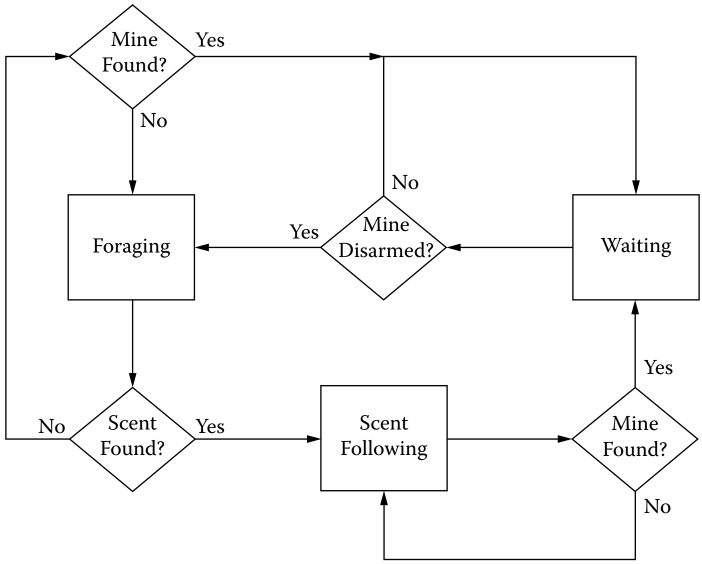


Figure 14.9 Flow chart of the implemented swarm algorithm.

The algorithm requires that multiple robots (four in our experiments) be present around a mine for the mine to be disarmed [8]. This creates the need for two different messages to be sent from robot to robot. One message indicates to other robots that the mine was found, to mimic a scent. Another message tells the other robots that the robot timed out. These two messages allow the other robots to know exactly how many robots are surrounding the mine.

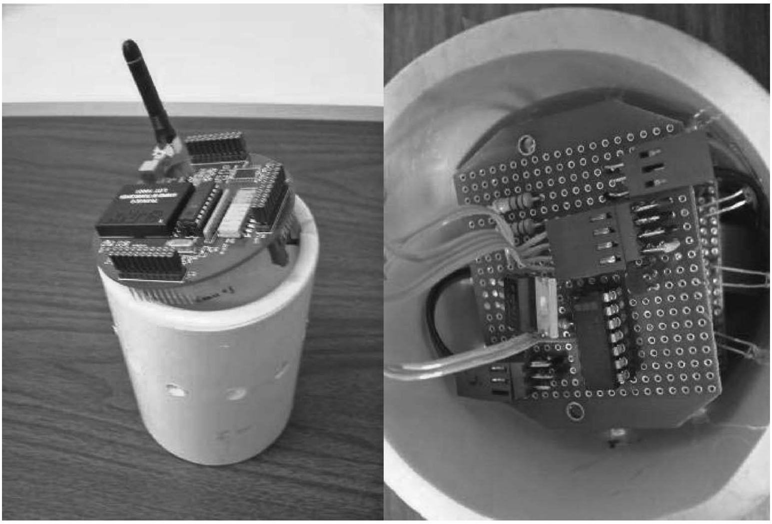
One thing to note is that, when a robot times out, it turns around completely and travels fifteen feet before it begins to forage again. This gets the robot far enough away so that it does not instantly go back to the mine it was just at. Also, the timeout count is reset when another robot arrives at the mine. For the experiments, five robots are used to disarm two mines. A mine must have four robots surrounding it in order to be disarmed. The robots will start in between the mines at the same location. The mines are placed far enough apart such that the communication radius of a robot at mine 1 and a robot at mine 2 does not overlap.

14.5.4 Application: mine detection

As mentioned, the ant colony–based swarm algorithm is applied to a mine-detection problem. First we will present the systems used as mines, and then we will present the results of the experiments run in a basketball court.

14.5.4.1 Mine hardware

The mines are composed of a beacon that constantly transmits an infrared signal that is modulated at 38 KHz in all directions. A picture of the beacon



(a) (b)

Figure 14.10 (a) Outside view and (b) inside view.

is shown in Figure 14.10. The signal can be sensed by the robot within a 7-foot radius. The robots are constantly searching for this signal. As soon as the signal is detected, the robot knows that it is close to a mine.

Directionality is found by viewing the five sensors that surround the robot. Early attempts were made to find the sensor with the best signal and assume that the mine is in that direction. This proved to be difficult, since the sensors are somewhat omnidirectional, creating a number of sensors having a good signal and making it difficult to really pinpoint the exact direction of the mine. It was concluded that finding the direction could be simplified by looking for the two sensors that have the worst signal. The robot could then move in the opposite direction, which would be directly toward the mine. The mine is disarmed using the GroundScout's communication module. A communication board was placed on the top of the mine as shown in Figure 14.10(a). When enough robots are surrounding the mine to disarm it, a message is sent by the command center to the communication board, telling it to disarm the mine. The PIC on the communication board will then toggle a pin that will turn the mine off. The robots will then shift back into the foraging state, since signals from the mine will not be available after the mine is disarmed.

14.5.4.2 Experimental results

The experiments were performed in a gymnasium so that the robots had plenty of room to work with. A picture of the starting point of the experiment is shown in Figure 14.11.

Figure 14.11 Starting point of the experimental setup.

(a) (b)

Figure 14.12 (a) Robots in the foraging state, (b) robot at the mine.

The robots are turned on one at a time, and each is allowed to move about 3 feet before the next robot is turned on. At the start of the algorithm, the robots are foraging. This is shown in Figure 14.12(a). It clearly shows the robots randomly searching for mines. The robots near the top of the figure are beginning to find the first mine. The algorithm used to find the mines using the infrared sensors will bring the robots toward the mine. The robot will then move until the back infrared sensors have no signal and the ultrasonic sensors are picking up an object that is within 6 inches. Figure 14.12(b) shows a picture of a robot at the mine.

As soon as the robot reaches the mine, it will begin sending out the recruitment signal to other robots. Since the implementation of the internal coordinate system neglects slippage, over time the robot's internal coordinates will begin to become off center. As a robot at a mine sends out the recruitment signal, other robots that are within the physical distance may not hear this

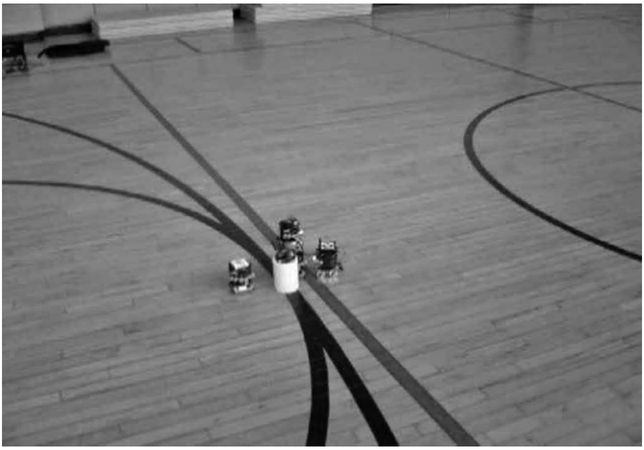


Figure 14.13 Robots disarming the mine and leaving.

signal because, according to the coordinate system, they are outside of *listening* range. Another problem is that sometimes a robot would hear the signal, but would go to the wrong location, because it is where the robot thinks the mine is.

As soon as four robots surround the mine, the mine can be turned off. The robots decide that a mine is turned off by checking their front infrared sensor. If no signal is detected, then the robots conclude that the mine has been disarmed; they then instantly switch into the foraging stage, which incorporates obstacle avoidance. This is shown in Figure 14.13.

This section presented a real-time implementation of an ant colony–based system of swarming robots to the mine-detection problem. In addition, an adaptive communication network that maximizes the efficiency of the network has also been implemented. It was shown that the algorithm can be effectively implemented with very few problems.

The robotic swarm, as a system of systems, shows fewer problems than heterogeneous systems exhibit. First of all, there is no compatibility issue among the system components, since all the robots have same or similar components. The robots also have the same software architecture and communication medium.

14.6 Conclusion

This chapter describes two examples of system of systems using autonomous rovers. In the first example, the systems were heterogeneous in terms of their hardware and software, which definitely requires the theory of system of systems. In the second example, a swarm of robots is examined as a system of systems. In this example, the hardware components were similar or the same for each robot. The advantage of this system of systems was the common software architecture and known system hardware, even though some of the robots could have different hardware components because of the modularity. In both cases, a communication medium is crucial so that the components of the system of systems can communicate properly and operate together. By developing a communication medium, system-of-systems concepts can be studied. The common communication medium can be achieved in hardware and/or software architecture of the communication modules of each system in the SoS.

References

1. Horan, B., S. Nahavandi, D. Creighton, and E. Tunstel. 2007. Fuzzy haptic augmentation for telerobotic stair climbing. In the *IEEE International Conference on Systems, Man and Cybernetics*. Montreal, QC, pp. 2437–2442.
2. Horan, B., D. Creighton, S. Nahavandi, and M. Jamshidi. 2007. Bilateral haptic teleoperation of an articulated track mobile robot. In *IEEE International Conference on System of Systems Engineering, 2007. SoSE '07. San Antonio, TX,* pp. 1–8.
3. Azarnoush, H., B. Horan, P. Sridhar, A. Madni, and M. Jamshidi. 2006. Towards optimization of a real-world robotic sensor system-of-systems. In *Proceedings of World Automation Congress*. Budapest, pp. 1–8.
4. Sahin, F., P. Sridhar, B. Horan, V. Raghavan, and M. Jamshidi.2007. System of systems approach to threat detection and integration of heterogeneous independently operable systems. In *IEEE International Conference on Systems, Man and Cybernetics,* Montreal, QC, pp. 1376–1381.
5. Sahin, F., W. Walter, and K. Kreigbaum. 2003. Design, build and test of modular mobile micro robots. In *Proceedings of IMECE'03 2003 ASME International Mechanical Engineering Congress and Exposition,* Washington, D.C.
6. Chapman, E. and F. Sahin. 2004. Application of swarm intelligence to the mine detection problem. In *Proceedings of 2004 IEEE International Conference on Systems, Man and Cybernetics,* vol. 6, pp. 5429–5434.
7. Opp, W. J. and F. Sahin. 2004. An artificial immune system approach to mobile sensor networks and mine detection. In *Proceedings of 2004 IEEE International Conference on Systems, Man and Cybernetics,* vol. 1, pp. 947–952.
8. Burr, A. G., T. C. Tozer, and S. J. Baines. 1994. Capacity of an adaptive TDMA cellular system: comparison with conventional access schemes. In *5th IEEE Conference on Personal, Indoor, and Mobile Radio Communications,* vol. 1, pp. 242–246.
9. Kanzaki, A., T. Uemukai, T. Hara, and S. Nishio. 2003. Dynamic TDMA slot assignment in ad hoc networks. In *International Conference on Advanced Information Networking and Applications,* pp. 330–335.
10. Papadimitriou, G. and A. Pomportsis. 1999. Self-adaptive TDMA protocols for WDM star networks: A learning-automoto-based approach. *IEEE Photonics Technology Letters* 11:1322–1324.
11. Stevens, D. and M. Ammar. 1990. Evaluation of slot allocation strategies for TDMA protocols in packet radio networks. In *IEEE Military Communications Conference, 1990,* vol. 2, pp. 835–839.
12. Kumar, V., F. Sahin, and E. Cole. 2004. Ant colony optimization based swarms: implementation for the mine detection application. In *Proceedings of 2004 IEEE International Conference on Systems, Man and Cybernetics,* vol. 1, pp. 716–721.

13. Kumar, V. and F. Sahin. 2003. Cognitive maps in swarm robots for the mine detection application. In *Proceedings of 2003 IEEE International Conference on Systems, Man and Cybernetics,* vol. 4, pp. 3364–3369.