A Team of Robotic Agents for Surveillance

Paul E. Rybski*, Sascha A. Stoeter, Michael D. Erickson,
Maria Gini, Dean F. Hougen, Nikolaos Papanikolopoulos†
Center for Distributed Robotics
Department of Computer Science and Engineering, University of Minnesota
Minneapolis, MN 55455

Abstract

This paper presents the hardware and software components of a robotic team designed for security and surveillance applications. The team consists of two types of robotic agents. The first type is a larger, heavy-duty robotic platform, called the "ranger." Rangers are used to transport, deploy, and supervise a number of small, mobile sensor platforms called "scouts", the second type of robotic agent. In an example scenario, the scouts are deployed into an office/lab environment, navigate towards dark areas, and position themselves to detect moving objects using their cameras. A ranger communicates with each of the scouts and determines whether there are objects of potential interest within the surveyed area. The paper also includes experimental results for individual scout and ranger-scout activities.

1 Introduction

For security and surveillance applications, an area is typically observed either by (1) multiple remote sensing devices that report to a coordination agent or (2) a mobile agent that patrols the required area. In both cases, the problem of adequate sensor coverage exists. In case 1, the problem is spatial: Are there enough sensors in the right locations? In case 2, the problem is temporal: Will the mobile agent be in the right place at the right time?

One possible compromise is to combine the two solutions into one. A mobile agent that is capable of long distance travel can cover a large area and deploy smaller, less mobile agents in various locations. The smaller agents can be given the responsibility of surveying a small area and can have the flexibility to change their vantage points to make sure that all of their local area is observed. A coordination agent can then communicate with the sensing agents, query them for information, and move them remotely to increase the area viewed by them.

*Student Author
†Corresponding Author

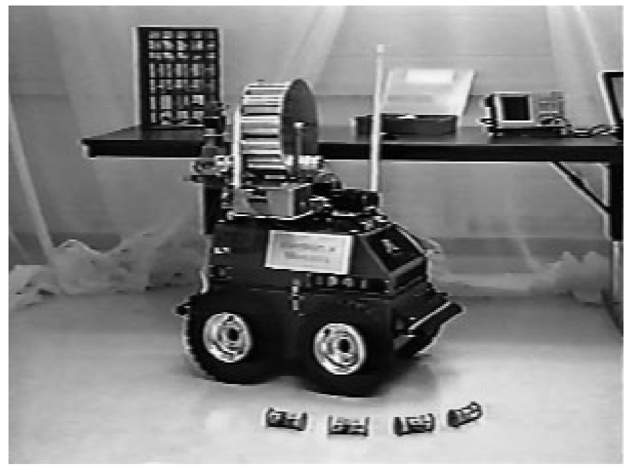

Figure 1: A ranger with four scouts in the foreground.

This is the solution that this paper suggests. The robots that are used are specially equipped RWI ATRV-Jr™-based robots called "rangers" and a group of extremely small custom mobile sensor platforms called "scouts" (see Figure 1). Rangers are capable of navigating long distances without needing to recharge their batteries and are capable of navigating off-road terrain. Due to their size, however, not all areas may be accessible to them. The small size of the scouts makes them much easier to operate in these areas but presents a different set of problems including decreased range, battery lifetime, computational power, and sensing ability. By putting both kinds of robots into a team, the benefits of both can be achieved.

In this team, rangers are used as the primary navigational and computational resources. Their responsibilities include traversing the environment, selecting appropriate locations that are to be observed, and deploying the scouts into those areas. Once the scouts reach their designated locations, a ranger contacts each of the scouts in turn to analyze the area.

The paper is organized as follows: Section 2 presents related work, Section 3 describes the hardware components of the team, and Section 4 describes the software aspects. Experimental results are presented in Section 5.

2 Related Work

Automatic security and surveillance systems using cameras and other sensors are becoming more common. These typically use sensors in fixed locations, either connected ad hoc or, increasingly, through the shared communication lines of "intelligent buildings" [15]. These may be portable to allow for rapid deployment [16] but still require human intervention to reposition when necessary. This shortcoming is exacerbated in cases in which the surveillance team does not have full control of the area to be investigated, as happens in many law-enforcement scenarios. Static sensors have another disadvantage. They do not provide adaptability to changes in the environment or in the task. In case of poor data quality, for instance, we might want the agent to move closer to its target in order to sense it better.

Mobile robotics can overcome these problems by giving the sensor wheels and autonomy. This research has traditionally focussed on single, large, independent robots designed to replace a single human security guard as be makes his rounds [8]. Such systems are now available commercially and are in place in, for example, factory, warehouse, and hospital settings [9, 11, 14], and research continues along these lines [3, 12, 17]. However, the single mobile agent is unable to be many in places at once—one of the reasons why security systems were initially developed. Unfortunately, large mobile robots are unable to conceal themselves, which they may need to do in hostile or covert operations. They may also be too large to explore tight areas.

Multiple robots often can do tasks that a single robot would not be able to do or do them faster, as described in the extensive survey by Cao et al. [2]. The tasks traditionally studied with multiple robots are foraging [10], which involves searching and retrieving items from a given area, formation marching [1], which involves moving while maintaining a fixed pattern, map making [6], and janitorial service [13], where robots have to clean a room in an unfamiliar building by emptying the garbage, dusting the furniture, and cleaning the floor.

Multiple mobile robots for security have recently been investigated [5]. In this case, the robots were meant to augment human security guards and fixed sensor systems in a known and semi-tailored environment.

3 Hardware Components

The two hardware component types in the system correspond to the two robotic agent types, the rangers and the scouts.

3.1 Rangers

Figure 2: A ranger robot with scout launcher.

Rangers are based on the ATRV-Jr.™ platform from the RWI Division of IS Robotics. Rangers can carry the scouts into position over distances of up to 20km, giving the scouts a much greater effective range than they would have if they needed to transport themselves. Further, by mounting a novel launching mechanism on a ranger (see Figure 2), scouts may be deployed more rapidly and into places rangers might have difficulty accessing. The launcher can selectively launch any of the 10 scouts in its magazine, at a selectable elevation angle and propulsion force, up to a range of 30m. Scouts are launched with a compressed spring.

Each ranger is equipped with a Pentium 233MHz-based PC running Red-Hat Linux which is linked to the robot's sensors and actuators with RWI's rFLEX™ control interface. The PC runs RWI's Mobility™ (an object-oriented, CORBA-based modular robotics control architecture).

3.2 Scouts

Scouts are custom cylindrical robots 40mm in diameter and 110mm in length (see Figure 3) possessing a unique combination of locomotion modes. A scout can roll using its wheels (one on each end of its body) and a leaf spring "foot" mounted underneath for stabilization. It is also able to hop by winching its spring foot around its body and releasing it in a sudden motion.

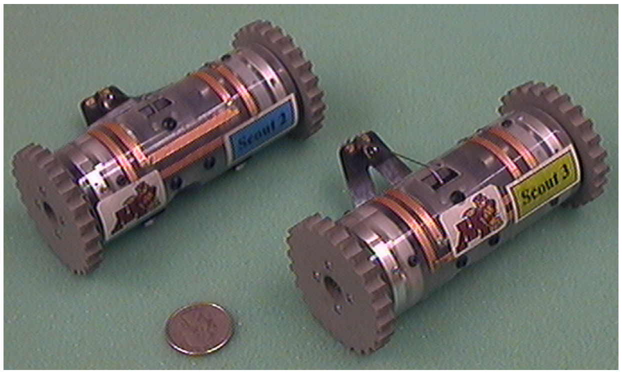

Figure 3: Two scout robots (shown next to a quarter for scale).

For the scenario presented in this paper, each scout possesses a miniature video camera and a wireless video transmitter. The camera consists of a monochrome single chip CMOS video sensor and a miniature pinhole lens. Video data is broadcast back to a receiver via a 900MHz analog video transmitter. Each scout also possesses a miniature RF data transceiver for receiving commands from rangers and transmitting status information back to rangers. Scouts are discussed more fully in Hougen et al. [7].

4 Software Components

In order for the rangers and the scouts to coordinate their efforts and work together properly, a proxy processing system has been developed which allows the ranger to control the scouts. The scout's limited computational resources restrict it to handling only the most basic low-level control routines (such as pulse width modulation control of the motors). High-level control is achieved through this proxy-processing scheme in which the individual control algorithms that direct the motion of the scout are run as separate threads on board the ranger's computer. This control is accomplished through the use of a client/server style of architecture where the ranger sends command packets through an RF data link to the scouts.

We have developed behaviors for a scenario in which rangers will find interesting areas to explore and deploy scouts into them. In our scenario a ranger is placed in a building to traverse the corridor and launch scouts into rooms that it finds along its path. A second ranger is used as a communication agent to coordinate the actions of the deployed scouts. The scouts must find dark areas in which to conceal themselves and watch for moving entities (such as people).

(a) real-world layout

(b) robot perception

Figure 4: The environment.

4.1 Ranger Behaviors

Door detection and motion control are solely based on sonar input. Concurrent to the ranger's motion, sonar readings from two side-sonars and one front-sonar are integrated into an evidence grid [4]. Evidence grids partition the world into a number of discrete cells. Each cell carries a probability value describing the likelihood of that part of the world being free space. A sensor model expresses the effect of a reading from that sensor on the evidence grid. This allows for readings from different sensor sources to be combined into a unified model of the world. Here, the evidence grid covers an area of 4m $\times$ 4m centered around the robot where each cell is 6.25cm on a side. The environment in Figure 4(a) is perceived by the ranger as depicted in Figure 4(b). White areas are considered free whereas black spots are likely to contain obstacles. Gray regions indicate insufficient knowledge to assume either occlusion state.

To identify doors or any other opening in a wall the evidence grid surrounding the ranger (Figure 5(a)) is treated as a grayscale image. Note that the ranger moves to the right of the image. First, a threshold is applied to retain occluded regions resulting in Figure 5(b). Figure 5(c) shows the cells containing obstacles closest to the axis of motion. The remaining pixels to the left and right of the ranger are split into two sub-images and then projected into Hough space to find lines in the image that correspond to the walls. Figure 5(e) shows the Hough space of the right side of the ranger. The darkest pixel in this image corresponds to the location of the wall with respect to the ranger. Lastly, openings are searched for along these lines within a dynamically

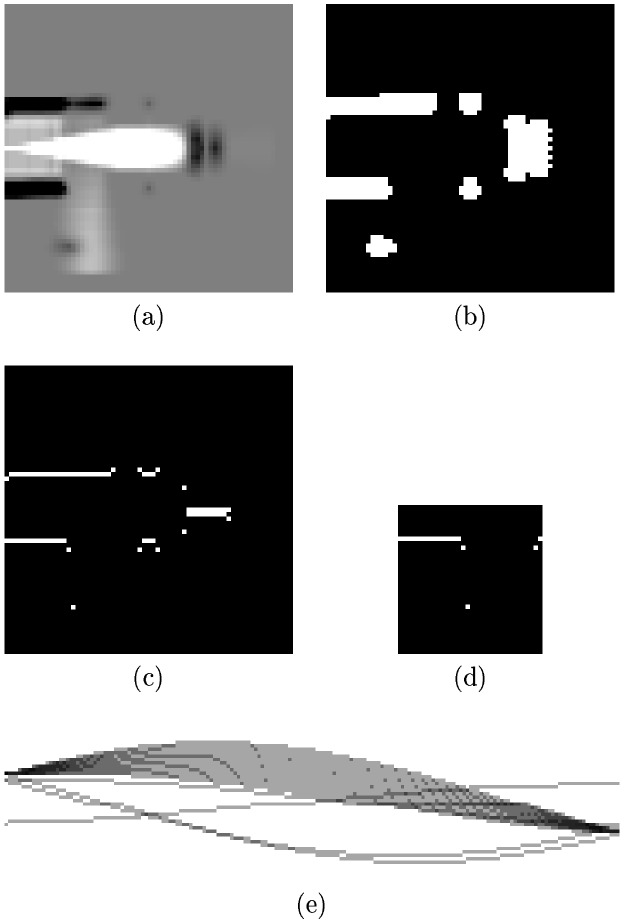

Figure 5: Processing of an evidence grid.

chosen strip. If the opening is wide enough, i.e. about 1m, then it is classified as a door.

The ranger moves back to center itself in the door frame, turns to face the door and launches a scout. After successful deployment, it continues to seek out further rooms until all scouts have been exhausted from the magazine.

4.2 Scout Behaviors

Several simple behaviors have been implemented for the scouts. The only environmental sensor available to the scout is its video camera, the use of which presents several problems. First, the scout's proximity to the floor severely restricts the area it can view at a time. Secondly, since the video is broadcast over an RF link to the ranger for processing, the quality of the received video often degrades due to of range limitations, proximity of objects that interfere with transmission, and poor orientation of the antennas. Figure 6 shows an example image received from the scout's camera.

The behaviors are:

Locate Goal: Determining the location of the darkest (or lightest) area of the room is accomplished by spinning the scout in a circle and checking the mean value of the pixels in the image. Since the scout has no encoders on its wheels to determine how far (or even if) it has moved, frame differencing is used to determine whether motion took place. The circular scan is accomplished in a number of discrete movements. Before each move, the scout must determine the quality of the video and set a threshold to filter out RF noise. It does so by doing image differencing and increasing the difference threshold until noise is no longer detected. Once the threshold is set, the robot rotates for half a second and compares the current image against the previous image. A large difference indicates movement. There are several instances where this approach can fail, however. First, if the transmitted image quality is so low that motion in the image cannot be distinguished from noise. Second, if the robot is operating in an area of very low light or very uniform color, there may not be enough detail in the images to generate significant differences.

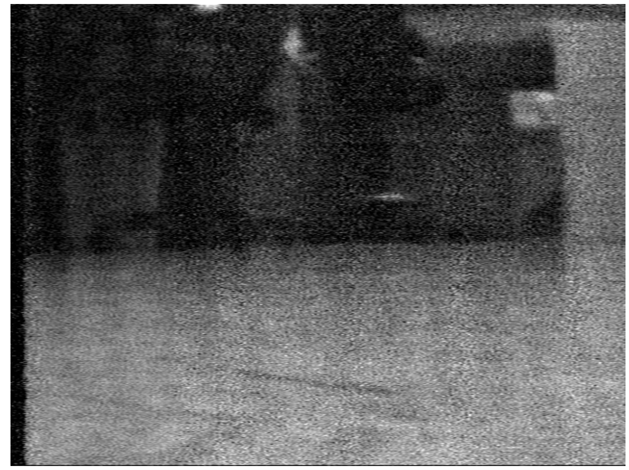

Figure 6: The world from the scout's point of view. Here the scout is viewing a lab bench and two chairs at a range of 2m.

Drive Towards Goal: Moving towards a dark area is a simple matter of scanning across the image at a fixed level on or about the level of the horizon and determining the horizontal position of the darkest area in the image. The mean pixel values in a set of overlapping windows in the image are determined. The robot selects the darkest window and drives in that direction. The robot knows that it should stop when it is either pressed up against a dark object, in which case the entire image is uniformly colored, or it is in shadows and the floor is reflecting roughly the same illumination as what is coming down from above the robot. Scout motion in this behavior is continuous and the scout does not check its movements by frame differencing (unlike the discrete movements of the previous behavior). This is because the scout is unable to move very quickly. The difference between subsequent frames captured during forward motion is minimal, making it very difficult for the robot to detect forward motion.

Detect Motion: Detecting moving objects is accomplished using frame differencing. Once the scout has been placed in a single location, it sets its frame differencing noise threshold. From there, the ranger can activate the scout's camera and determine if there is motion in the field of view of the scout.

Handle Collisions: If the scout drives into an obstacle, all motion in the image frame will stop. If no motion is detected after the scout attempts to move, it will invoke this behavior and start moving in random directions in an attempt to free itself. In addition to unsticking the scout from an object that it has driven into, this random motion has an additional benefit. If the scout is in a position where the video reception quality is extremely bad, the static in the image will prevent the scout from detecting any motion (regardless of whether it is hung up on an object). Moving the scout changes the orientation of the antenna which may help improve reception.

5 Experiments and Results

In order to examine the scout's ability to hide itself in an environment and report back useful data, three different experiments were run.

5.1 Experiment 1

The first experiment was to determine, in a controlled environment, how well the scout could locate and move towards an appropriately dark area. These experiments were designed to examine the scout's behaviors in an analytical fashion.

For the first experiment, a controlled environment consisting of uniformly-colored walls and a single dark object was constructed. An area, roughly a 2.5m × 3m rectangle, was defined. The target was a 1m × 0.5m black rectangle set up on one side of the environment. The robot was started 1.5m away from the center of the target.

Nine experiments were run to see how long it would take the robot to locate the black target object and place itself next to it. A camera was mounted on the ceiling of the room and was used to view the progress of the robot from above. A simple tracking algorithm was used to automatically chart the progress of the scout as it moved towards the target. Figure 7 shows the view from this camera as well as a superimposed plot of the path that the scout took to reach its objective. Figure 8 shows a plot of average distance the scout was away from the target vs. time for all of these runs. In each case, the robot successfully located the target and moved towards it.

Figure 7: Top view of experiment 1.

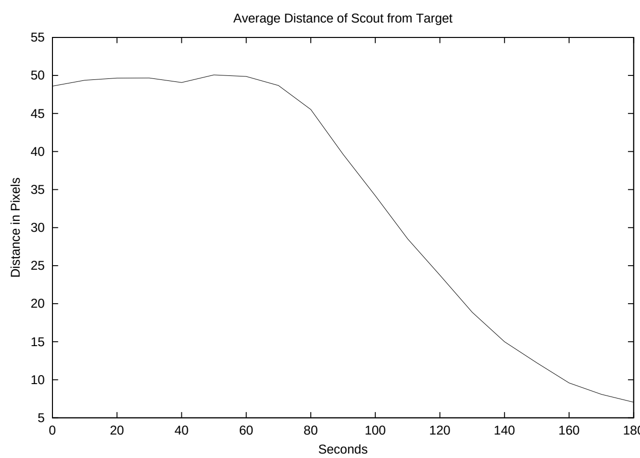

Figure 8: Experiment 1: Average distance (nine runs) of the robot from the target. Distance is in pixels, determined in Figure 7. 1 pixel is approximately 3cm.

5.2 Experiment 2

The second experiment was set up to determine how well the scout could position itself in a more "real world"

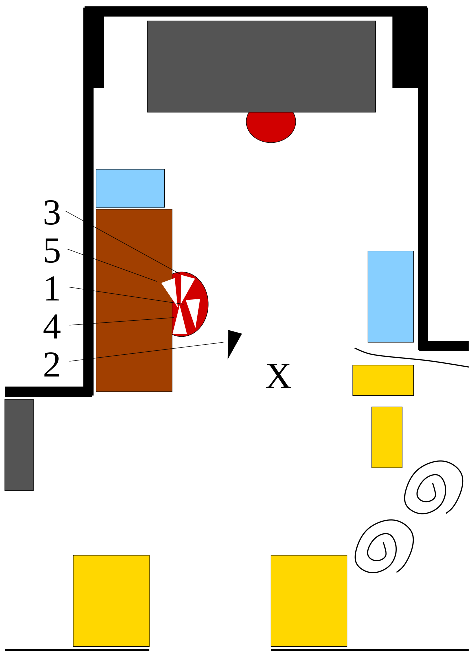

Figure 9: Experiment 2: Lab environment, showing locations of scouts for all five runs. X marks the starting position used in all runs and numbered arrows correspond to final position and orientation for individual runs. Ovals represent chairs under which scouts may hide. Chairs are positioned at a table and a lab bench, both of which also provide hiding opportunities. Other objects are impassable.

environment, meaning that of a somewhat cluttered office or lab space. For these experiments, the scout's ability to locate a dark area was combined with the ability to turn towards the lighter areas and search for moving objects.

Two environments were used for this experiment. One was a lab environment with chairs, a table, lab benches, cabinets, boxes, and miscellaneous other materials (see Figure 9). The other was an office environment with chairs, a table, desks, cabinets, and boxes (see Figure 10). The floor of the lab is a shiny, light tile surface of relatively uniform color whereas the floor of the office is a carpet of medium and dark piles providing a high localized contrast. This difference in surface brightness and contrast were accounted for in the scouts vision behaviors which were effectively self-calibrating. Five runs were conducted in each environment, using a fixed starting point for the scout in each room (shown as an X in Figures 9 and 10).

In four of the five runs in the lab environment, the scout chose the same chair under which to hide (location 1 in Figure 9). On run number 2, however, the scout wound up roughly 0.5 m out from under the chair in a relatively exposed position (location 2 in Figure 9).

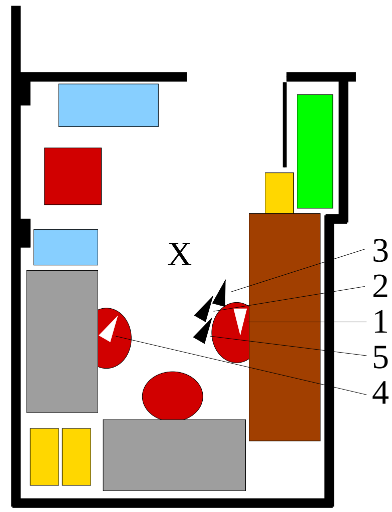

Figure 10: Experiment 2: Office environment, showing locations of scouts for all five runs. X marks the starting position used in all runs and numbered arrows correspond to final position and orientation for individual runs. Ovals represent chairs under which scouts may hide. Chairs are positioned at a table and at two desks, all of which also provide hiding opportunities. Other objects are impassable.

In all five runs the scout ended up facing towards a relatively bright area of the room. However, in run 4 this happened to be towards the rear of the room. Time required for these runs are given in column 2 of Table 1.

Similarly, in four of the five runs in the office environment, the scout chose the same chair as its destination (location 1 in Figure 10). On run 4 the scout chose the other nearby chair (location 2 in Figure 10). In four of the five runs the scout wound up facing brightly lit areas roughly towards the door of the office. On run 1, though, the scout faced a somewhat darker area towards the back of the room. Time required for these runs are given in column 3 of Table 1.

Problems due to poor radio communication between the scout and the ranger caused several runs to have to be aborted and restarted. Other times, the scout's batteries ran out and had to be replaced before the data collection could continue.

5.3 Experiment 3

The third experiment was designed to determine if the combined scout/ranger team could carry out an entire surveillance mission. This mission combines all behaviors described above. The scouts are initially manually loaded into the launcher, mounted on Ranger 1. Rangers 1 and 2 are positioned as shown in Figure 11(a). From there on the actions of the team are autonomous. Ranger 1 moves down the hall, finds doors, and launches

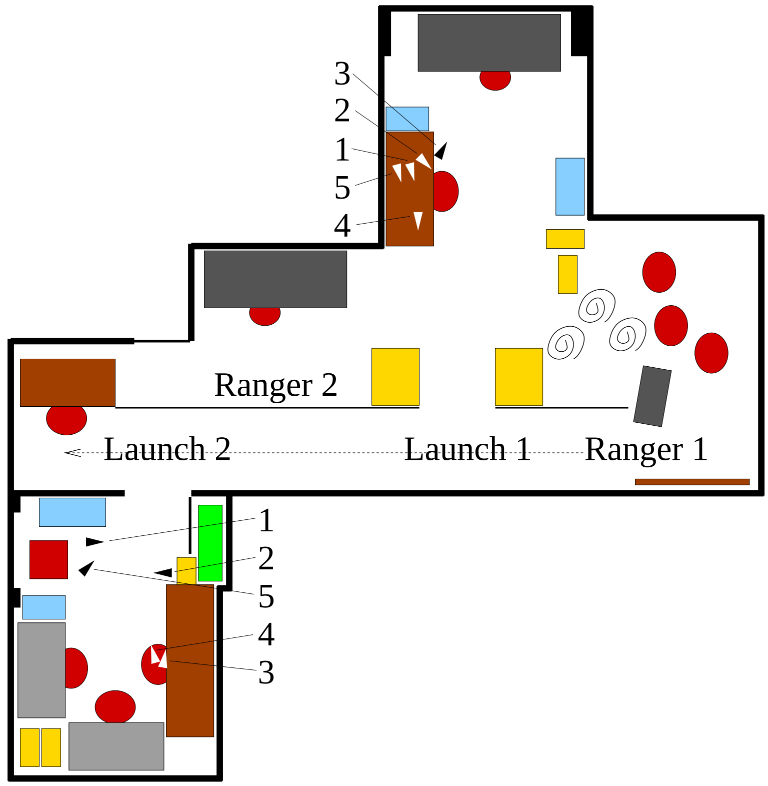

Figure 11: Experiment 3: Coordinated agent behaviors, showing path taken by Ranger 1, launching sites, and final location of scouts on all five runs (numbered arrows showing orientation and position). Ovals represent chairs under which scouts may hide. Chairs are positioned at tables, desks, and lab benches, all of which also provide hiding opportunities. Other objects are impassable.

Run	Lab Environment	Office Environment	Coordinated Actions
1	3	4	11
2	4	4	8
3	3	4	19
4	2	6	11
5	5	4	14

Table 1: Duration of Experiments 2 (Lab and Office Environments) and 3 (Coordinated Actions). Time in minutes.

the scouts through doorways. Each scout, through proxy processing with Ranger 2, finds the darkest area visible from its landing site, drives to the dark area, turns around to face the more brightly-lit room, and begins watching for motion. The final positions of the rangers and scouts are shown in Figure 11(b). Time required for these runs are given in column 4 of Table 1.

6 Conclusions

The system as presented in this paper handles a task where cooperation increases performance by increasing reliability. By having its sensors spread throughout the environment with several agents, rather than concentrated on a single agent, there is less chance of an observation being missed. Further, because some of the agents are small and more easily hidden, even persons attempting to avoid detection by the system are more likely to be detected than in the case of a single, large robotic security guard.

Our future work will be to improve our system to handle security and surveillance tasks that *require* cooperation. For example, in some cases we may want members of our team to work in locations beyond the range of their RF links to one another. That is, while increasing the power and, therefore, the range of the ranger radios would be highly beneficial, there will always be cases where we would need our agents to work at distances where direct communication between supervisors and their subordinates is not possible. We plan to use some team members as mobile communication relays (as well as mobile sensors) to achieve success in such domains.

7 Acknowledgements

This material is based upon work supported by the Defense Advanced Research Projects Agency, Electronics Technology Office (Distributed Robotics), ARPA Order No. G155, Program Code No. 8H20, issued by DARPA/CMD under Contract #MDA972-98-C-0008.

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