A Miniature Robotic System for Reconnaissance and Surveillance[*]

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Abstract

This paper presents a miniature robotic system ("scout") useful for reconnaissance and surveillance missions. A large number of scout robots are deployed and controlled by humans and/or larger "ranger" robots. The specially designed and constructed scouts are extremely small (roughly 116cc volume) yet are readily deployable (by tossing or launching), have multiple mobility modes, have multiple sensing capabilities, can transmit and receive data and instructions, and have a limited capability for autonomous action. The rangers are significantly larger vehicles, based on a commercial-off-the-shelf platform, augmented with scout launchers, radios, and additional sensors. Together, the scouts and rangers form a hierarchical team capable of carrying out complex missions in a wide variety of environments.

1 Introduction

Reconnaissance and surveillance are important activities for both military and civilian organizations. Hostage and survivor rescue missions, illicit drug raids, and responses to chemical or toxic waste spills are just some of the operations requiring a reconnaissance or surveillance component. To address these needs, we have developed a distributed heterogeneous robotic team which is based mainly on a miniature robotic system.

Because some of these operations require covert action, we have chosen to make most of the robots on the team extremely small so that they will evade detection. This small size also allows them to be easily transported and allows for a greater number (dozens) to be brought into use for a single operation. The small size and large number also makes individual robots expendable without jeopardizing the overall mission. We call these small robots *scouts* and they act as the roving eyes, ears, noses, etc. of our system.

The small size of the scouts creates great challenges, however. The individual components must all be exceedingly small and the overall design of the scout must make maximum use of all available space. Further, the scouts must make efficient use of resources (e.g. batteries) in order to survive for a useful period of time. We meet these challenges with an innovative scout design and creative use of additional support.

We team the scouts with larger *ranger* robots. The rangers can transport the scouts over distances of several kilometers and deploy the scouts rapidly over a large area. Rangers also serve to coordinate the behaviors of multiple scouts, and to collect and present the data in a organized manner to the people who will ultimately make use of it.

In this paper, we present the scouts (Section 3) and rangers (Section 4), discussing the capabilities of each (in the case of the ranger the emphasis is on its role as a utility platform for the scouts) and describe demonstrations conducted to test the innovative aspects of the system (Section 5). We also discuss related work (Section 2), analyze our results (Section 6), and draw conclusions about our system (Section 7).

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2 Related Work

Traditionally, mobile robots have ranged in size from roughly dog-sized to somewhat larger than a human. For small robots, Lego blocks and microprocessor boards, such as the Handyboard [6], are often used to quickly prototype robots. We have designed multiple Lego-based robots and used them for a variety of navigation tasks [9].

Recently a significant interest has arisen in designing even smaller mobile robots for exploration and reconnaissance. These include the popular Khepera robot, designed at the Ecole Polytechnique Federale de Lausanne for robotics research [7], and other prototypes developed by various research groups and not commercially available.

The major challenge in designing miniature robots is in fitting all the mechanical parts and electronics into a limited volume and in designing an adequate method of locomotion. Many miniature robots have wheels [1], but others can jump [4], roll [2], fly [10], swim [3], or float in space as the Personal Satellite Assistant from NASA Ames [8]. Our miniature robots have two rolling wheels but can also jump to go over small obstacles, as shown later in Figure 6. Due to the small size, most miniature robots use proxy processing, as in [5], and communicate via a radio link with the unit where the computation is done.

3 Scouts

Scouts must be small yet highly capable robots. They must be easily deployable and able to move efficiently yet traverse obstacles or uneven terrain. They must be able to sense their environment, act on their sensing, and report their findings. They must be able to be controlled in a coordinated manner.

To support all of these requirements, we have designed a robot 40mm in diameter and 110mm in length (see Figure 1). Its cylindrical shape allows it to be deployed by launching it from an appropriate barreled device (see Subsection 4.1). Once deployed, it moves using a unique combination of locomotion types. It can roll using wheels (one on each end of the cylinder body) and jump using a spring "foot" mechanism. The rolling allows for efficient traversal of relatively smooth surfaces, while the jumping allows it to operate in uneven terrain and pass over obstacles.

Besides the mechanical components, scouts contain a vast array of electronic devices (see Figure 2). Each scout is provided with a sensor suite, which may vary with the scout's mission. All scouts contain magnetometers and tiltometers. Scouts may also contain some combination of a CMOS camera, a passive infrared sensor, a microphone, a MEMS vibration sensor, a MEMS gas sensor and other sensors. The camera may be mounted on a pan-tilt mechanism or in a fixed position within the scout body. The scouts contain transmitters/receivers for transmitting video and audio signals and other sensed data and for receiving commands. The scouts contain microcontrollers for radio/network management and implementation of autonomous behaviors.

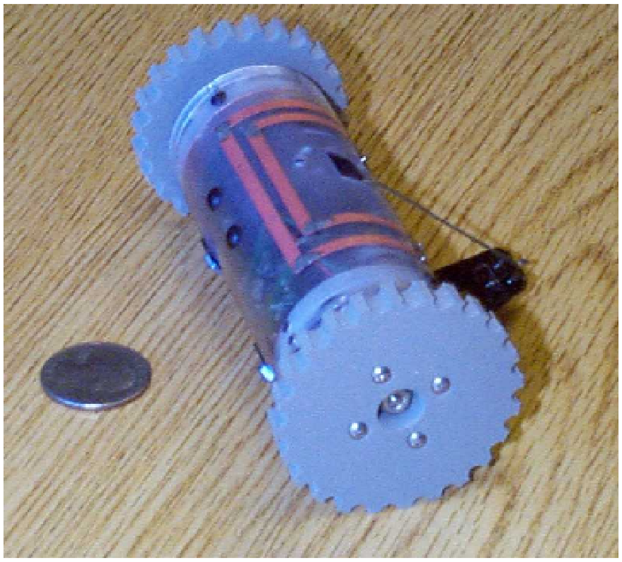

Figure 1: An assembled scout, ready for operation (shown next to a quarter for scale).

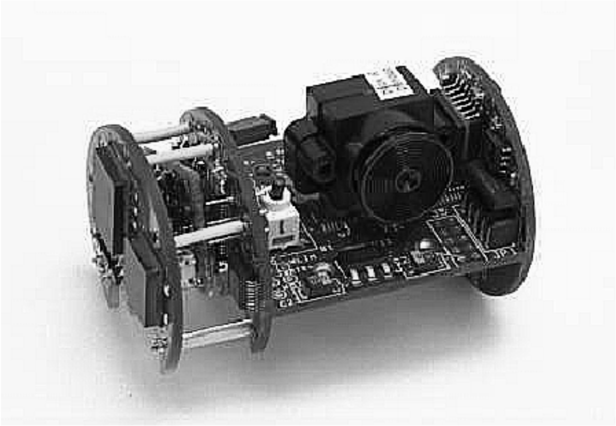

Figure 2: Scout's internal structure.

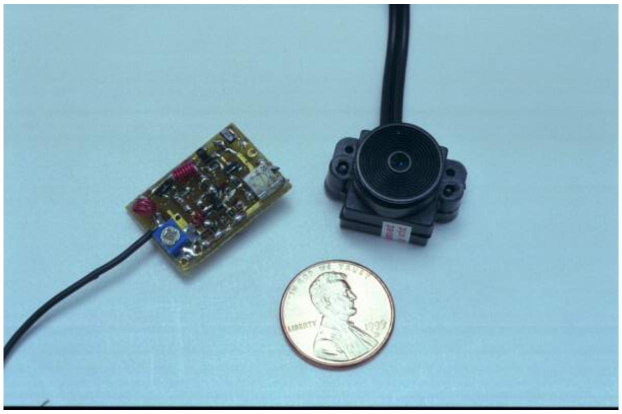

Figure 3: The scout camera and transmitter (shown next to a penny for scale).

3.1 Scout Video

A video reconnaissance module that consists of a miniature video camera, an optional pan-tilt mechanism, and a wireless video transmitter was built to provide visual feedback from the scouts. The camera consists of a single-chip CMOS video sensor and a miniature pinhole lens. Unlike the common CCD type video sensors, the CMOS sensor is able to integrate all functionality within a single chip, reducing its size dramatically. Additionally, CMOS sensors typically consume 3 to 5 times less power than a comparable CCD sensor. The overall dimensions of the camera are 15x15x16mm and the power consumption is 100mW.

A pan-tilt mechanism provides increased field of view to the camera. Micromotors, which became recently available, are utilized for actuation. These brushless dc motors are only 3mm in diameter and 15mm in length. They contain a 3-stage planetary gearbox with a 1:125 reduction ratio. The video is sent back to the ranger through a wireless video transmitter working at the 900MHz band. The wireless video transmitter may also be used to send audio signals.

3.2 Scout Audio

Another payload that the scout may carry is audio. The scout audio circuit makes use of a 6mm diameter electret condenser microphone with a sensitivity of -45 ± 4dB. The audio signal is conditioned using a noise gating preamplifier with a variable compression (amplification) feature. The low-end cut off of the transfer function is -25.7dBu (40mV) and the high-end attenuation point is -7.7dBu (320mV). All signals within that range are amplified to near the high-end attenuation point. The audio signal is transmitted to a host system for post processing via the scout's 900MHz video transmitter.

3.3 Scout Communication

For other communication with the scouts a miniature transceiver has been developed that employs OOK modulation and operates at 434MHz. The communications make use of a media-access control (MAC) protocol implemented on a Scenix SX processor using RF Monolithics Virtual Wire components. The MAC's reliable delivery scheme is augmented with a version of Architecture Technology Corporation's Source Adaptive Routing Algorithm (SARA) that has been simplified to operate within the confines of the SX processor's 2-KB program ROM and 128-byte RAM. The simplified SARA implementation allows RF nodes (rangers or scouts) to act as routers in order to increase end-to-end communications range. As the nodes move, routing information is dynamically updated throughout the wireless network.

3.4 Scout Microcontrollers

Each scout uses two Scenix SX microcontrollers for radio/network management and general-purpose computing. (Each ranger also uses one SX for radio/network management for communication with the scouts. See Subsection 4.2 for details of other ranger computing resources.) The Scenix SX 8-bit microcontrollers are fabricated with an advanced CMOS process technology. This advanced process, combined with a RISC-based architecture, allows high-speed computation, flexible I/O control, and efficient data manipulation. Throughput is enhanced by operating the device at frequencies up to 50 MHz and by using an optimized instruction set that includes mostly single-cycle instructions. The SX is a single-chip Harvard architecture microcontroller that incorporates clock, RAM, ROM, and I/O functions on a single chip.

A distinguishing feature of the SX family is the reliance on "virtual peripherals." Peripheral functions are implemented in software (rather than hardware) with the aid of a deterministic interrupt system and the SX's very high throughput. Virtual peripherals used in the Scout include dual 10-bit sigma-delta ADCs, multiple specialized timers, triple bi-directional PWM motor controllers, dual PWN inputs, non-volatile serial memory driver, a duplex Manchester coding radio interface, and a standard asynchronous UART.

The scouts contain two Honeywell single-axis magnetometers (HMC1021S and HMC1021Z) for determining a compass heading, and an Analog Devices two-axis accelerometer (ADXL202AQC) for determining the rotation of the body about the roll axis (i.e., tilt). The magnetometers have a full-scale range of ±6 gauss (earth's field ≈ 0.5 gauss), and a resolution of about 85μgauss. The accelerometers have a full-scale range of ±2g, and a resolution of about 5mg.

4 Rangers

The scouts function in conjunction with the rangers which act as utility platforms. Rangers move the team rapidly into place and deploy the scouts. They process the sensor data as needed for scout behaviors and group behaviors and act as coordinators for the team. Finally, they organize the data streams for presentation to people.

Our rangers are based on the ATRV-Jr.™ platform from the RWI Division of IS Robotics. The "Junior" was developed by RWI with input from our team and others wanting a smaller platform than the existing ATRV-2™, suitable for both outdoor and indoor operation.

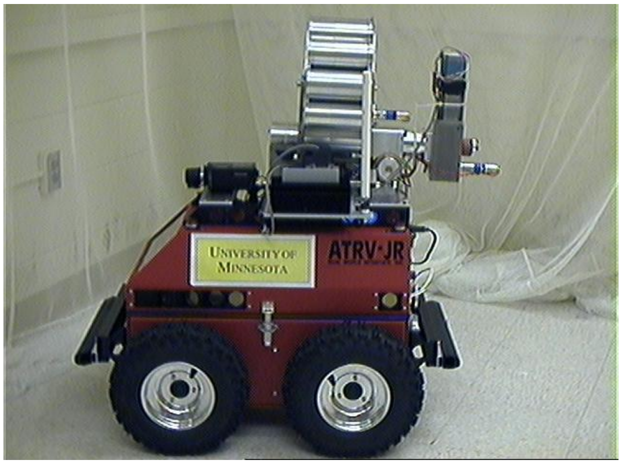

Figure 4: A ranger with scout launcher.

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 each ranger (see Figure 4), scouts may be deployed more rapidly and into places rangers might have difficulty accessing. Rangers also are equipped with significant computing resources that allow for proxy processing for scout behaviors and for mission coordination.

4.1 Launcher

The launcher system is used to deploy the scouts around the field of operation. 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. A stepper motor is used to compress the spring via a rack and pinion setup. The pinion is engaged to the motor when the spring is to be cocked and is disengaged when the scout is launched. The mechanical energy efficiency is about 45% due to the weight of the piston and the rack and pinion mechanism. The indexing of the magazine to select a particular scout is achieved accurately with an internal Geneva mechanism, without the need of an encoder.

4.2 Ranger Computer Resources

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). Ranger-to-ranger data communications are implemented using a 2.4GHz frequency-hopping wireless LAN system.

5 Experimental Results

To test the innovative aspects of our system, we conducted two basic sets of tests. The first set was aimed at testing the capabilities of our scout robots alone and the second was aimed at testing the survivability of our scouts when deployed and controlled by the rangers.

5.1 Scout Capabilities

To test the capabilities of individual scout robots, we constructed an obstacle course (see Figure 5). The five major components of the obstacle course are:

Alley The scout must follow a straight path between two large obstacles without hitting either. The obstacles form an alley 1m in length and 0.4m wide.

Ramp The scout must roll up a ramp at a 20° incline then, from the top of the ramp, jump or fall back to the floor. The scout must not fall from the sides of the ramp nor roll back down the incline.

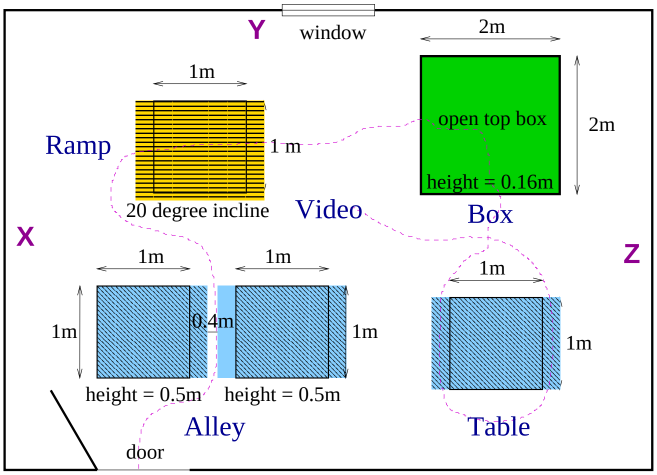

Figure 5: The obstacle course.

Box The scout must jump into and out of an open box (see Figure 6). The height of the box's walls is 0.16m.

Table The scout must circle around a 1m square table without touching it.

Video The scout must drive to the center of the room and look for items of interest around the room. These were large letters affixed to the walls of the room at a height of 1.5m (X, Y, and Z in Figure 5).

Besides success or failure at completing each component of the obstacle course, we measured time required to complete the entire course. During this test, the scout was teleoperated by the same human operator. The results are given in Table 1. In the table, superscripts indicate different events during the trial while the numbers in the middle five columns indicate the frequency of a specific event. The maximum jump had a height of 0.25m

We also tested the audio unit and were able to receive audio even when the audio scout was 20m away. The pan/tilt module was tested five times. The deployment lasted 10s on the average and we were able to perform a tilt of 90° and a pan of 360°. The average time for pan was 4s and for tilt was 2s.

We also tried to find the narrowest corridor (0.2m) that the scout could master. It traversed this corridor (length 1.2m) without touching its walls in 9s. We also checked the maximum range of communication (indoors) for the ranger-scout model. We found this range to be 9.5m. With a scout as a repeater, this distance almost doubles.

Trial	Alley	Ramp	Box	Table	Video	Time
1	ok	ok	ok	ok	ok	6:30
2	ok	ok	2[3]	ok	ok	6:59
3[1]	ok	ok	ok	ok	ok	7:02
4	ok	ok	ok	ok	ok	7:30
5[2]	ok	ok	1[3]	ok	ok	8:45
6[2]	ok	1[4]	ok	ok	ok	5:50
7	ok	ok	ok	ok	ok	4:28
8	ok	ok	ok	ok	ok	4:52
9	ok	ok	ok	ok	ok	7:28
10	ok	ok	ok	ok	ok	7:18
11[2]	ok	ok	ok	ok	ok	7:12
12[2]	ok	ok	ok	ok	ok	7:52
13[2]	ok	ok	1[3]	ok	ok	10:05
14[1]	1[3]	ok	1[3]	2[3]	ok	9:15
15	1[3]	ok	ok	ok	ok	5:55

Table 1: Scout performance on obstacle course. Time is in minutes. Numbers in middle five columns indicate frequency of specific errors, "ok" indicates perfect performance. Possible errors: for Alley and Table, collision; for Ramp, falling off side; for Box, missed jump. The superscripts indicate reasons for suboptimal performance. [1]Faulty reassembly of scout after battery change. [2]Manual reset of scout required. [3]Operator error. [4]Loss of communication link.

5.2 Launching and Survivability Tests

The objective was to test the basic functionality of the ranger-scout system and the durability of the scout. First, the ranger launched a scout through a glass window (Figure 7). The launching distance was 5m and the height was 2m. The scout needed to survive both the launch and landing as demonstrated by rolling and hopping when powered on after impact. We repeated this experiment twice. In both cases, the scout survived the impact. In two other tests, a human tossed a scout 21m and 25m. Similarly to the previous trials, the scout was functional when powered on after impact. In a final experiment, the ranger launched four scouts in a single room. In this experiment the scouts were launched already powered on. Three out of the four scouts were functional immediately after the launch while the fourth needed a manual power cycling to restart.

6 Analysis

One of the major issues of the whole system is the power consumption. We can currently perform eight jumps of 0.25m on a set of nine 3V batteries. A single scout in idle mode has a power draw of 1.725W,

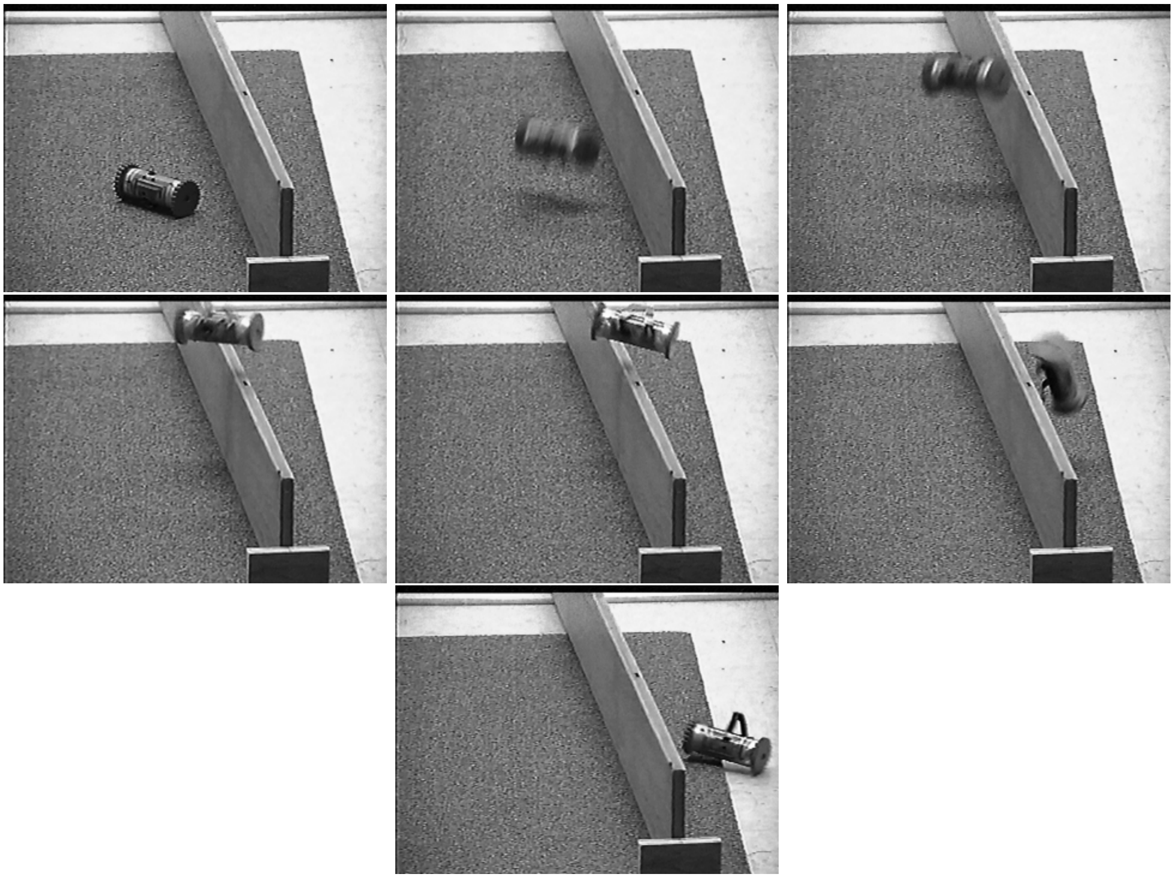

Figure 6: A scout jumping over a barrier (sequence starts from the upper left corner).

Figure 7: Launching a scout through a window.

while rolling over a level surface it has a power draw of 2.145W, and during video transmission the power draw is 2.040W. However, the most expensive action is “winching in” the spring foot with a power draw of 3.465W.

We plan to address the issue of power consumption in the following ways. (1) By reducing the speed of both CPUs to 20MHz from 50MHz we can save 1W. (2) By using 3.3V parts we can save another 0.23W. (3) By using a chopper power supply (vs. linear) we can save another 0.15W. Our goal is to have a power draw of 0.345W in idle mode which would give a five fold or greater increase in battery life.

Due to the power requirements for jumping, we plan to revisit the design of the jumping mechanism. Hardening the scout is important in order for the scout to survive long distance launching. Finally, we need to extend the communication range between the ranger and the scout, to improve the human-ranger-scout interaction, and address the miniaturization of other sensors which are useful payloads for the scout.

7 Conclusions

We have presented an innovative miniature robotic system called the scout which is the basis of a large heterogeneous distributed robotic team. The scout effectively combines rolling and jumping locomotion capabilities. It has a small size that makes it suitable for several challenging reconnaissance and surveillance tasks. It can be deployed manually or by a launcher. The scout functions in conjunction with a larger utility platform which is called the ranger. Both systems carry a large number of processing, communication, control, and sensing modules that make the whole system an effective reconnaissance tool. Experimental results are given which highlight the effectiveness of the scout design.

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