Autonomous mobile communication relays

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ABSTRACT

Maintaining a solid radio communication link between a mobile robot entering a building and an external base station is a well-recognized problem. Modern digital radios, while affording high bandwidth and Internet-protocol-based automatic routing capabilities, tend to operate on line-of-sight links. The communication link degrades quickly as a robot penetrates deeper into the interior of a building. This project investigates the use of mobile autonomous communication relay nodes to extend the effective range of a mobile robot exploring a complex interior environment. Each relay node is a small mobile slave robot equipped with sonar, ladar, and 802.11b radio repeater. For demonstration purposes, four *Pioneer 2-DX* robots are used as autonomous mobile relays, with SSC-San Diego's *ROBART III* acting as the lead robot. The relay robots follow the lead robot into a building and are automatically deployed at various locations to maintain a networked communication link back to the remote operator. With their on-board external sensors, they also act as rearguards to secure areas already explored by the lead robot. As the lead robot advances and RF shortcuts are detected, relay nodes that become unnecessary will be reclaimed and reused, all transparent to the operator. This project takes advantage of recent research results from several DARPA-funded tasks at various institutions in the areas of robotic simulation, wireless ad hoc networking, route planning, and navigation. This paper describes the progress of the first six months of the project.

Keywords: robotics, communications, RF, relays, 802.11, ad hoc networking

1. OBJECTIVES

One of the vulnerabilities of current mobile robots operating in real-world scenarios is the communication link to the operator's console. Fiber-optic cables reduce mobility and often become entangled and broken, rendering the robot inoperable. User surveys have identified radio-frequency (RF) communications systems as more desirable.[1,2] However, most RF communication systems currently employed on teleoperated robots in the field are analog, which very often experience signal interference, multipath, and attenuation problems when used in an urban environment. Spread spectrum digital systems are more immune to these problems and provide a level of transmission security, but operate at shorter ranges and mostly on line of sight.

To extend the range of digital radios and provide non-line-of-sight service, the use of dropped static relays or autonomous robots as relays have been discussed, usually in the context of a larger project, from creating a network of distributed mobile sensors[3] to exploring for life on Mars.[4] Our project goal is to move this concept out of the discussion and simulation stages and demonstrate it using real hardware to solve a real-world problem.

We want to automatically maintain a solid high-bandwidth digital RF communication link between a robot exploring a large indoor environment and the operator stationed outside the building. This task must be performed without operator intervention or—under ideal conditions—knowledge. This task could be accomplished simply by having the robot drop relay units behind it at critical junctions, where relays are needed. However, since the lead robot is exploring an unknown environment, its wandering may often lead to situations where intermediate relay nodes are no longer needed

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(RF shortcuts are encountered). To maximize resources and allow for extended explorations, unneeded relay nodes should be reclaimed and reused. We propose to perform this function through the use of mobile relay nodes that follow the lead robot in convoy fashion into a building, stop and act as relay nodes where needed, and (when no longer needed) catch up to the lead robot to be redeployed. With minimal additional sensory hardware, these relay nodes will also act as rearguards, preventing areas previously tagged as clear of hostile elements by the lead robot from being re-occupied without detection.

2. APPROACH

This project will be conducted in two phases. Phase 1 will address the deployment of static relay units and establishing a relaying network. However, it will lay the foundation for phase 2 by using mobile relay nodes. The specific steps to be accomplished in phase 1 include:

1. Developing a convoying strategy to allow four mobile relay robots to follow a teleoperated lead robot into a building.
2. Developing a strategy for deploying the relay nodes at appropriate locations. Since there can be many RF nulls (locations where the RF signal strength is locally low), this most likely involves the lead robot issuing a command for a relay robot to stop only when the received signal strength at its end has decreased beyond a set point and further forward movement fails to improve it.

In phase 2, the re-deployment and rearguard functions are addressed. The ability of the relay robots to find and catch up to the lead robot means that a map is needed. (Two robots can be in RF range of each other, but far enough to be outside visual range. Navigation by RF direction is also very difficult in an indoor environment.) Thus the specific steps of phase 2 are:

1. Acquiring a real-time mapping ability for the lead robot. The lead robot will map the environment as it passes through it.
2. Adding the ability for the lead robot to pass the map back to a relay node it needs to recall.
3. Developing the navigational skill to allow a relay robot to catch up to the lead robot to be reused.
4. Adding rearguard functions (detection of intruders) to deployed relay nodes.

3. HARDWARE CONFIGURATION

To leverage our existing pool of laboratory robots, we are using *ROBART III* as the lead robot and ActivMedia *Pioneer 2-DX*'s as the relay robots for project demonstrations. A transition to the real world (and possibly also outdoor scenarios) will probably require more rugged tracked robots that can handle more unpredictable terrain. Below is a brief description of the project hardware, including lead robot, relay robots, and the RF modems used.

3.1 Lead robot

ROBART III, developed in-house by the Space and Naval Warfare Systems Center, San Diego (SSC San Diego), is used in the role of lead robot (Figure 1). *ROBART III* is intended as an advanced technology-base development and demonstration platform for non-lethal tactical response, extending the concepts of supervised autonomy and reflexive teleoperation into the realm of coordinated weapons control (i.e., sensor-aided control of mobility, camera, and weapon functions) in law-enforcement and urban warfare scenarios. A rich mix of ultrasonic and optical proximity and range sensors facilitates remote operation in unstructured and unexplored buildings with minimal operator oversight. Supervised autonomous navigation and mapping of interior spaces is significantly enhanced by an algorithm that exploits the fact that the majority of man-made structures are characterized by parallel and orthogonal walls.[5]

ROBART III has been equipped specifically to support supervised operation in previously unexplored interior structures. The system has been operational in both autonomous mode as well as reflexive teleoperation mode since 1997, supporting extensive testing and evaluation of the high-level drive control interface by a variety of users. The resulting feedback has significantly influenced subsequent upgrades to both hardware and software.

Two self-contained Electro Corporation piezoelectric PCUC-series ultrasonic sensors operating at 215 KHz are used to generate range data for the wall-following algorithm. These sonar sensors operate at a much higher frequency than the 49.4-KHz Polaroid sensors (14 of which are used for collision avoidance), so there are no problems associated with cross talk from simultaneous operation of both types. In addition, the higher frequencies support better accuracy with a maximum effective range of about 6 feet, which is ideal for wall following. (The shorter effective range limit allows the left and right sonar sensors to asynchronously operate without mutual interference, for a faster update rate).

In support of the collision avoidance and world-model-generation needs of this project, the Hammamatsu *Triangulation Ranging Module* currently located on the left shoulder pod will be replaced by a SICK *LMS200 2-D Scanning Laser Rangefinder* mounted on the mobility base. In addition, the line-oriented video motion detection hardware, initially developed in 1988 for *ROBART II,* proved to be fairly inadequate in very dynamic intruder-tracking scenarios, due to the limited resolution and update rate. Current efforts are underway to upgrade to the stereoscopic SRI *Small Vision Module* for dual use as an intruder-detection and target-tracking sensor, in addition to collision avoidance. A KVH fiber-optic gyro has also been incorporated for improved dead-reckoning accuracy. The master onboard processor has been upgraded from a 68HC11-based microcontroller to a more powerful Bright Star Engineering (BSE) *ipEngine*. The credit-card-sized ipEngine hosts a 66 MIPS PowerPC CPU, 2 MB of flash memory, 16 MB of RAM, 16,000-gate FPGA, and dual RS-232 and 10Base-T Ethernet ports. The FPGA can be configured to provide additional input/output ports for various sensors.

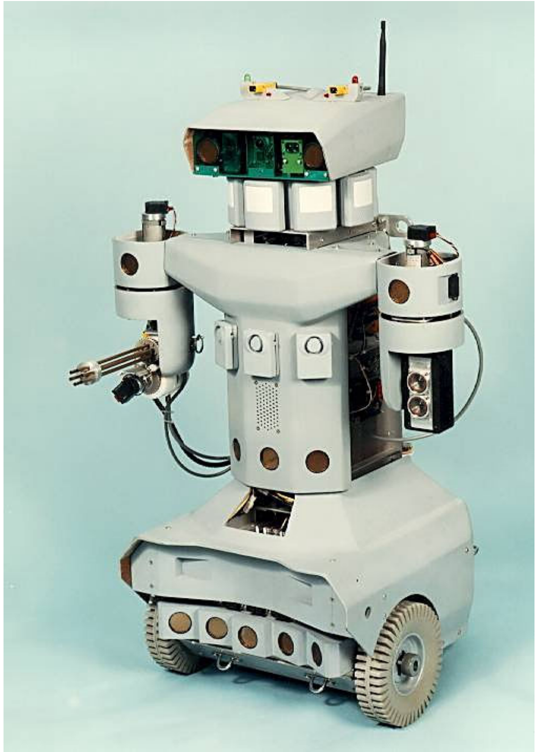

Figure 1. ROBART III

3.2 Rearguard/ relay nodes:

For use as the rearguard/relay nodes, we equipped four *Pioneer 2-DX* robots with a suite of navigation and security sensors, processors, and RF modems. Figure 2 shows one of the Pioneer robots as configured for our project, and an exploded view showing the added components. For navigation, each Pioneer robot comes with built-in front and rear rings of sonar sensors. We added a SICK *LMS200* laser radar (ladar) and a magnetic compass (on a long boom to remove it from possible magnetic interference from the large metallic robot chassis). The ladar and sonars will allow the Pioneers to avoid obstacles and navigate through their environment while following the lead robot. When in recall-for-redeploy mode, the Pioneers will have to localize and orient themselves to the map passed back from the lead robot. The compass will provide a rough heading direction to allow the Pioneer to register its internal local map with the lead robot's map.

To provide rearguard functions, we installed on each Pioneer a Sony pan-tilt-zoom (PTZ) camera and a microphone. These will be used in conjunction with the sonars and ladar for intrusion detection in areas that the lead robot has passed through and are supposed to be clear of hostile elements.

Processing power is provided by two BSE *ipEngine* boards and an Indigo Vision *VP500* video CODEC board. Both *ipEngines* run BSE's embedded Linux. One *ipEngine* hosts robot device drivers and interfaces with the lower level components on the Pioneers. The other hosts higher-level software and interfaces with SSC's Multiple Resource Host Architecture (MRHA),[6] which allows the *Pioneers* to integrate smoothly with the rest of SSC's robot fleet and control stations.

The *VP500* video CODEC board forwards audio from the microphone and video from the PTZ camera to the Ethernet input of the radio modem in a separate channel from the processor boards (i.e., video images do not pass through the *ipEngines*). The *VP500* has its own advanced image processing and motion detection functions, taking the processing load off the two *ipEngines*.

We also added a small caster to the front of the *Pioneer* robots. This caster does not contact the floor in normal operation, but prevents the robot from falling forward in case of a sudden stop, since the center of gravity has been raised with the added equipment.

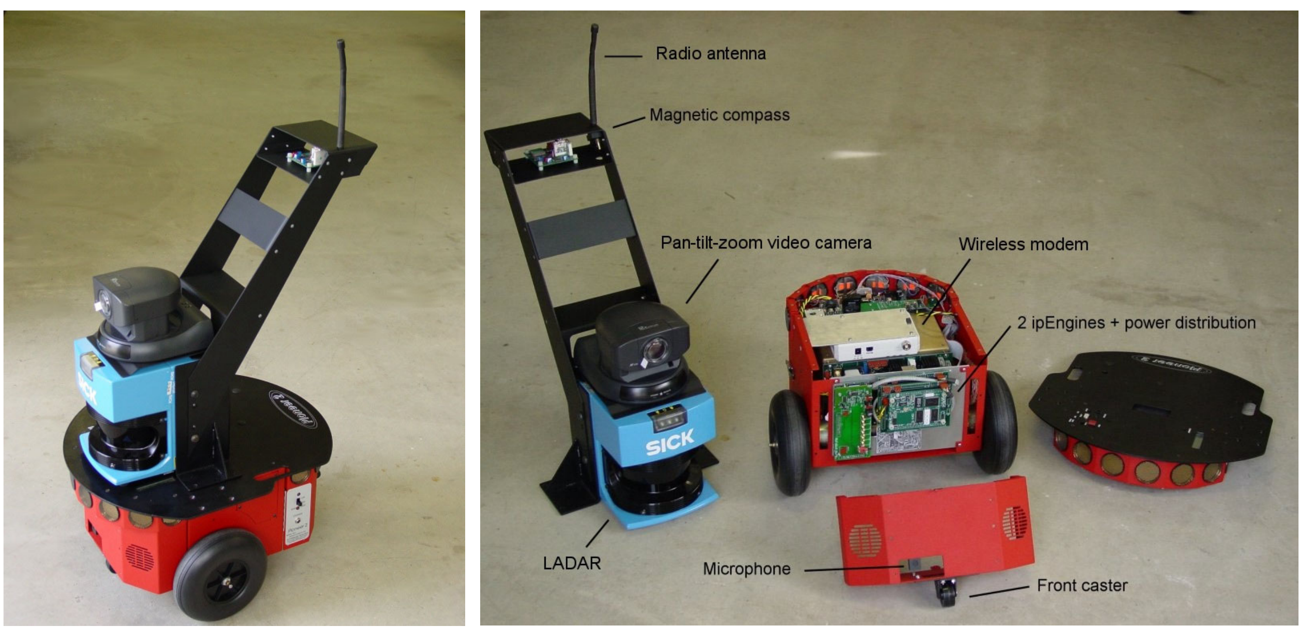

Figure 2. One of our four *Pioneer* robots, configured as an autonomous mobile communication relay and rearguard (left). Exploded view shows components that we have added (right).

3.3 Compact ad hoc networking wireless modems

There are several problems with currently available IEEE 802.11-type wireless modems that make them difficult to use in a mobile robot-based network. The first is the size factor. Most are either rather large or require two units (access point and bridge) to operate in relay mode. The second issue is the inefficiency in network reorganization in the presence of node mobility. To solve these problems, we are working with BBN Technologies to implement a new ad hoc networking solution developed separately by BBN under the DARPA/ITO's Software for Distributed Robotics (SDR) program. BBN's ad hoc networking software uses a proactive link-state protocol.[7,8]

Each node in the network has complete information about the characteristics of the links. It can execute a routing algorithm of its choice and determine the paths most suitable for the chosen criteria. Each node uses broadcast messages (sent at intervals determined by the network criteria and the environment) to determine the characteristics of the links and set up the routing table. The routing table is recomputed whenever certain network events occur, such as when the link quality between two nodes has dropped below the appropriate level for a desired scenario. Thus the routing table can be updated before a link goes down, and the network is automatically maintained for optimal information transmission and minimal lag. There is no delay incurred for route re-selection due to broken links.

We are working with BBN to package this software into a set of compact ad hoc networking wireless modems, each the size of a pack of playing cards. Each modem will contain an 802.11b wireless LAN card (the ORiNOCO *WaveLAN* PC Card Gold), a BSE *nanoEngine* (a 1.4" x 2.4" processor card with a 200 MHz *StrongARM* CPU), and an interface card being developed by us. Each radio will have connectors for external power and antenna, as well as Ethernet and serial communication ports.

4. SOFTWARE DEVELOPMENT

4.1 Relay Robot Software

We are currently writing software for the *Pioneer* relay robots using a set of tools developed by the Robotics Laboratory at the University of Southern California, namely the *Stage* simulator and the *Player* robot device server. *Player* comprises a set of drivers that provide Unix-file-like read/write access to individual devices on the robots.[9] Most devices associated with the *Pioneer 2-DX* have been modeled, including mobility-related components, the integrated sensors, SICK laser, etc. *Stage* is a graphical user interface and simulator for the robot devices and environment.[10] It loads a binary image file for use as a map of the operating environment, spawns simulated *Player* devices as specified in a configuration file, and runs external high-level programs that control the robots' behaviors. Figure 3 shows a screen shot of *Stage* running a convoying simulation using retroreflective beacons (discussed later in section 4.3). High-level software developed on *Stage* is directly transferable to the Pioneer robots, where real *Player* devices will replace the simulated instances.

4.2 Convoying Strategy

We planned on having the relay robots closely following the lead robot as it advances into the building interior, and dropping off at critical points as needed. Although intuitive, this is not the only deployment strategy that would achieve a relaying network. Relaying nodes could stay at the base station, to be called by the lead robot as needed, or a heuristic could be developed that spreads out the nodes as they advance—a compromise between the first two strategies. The Laboratory for Perceptual Robotics at the University of Massachusetts, Amherst, has developed a program that can simulate these various convoying strategies, as part of another DARPA/ITO SDR project that explores techniques for exploiting redundancy in teams of mobile robots.[11] The goal of this simulation program was to maintain a chain of line-of-sight links between the lead robot and the root node. However, as mentioned earlier, modern high-bandwidth radios also operate mostly on line-of-sight links. Thus we obtained a copy of this simulation program and experimented with the various strategies. Indeed, the strategy where all relay nodes closely follow the leader resulted in the fastest time to the goal for the lead robot, with the fewest number of pauses (Figure 4). The strategy where the relay nodes only move when called by the lead robot resulted in the least energy expenditure by the system, but the longest time for the lead robot to reach the goal. Since one of our design criteria was the automatic and transparent deployment of relay nodes with minimal or no impact on the lead robot's mission, the first strategy was indeed the correct choice.

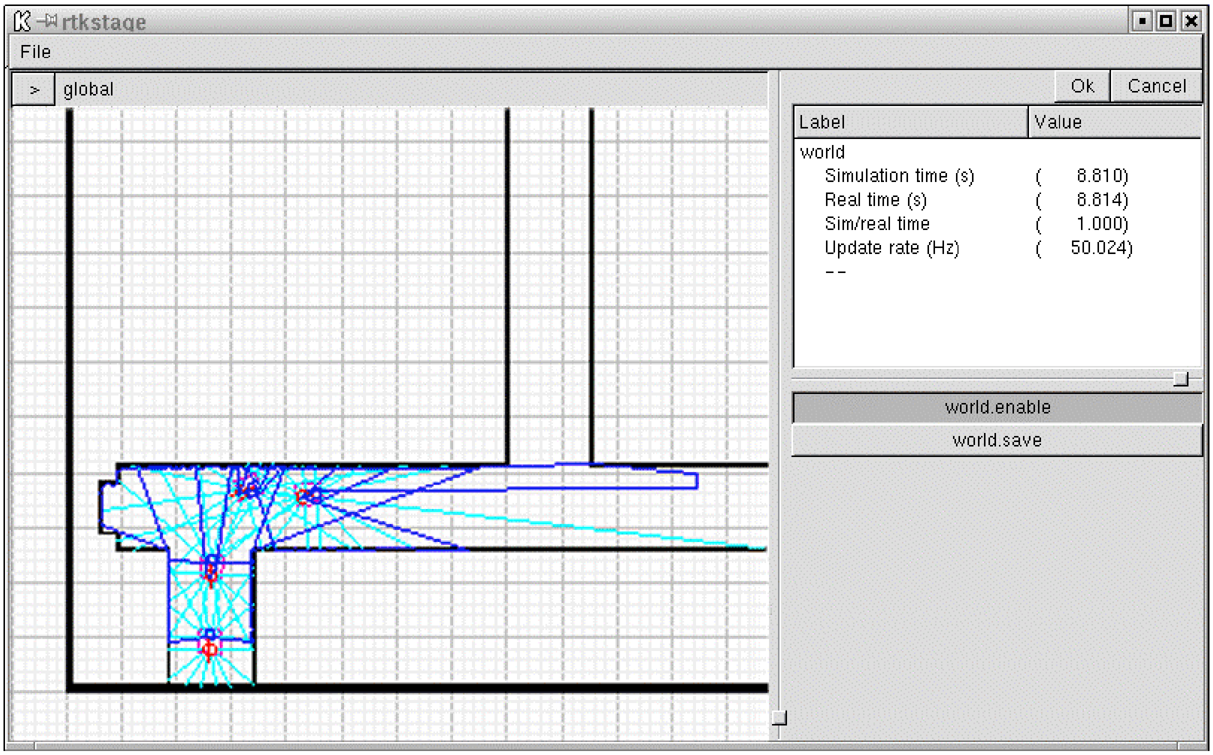

Figure 3. A simulation of the convoying behavior using laser-retroreflective beacons mounted on the back of each robot. The lead robot is moving randomly. The dark lines outline the areas visible to each ladar. The light lines represent sonar pings.

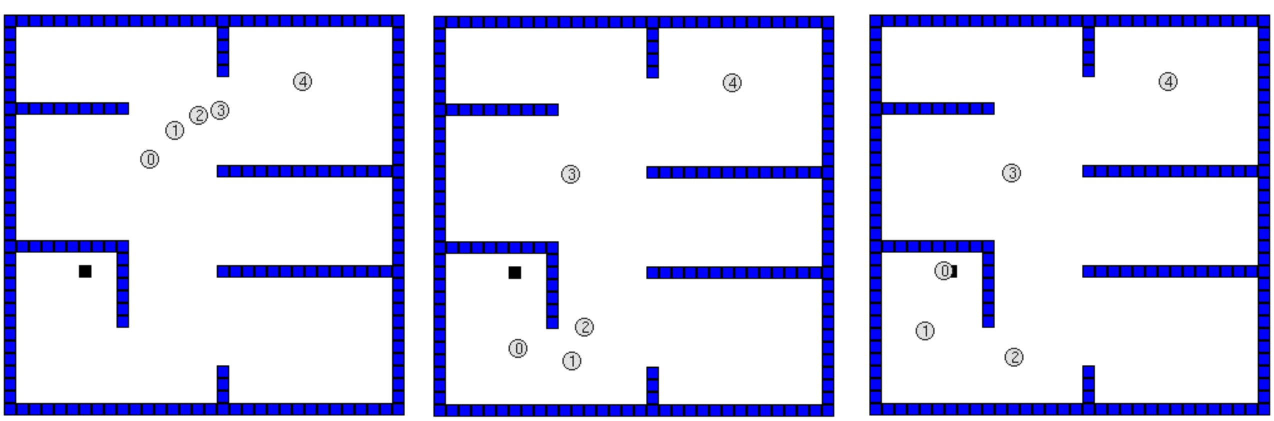

Figure 4. A simulation of the convoying strategy, developed by the University of Massachusetts, Amherst. Robot 0 is the leader, who is trying to reach the goal (black square). Robot 4 is the base station. The others act as relay nodes.

4.3 Retroreflective Laser Beacons

We are using the SICK ladars for both obstacle avoidance and convoying. The *Player* library includes a retroreflective laser device normally used for locating fixed retroreflective tags mounted on walls. We configured this *Player* device for smaller tags that can be mounted on the back of each robot. The tags are constructed using 1" strips of retroreflective tape, arranged in 5-bit binary patterns. The *Player* device required the first and last bit to be 1 (reflective), so we are left with eight possible IDs (17 through 31, in increments of 2). Figure 5 shows the retroreflective tag with ID of 21 on the back of one of the Pioneer robots. We tested the tags with this configuration, and the beacons were detectable to 12 ft and identifiable to 6 ft.

With the above parameters, we developed a simulation of the convoying behavior with retroreflective laser beacons using the *Stage* simulator (see Figure 3). We are in the process of transferring this software onto the *Pioneer* robot for real-world testing. We also set up and operated several SICK lasers with several retroreflective tags simultaneously, in the configuration they would encounter in the real world, and tested for interference between the lasers. No interference was found. This is as expected since the SICK lasers operate on time-of-flight principle.

Figure 5. A *Pioneer* robot with laser-retroreflective tape attached to the back. This unit's beacon ID is 21 (10101_2).

5. CURRENT STATUS

We are currently a little over six months into this planned two-and-a-half year project. The hardware and software infrastructures are largely in place. We have equipped the relay robots with the necessary sensors and processors. Enhancements to the lead robot are almost complete. A set of ad hoc networking RF modems is being developed jointly with BBN Technologies. We have installed the *Player* robot device drivers from USC on the relay robots and have verified the retroreflective laser beacon *Player* device using real retroreflective targets. We have developed a convoying algorithm using retroreflective laser beacons on the *Stage* simulator. The choice of convoying strategy has been verified using a simulation program from University of Massachusetts.

Work is progressing on schedule along the steps outlined in section 2. A demonstration of the deployment of relay units (phase 1 objectives) is expected at the end of 2002. For phase 2, we are looking into using a real-time mapping algorithm developed by Carnegie Mellon University,[12] also under DARPA sponsorship. A demonstration of the recall and reuse of relay nodes (phase 2 objectives) is expected at the end of 2003.

ACKNOWLEDGMENTS

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