Maintaining Communication Link for Tactical Ground Robots

Hoa G. Nguyen, Nathan Farrington, and Narek Pezeshkian

Space and Naval Warfare Systems Center, San Diego
Tel: (619) 553-1871
Fax: (619) 553-6188
hoa.nguyen@navy.mil
http://www.spawar.navy.mil/robots/

ABSTRACT

The communication link between a tactical mobile robot and its control station is currently the Achilles' heel of any ground robotic operation in the field. High-bandwidth digital radios, while providing the robot greater mobility than tethered links, perform mostly on lines of sight. The communication link degrades quickly as a robot penetrates the interior of a building, tunnel, or cave, or is shielded by intervening structures. We have demonstrated a solution to this problem through the use of autonomous mobile relay nodes. Each node is a small robot carrying a high-bandwidth digital radio. The relay robots convoy behind the main robot at the start of a mission, and automatically stop where needed to form an ad hoc network guaranteeing a link between the lead robot and the base station. This is accomplished without the need for an operator's intervention. The relay robots' mobility allows for even more versatility in the network. At any instance, nodes that are not needed in the network have the ability to request a map that has been generated by the lead robot as it moves through the environment, and use it to rejoin the convoy, further extending the lead robot's range. This paper describes the system, strategy, hardware development, software algorithms, and experiments conducted. It also briefly describes a follow-on project that demonstrates automatic deployment of static relay bricks by the lead robot.

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1. INTRODUCTION

One of the vulnerabilities of current mobile robots operating in real-world scenarios is the communication link to the operator's console. Hard cable tethers are cumbersome, limit maneuverability, and require large spools for extended range. Thinner optical fibers, even reinforced, have been found to be fragile in field use in the Afghanistan and Iraq theaters. The cables often get run over by the robot as it is maneuvered around obstacles. Snagging and stretching of the fiber around corners often cause signal loss.

User surveys have identified radio-frequency (RF) communications as more desirable [1]. However, high-bandwidth RF links, capable of carrying the real-time video data required for teleoperation, operate at shorter ranges and mostly on lines of sight.

To extend the range of these high-bandwidth radios and provide non-line-of-sight service, we are exploring the use of relay nodes. These nodes could be non-mobile bricks dropped by the robots where required. However, in tactical and reconnaissance missions, the robot's convoluted path may often lead to situations where intermediate relay nodes are no longer needed (e.g., RF shortcuts are encountered). To maximize resources and allow for extended explorations, unneeded relay nodes should be reclaimed and reused. We accomplish this function through the use of mobile relay robots that follow the lead robot in convoy fashion (Figure 1), stop and act as relay nodes where needed, and catch up to the lead robot to be redeployed when no longer needed. These activities are all performed without requiring the operator's involvement.

2. APPROACH

To accomplish these goals, we have developed a system of mobile relay nodes (essentially slave robots carrying radio relays) that automatically establishes an ad hoc radio network providing an end-to-end link between the robot and its control station. We examined several strategies for network deployment [2], with the main selection criterion being autonomous operation without operator intervention or distraction. The selected deployment strategy calls for the relay nodes to convoy behind the lead robot at the start of each mission (see Fig. 1). Each node monitors the radio link to the node behind it (with the base station being the last node in the system). When the quality of that link drops below a preset threshold, the node stops and becomes a stationary relay node.

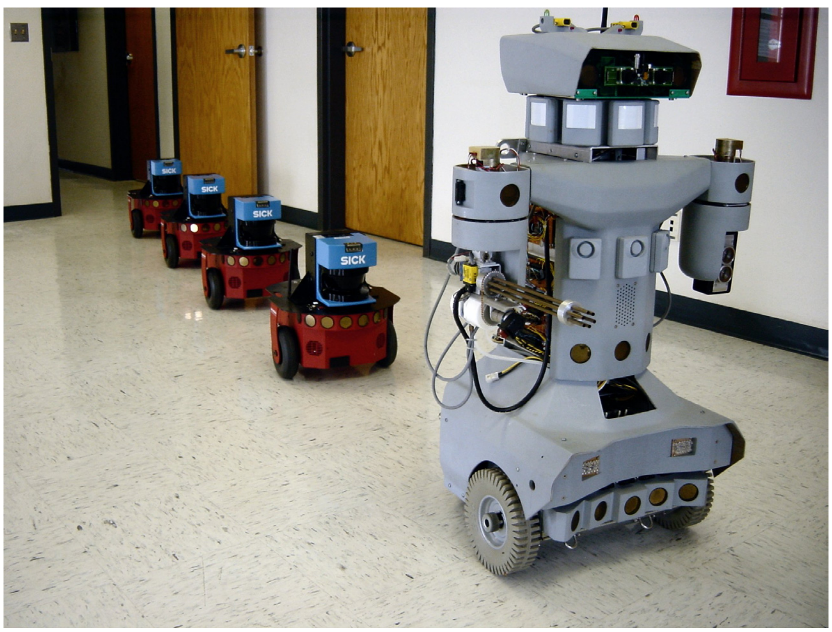

Fig. 1. Relay nodes convoy behind lead robot at the start of a mission.

The second half of the project deals with relay redeployment and extraction. As the lead robot maneuvers in a large and complex environment, it may encounter radio-frequency (RF) short cuts that may make a relay node become unnecessary. Each relay node monitors its own usage, and when it detects that it is no longer in the network path between the lead robot and the base station, it will initiate a sequence of steps to allow it to be reused by the system. This begins with a request for a map from the lead robot. Regardless of the mission, an independent subsystem of the lead robot automatically maps the space it traverses, and passes this map back to any relay robot that requests it. The relay robot will then use the map to seek out and catch up to the lead robot, rejoin the remaining convoy, and redeploy as needed. This will extend the range of the lead robot significantly. The map navigation capability of the relay nodes also means that they can be recalled at the end of the mission.

For laboratory demonstrations, we leveraged our existing pool of laboratory robots. We have used several different robots as the lead robot, including an iRobot ATRV, our own ROBART III [3], and a Segway Robotic Mobility Platform, which was developed by Segway LLC with our coordination. [4, 5] ActivMedia Pioneer 2-DX robots are being used as relay nodes. This configuration was only meant for laboratory demonstrations; all system functionalities can be readily transferred to actual ruggedized field robots.

The robots use ladar (laser radar) data for mapping and identification of other robots in the team (through robot-mounted laser retro-reflective barcodes). Obstacle avoidance and navigation are performed using a combination of ladar and sonar data. [6]

3. COMPACT AD HOC NETWORKING RADIOS

For uninterrupted operations requiring no operator intervention, we needed a wireless networking system that guarantees a robust link between the lead robot and the base station at all times. We worked with BBN Technologies to produce this capability in a small package, using a network protocol developed by BBN. [7]

BBN's ad hoc networking software uses a proactive link-state protocol. Each node in the network has complete information about the characteristics of all 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, which is recomputed whenever certain network events occur (such as when the link quality between two nodes has dropped below a preset level appropriate for a desired scenario). The routing table can therefore be updated before a link is broken, and the network is automatically maintained in a proactive fashion, for optimal information transmission and minimal lag. Network delays normally associated with route re-selection due to broken links—which are common for moving radios—are thus eliminated.

Some other features of BBN's networking protocols include:

- **Scalability:** Unlike other proactive protocols, BBN's software uses "hazy-sighted link state protocol" [8] to provides a method that allows the network to use a Quality-of-Service (QoS)-aware, flexible routing system that can scale to a thousand nodes.
- **Low Overhead:** In real-world tests of these protocols (under the DARPA FCS Communications program) BBN demonstrated overhead network control traffic of only approximately 3 kbps while delivering 14,000 kbps of user data in a rapidly moving 20-node network.
- **Multicast:** The network protocols use their knowledge of the topology to generate optimal spanning trees to provide a nearly unlimited number of multicast groups for use in situational awareness or other group communications.
- **Embeddable:** The protocols plus the Linux operating system current fit in a 4MB flash chip and require less than 16 MB of memory to run.

- **Detailed Network Information:** Via the Simple Network Management Protocol (SNMP), the network provides information on all links in the network, the locations of the nodes, the importance of each node in the network (e.g. articulation points), statistics on the links, and other information that are critical for network monitoring and management, as well as for autonomous robotic behaviors.
- **Directional Antenna Capability:** As a descendant of the FCS-C program that demonstrated a 20-node directional system, these protocols are ready to take advantage of directional antennas, given an appropriate radio MAC layer underneath. [9]

We integrated this ad hoc networking software into a small radio only slightly larger than a pack of playing cards (Fig. 2). Each radio consists of a StrongARM-based processor card, an off-the-shelf 802.11b PC Card, and a radio-interconnect board (RIB) that interfaces the two components. [6] Over one hundred radios were produced and currently used on robotics projects at SSC San Diego, University of Pennsylvania, Georgia Institute of Technology, University of Southern California, BBN Technologies, Army Research Laboratory, and Naval EOD Technology Division.

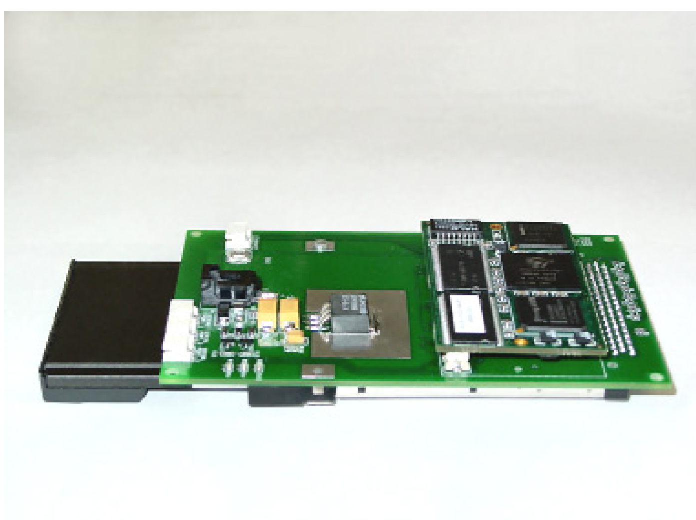

Fig. 2. The Compact Ad Hoc Networking Radio.

4. RELAY DEPLOYMENT EXPERIMENTS

The following section describes two relay-deployment experiments conducted at our facilities. The first experiment was performed in a mixed indoor/outdoor environment, while the second involved traversing an underground bunker.

***Mixed Indoor/Outdoor Environment Experiment*:**

Fig. 3 shows the path taken by a teleoperated lead robot (a Segway RMP) and the relay convoy, and the final locations of the deployed relay nodes. Node 1 is the lead robot, and node 5 is the base station (one of the radios connected to a laptop via an Ethernet cable), located in the first author's office. The convoy started in the hallway outside this office. Node 4 (the last Pioneer robot in the convoy) stopped just after the turn into the open laboratory area, as the link quality between it and node 5 dropped below a preset level. Nodes 3 and 2 likewise stopped in the open courtyard between the buildings. In each case, the relay node stopped just after line of sight is lost to the node behind it, consistent with the expectation that high-bandwidth digital RF links operate mostly on lines of sight (an assumption we made at the start of the project).

Underground Bunker Experiment

The objective of our second experiment was to teleoperate a mobile robot (again, a Segway RMP) through an underground bunker with thick concrete walls, from one side of a hill to the other. This would approximate the environments encountered in tunnel and cave explorations, as well as inspection of underground nuclear storage facilities.

The operator's control station (node 5) was stationed outside the southwest entrance of Battery Woodward (an abandoned World War II gun battery and underground bunker protecting the coast of San Diego, see Fig. 4). As in the previous experiment, each relay node stopped just after losing line of sight to the node behind it. The experiment stopped after a high iron door threshold blocked node 2's advance. Nevertheless, the lead robot had made it through to the east entrance of the bunker, from one side of the hill to the other, operated solely by real-time video relayed through the network.

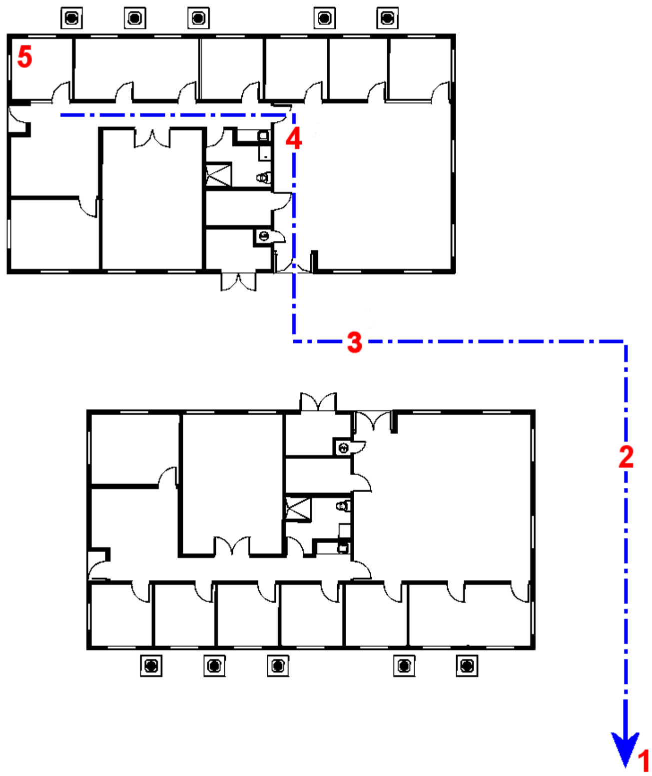

Fig. 3. Mixed indoor/outdoor relay deployment experiment.

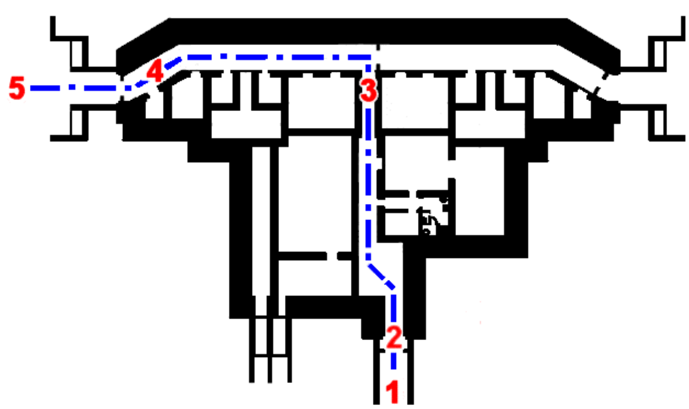

Fig. 4. Underground bunker relay deployment experiment.

5. DEPLOYMENT OF RELAY BRICKS

While we are completing the second phase of the project (relay recall and redeployment), we have also initiated a follow-on project aiming at reduced-resource scenarios. In the first phase of the original project, we demonstrated autonomous mobile relay nodes that follow the lead robot and can stop and become static relay nodes. This is functionally equivalent to having the lead robot carry a number of relay "bricks" and automatically drop them where needed. Indeed, this method may be more appropriate for certain frequently encountered operations, such as where only one robot is available, and the robot is used in a vanguard role, ensuring the path ahead is safe for human warfighters or law enforcement officers. In this scenario, the human operator can manually retrieve the relay nodes after the completion of the operation.

Fig. 5 shows a block diagram of a system that performs this function. The original set of two digital wireless modems are replaced with two of our compact ad hoc networking radios, a deployer module, and a number of relay bricks, shown both on the deployer module and dropped in the environment. Note that there may be more than one path between the robot and the operator control unit (OCU), due to the ad hoc networking nature of the system. The deployer module contains a fixed modem (with a * in Fig. 5), through which it can monitor the network and issue commands to drop the relay bricks. To conserve energy and also avoid interferences between radios that are too close to each other, only one of the relay bricks on the deployer module (the one next in line to be deployed) would be active at any time (the other nodes are greyed out in the diagram). The fixed node on the deployer module can be eliminated by a hard Ethernet cable to the node on the robot. However, having this additional node allows flexibility in the attachment of the deployer module—it can be physically mounted on separate mobile platform, unconnected to the robot, as described below.

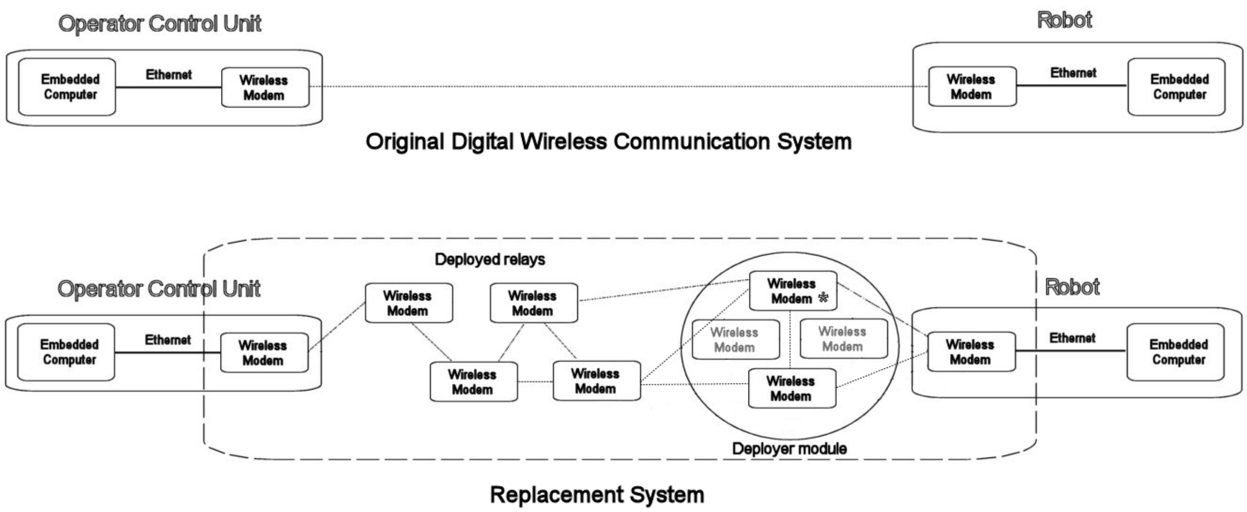

Fig. 5. Block diagram of the automatically deployed communication relays (ADCR) system.

There are three ways the deployer module can be used in the system, and we are designing a module that will work in all three cases.

1. The module can be mounted on the robot itself. Fig. 6 shows such a design for the iRobot PackBot Scout that would also fit on a PackBot Explorer, Foster-Miller Talon, Mesa Associates' Matilda, or other robots with payload space.

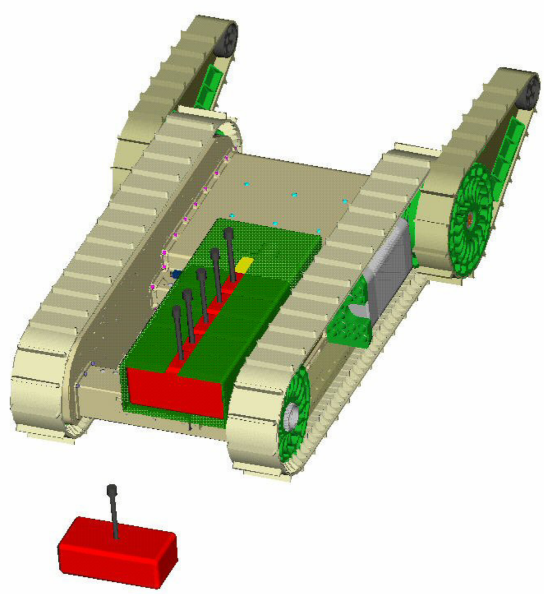

Fig. 6. The relay deployment system on a PackBot Scout.

2. In cases where there is no room on the robot, as is usually the case with EOD robots, the deployer module can be mounted on a passive towed platform, as shown in Fig. 7. The towed platform can also contain larger batteries that maintain the deployer module for longer periods of operation.

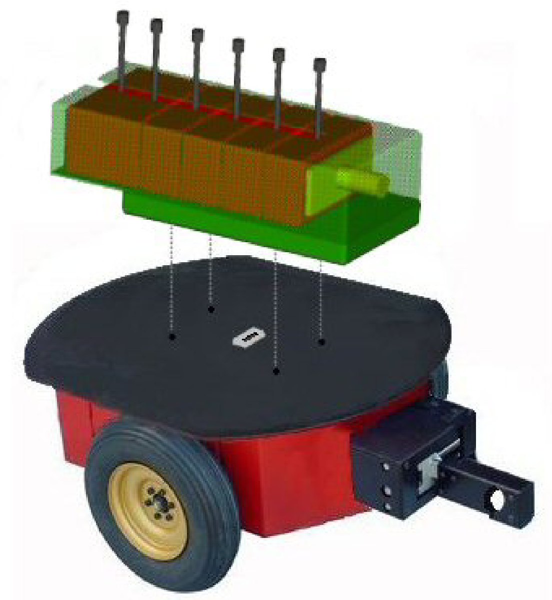

Fig. 7. The relay deployment system on a passive towed platform.

3. If the towed platform cannot be used due to concerns regarding reduction in agility or mobility, then a second robot can be dedicated to the task of deploying the relay bricks. For example, one of the robots mentioned in case (1) could follow an EOD robot and provide the communication relays deployment function. The EOD robot would host an additional node of the network. The second robot could be teleoperated by another operator, or follow the lead robot autonomously as we have previously demonstrated.

6. SUMMARY

Maintaining robust RF communication links for tactical robots is a well-recognized and persistent problem. In this paper, we described two related systems we are developing for solving this problem, both using radio relays. The first system consists of a convoy of relay robots that follow a lead robot and deploy themselves where needed to provide an ad hoc network. We presented the results of two separate experiments, and showed that the relay robot system works successfully in a mixed indoor/outdoor environment, as well as in underground tunnels.

The second system consists of a set of relay radio bricks that can be dropped behind a robot. For this system, we described a universal design that can accommodate a wide range of robots and missions.

Both systems use a set of compact ad hoc networking radios that we have developed to support mobile robotic missions.

ACKNOWLEDGMENTS

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