UNMANNED GROUND VEHICLE RADIO RELAY DEPLOYMENT SYSTEM FOR NON-LINE-OF-SIGHT OPERATIONS

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ABSTRACT

Tactical mobile robots used in military and law-enforcement operations normally require a robust, long-range, and non-line-of-sight (NLOS) communications link to the remote control station. This is especially true for Explosive Ordnance Disposal (EOD) operators using robots to defeat Improvised Explosive Devices (IEDs). High-frequency digital radio communications, currently the preferred technology, are subject to line-of-sight (LOS) limitations, and thus are often impossible to maintain in urban environments. We have developed a system that will allow the mobile robot to carry multiple relay radios that are automatically deployed when and where needed in order to maintain robust communications. This process is completely transparent to the operator and is entirely handled by the ad-hoc network formed by the relay radios. The system is plug-and-playable, and can be attached to many manned and unmanned vehicles requiring long-range and non-LOS operational capability. Experimental data compares the effective range achieved with and without the use of our relay deployment system.

KEY WORDS

Robotics, communications, relay, ad hoc networking

1. Introduction

Mobile robots used by the military and law enforcement agencies require a robust communications link for successful mission executions. Such mobile robots are increasingly used in life-threatening situations and hazardous environments, rendering a solid communications link to be of vital importance.

In such situations using a tethered system is problematic. They are cumbersome, have limited range, and can snag or break as the robot maneuvers around obstacles or inadvertently runs over the cable. Analog radios suffer greatly from multi-path interferences and fading. Wireless broadband digital communications, on the other hand, have proven to be much more robust and versatile. However, their high operating frequencies require a line of sight (LOS) to the control station—a requirement that is difficult to maintain in many environments. This problem can be somewhat alleviated by proper antenna placement and signal amplification, but these methods are limited by real estate and spectrum-use regulations, respectively. As a result, users have often expressed desire for a radio relay system. We have developed an automatic radio relaying system that is completely transparent to the user and the operation of the robot.

2. Background

The current project is based on our previous effort completed for the Defense Advanced Research Projects Agency (DARPA) under the Autonomous Mobile Communication Relays (AMCR) project [1-4]. This prior work demonstrated the use of mobile relay nodes that follow a lead robot in a convoying fashion as it traverses an unknown environment, and stop automatically when needed in order to maintain the communications link back to the control station.

2.1 Convoy

The convoy formation comprises a lead robot, followed by several relay robots, as shown in Figure 1. Each relay robot is programmed to follow the one immediately in front of it while simultaneously avoiding obstacles.

Figure 1. Convoy formation with SSC-SD's Robart III as the lead robot followed by Pioneer 2DX relay robots.

The rear-most robot in the convoy automatically stops as required to become a stationary relay node, providing transparent relaying, while the rest of the convoy continues its mission. The process continues until all relay robots have been used.

2.2 Network

The networking software [5] was developed by BBN Technologies under a separate DARPA project. The ad hoc network (based on IEEE's 802.11b protocol) formed by the radios 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 link and set up the routing table. This table is recomputed whenever certain network events occur, such as when the link quality (determined by a predictive filter) between two nodes drops below a predetermined level chosen for the scenario, or when a new node enters the network. The routing table can then be updated before a link is broken, automatically maintaining the network in a proactive fashion for optimal information transmission. There is no delay incurred due to route reselection caused by broken links.

Using this network information, each relay robot in the convoy monitors the link quality to the node immediately behind it. As the quality drops to a threshold, the relay robot stops to prevent further signal degradation that could lead to link breakage. The networking software has been implemented on a radio slightly larger than a pack of playing cards.

2.3 Transition

The use of mobile relay nodes, while providing more versatility, is not practical for some tactical applications. Mobile nodes add logistical and maintenance challenges, cost, and set up time. For most tactical scenarios, static relay nodes can be carried and dropped by the robot to maintain its communication link. This application is being demonstrated under the Automatically Deployed Communication Relays (ADCR) project, funded by the Office of the Secretary of Defense (OSD) Joint Ground Robotics Enterprise (JGRE).

3. ADCR System

The goal of the ADCR project is to develop a practical, stand-alone, plug-and-playable deployment system capable of carrying relay-radios that are automatically released when needed in order to maintain the communications link back to the control station. This system, requiring no external power, attaches to the payload area of an unmanned ground vehicle (UGV) and interfaces to the UGV through an Ethernet port.

The basic components include several relay radios and a deployment mechanism. The packaged relay radios, known as Relay Bricks, are self-contained ruggedized versions of the compact ad hoc networking radio (CANR) developed under AMCR. They are carried aboard a module called the Deployer, which is carried by the UGV. The Deployer releases the Relay Bricks as needed to maintain the link. Once dropped off, the Relay Brick turns itself upright and raises its antenna to establish proper radio connectivity. At the end of the mission the Relay Bricks may be collected and stowed back in the Deployer for future deployment.

The deployment system is currently limited to UGVs that are capable of communicating over the Ethernet standard. This limitation is based on the network formed by the Relay Bricks, which uses the IEEE 802.11b protocol. The advantage is that this common and versatile protocol allows the system to be plug-and-playable, with minimal modifications to the UGV hardware and network setup. Most modern UGVs already use the Ethernet standard.

3.1 Relay Brick

The Relay Brick (Figure 2) is a self-contained CANR, ruggedized to work in outdoor environments. It is designed to be launched from the Deployer and withstand the impact of hitting the ground. The Relay Brick is geometrically constraint from landing on its ends, however, it may land on any of its sides. Spring-loaded bay doors, which must open to release the antenna, are also used as a self-righting and support mechanism to ensure that the Relay Brick always comes to rest right side up. As the bay doors fly open, the antenna lift mechanism, also spring-loaded, fully extends the mast.

Figure 2. Relay Brick, open with antenna mast extended.

Antenna height is of vital importance. Antennas placed close to the ground suffer from increased multi-path interference, surface-wave attenuations, Fresnel Zone violations [6], and the effect of ground moisture

evaporation turbulence on RF propagation close to the ground [7]. Computer simulations were conducted to provide approximate maximum attainable range as a function of antenna height under best case scenarios [8]. Based on the simulation results and design constraints, e.g., brick size and practicality of the antenna lift mechanism, the Relay Brick antenna is designed to stand 45 cm above the ground as measured to the dipole feed point.

The Relay Brick does not incorporate a main on/off switch. The purpose is to eliminate the need for the operator to have to remember to activate each Relay Brick before stowing them in the Deployer. This is part of the effort to minimize the amount of user interaction with the system. Part of the Relay Brick electronics is always active, looking for a power activation signal from its Hall Effect sensors. A momentary magnetic field provided from the Deployer activates the main power. Special attention has been given to the power consumption and operational period of the Relay Brick. While inactive, the Brick electronics consumes extremely low levels of power, allowing it to last months without recharging. When activated, high efficiency DC-DC converters along with Lithium-ion batteries allow the Relay Brick to operate for approximately 10 hours, which is well over the operating time of most battery–powered UGVs.

3.2 Deployer

The Deployer is the module that carries the Relay Bricks and releases them as needed. Size constraints and practicality allow the Deployer to carry six Relay Bricks. The Deployer only requires an external Ethernet interface from the UGV to which it can connect. Due to various shapes and sizes of candidate UGVs, a unique attachment bracket must be designed for each UGV.

The Relay Bricks are stowed in the Deployer by loading them in individual chambers (see Figure 3). Each chamber contains a spring loaded catapult, onto which the Relay Brick rests, and a push-pin that locks the Relay Brick inside the chamber. Servo motors linked to the push pins release the lock, launching the Relay Bricks out of the Deployer when needed. Once locked into place, the Relay Bricks can be manually released by pressing on a manual release button located close to the chamber opening.

The momentary magnetic field required to activate/deactivate a Relay Brick is provided via an electromagnet residing behind each chamber. Using a magnetic field provides a non-contact and environmentally robust method for activating power that does not suffer from dirt and dust build up.

Permanent magnets attached to the Relay Bricks provide a signal to Hall Effect sensors located behind each chamber that are used to detect the presence or absence of a Relay Brick.

Figure 3. Deployer module.

The CANR aboard the Deployer is the heart of the system. It monitors network events and communicates them to the Deployer microcontroller through an RS232 port. The microcontroller interprets these events and takes action. If, for example, the link is about to break, the CANR signals the microcontroller to release a Relay Brick. The microcontroller then unlatches the lock and the spring-loaded Relay Brick launches out of the Deployer.

4. System Function

The integration process of the Deployer with a UGV requires the bypass or shut down of the native radio hardware as well as any possible configuration of the network settings. These steps can be easily performed in software on many platforms. For proper radio connectivity a Relay Brick is connected to the Operator Control Unit (OCU) on the base station side with similar integration requirements.

A basic network of two nodes is formed when the base station and the Deployer radios are communicating. This is indicated by a green LED onboard the Deployer notifying the user that the UGV can now be controlled via the OCU. At this point Relay Brick in the Deployer is activated. It takes approximately forty seconds for a radio to fully boot. Therefore, a Relay Brick in the Deployer is always powered and stands by for immediate release. This allows the network to immediately take advantage of this node and reroute the communications path without any incurred delay due to radio boot time. Once a Relay Brick is activated, the Deployer queries the network to determine if a new node has entered the network. If so, this is confirmation that the newly activated Relay Brick booted successfully and is standing by. The Deployer's radio now begins monitoring the strongest signal strength in the overall network, excluding the active Relay Brick. The assumption is that the active Relay Brick inside the Deployer provides a very strong signal since it is physically

much closer to the Deployer's radio than any other radios. Hence, its signal strength is ignored until released.

As the UGV moves away the strongest link to the Deployer will diminish. The received signal strength indicator (RSSI) information of this link is used by a predictive filter running within the networking code to provide a filtered output signal. When this signal falls below a predetermined threshold it triggers the release of the active Relay Brick. This occurs before the strongest link breaks, which allows the overall link from the UGV to the OCU to be maintained. A few seconds after the Relay Brick is launched, a wireless message from the Deployer commands the deployed Relay Brick to release its antenna. Then, the next Relay Brick in the Deployer is activated.

The process of activating a Relay Brick, verifying its presence in the network, and launching it as needed continues until all units are spent. If for any reason a Relay Brick fails to boot properly or fails to launch, it will be shut down and the next one in the Deployer chamber will be activated. Throughout this process status messages reporting whether or not a Relay Brick is ready for launch and whether or not it launched successfully are sent to the base station radio. After the last Relay Brick is released the user is notified that the Deployer is empty. If the UGV moves past the point where the signal strength falls below the threshold, a "warning" message is sent to the user. A simple Windows program receives and displays such messages. The PC running this program can be optionally connected to the OCU and the Relay Brick via a hub.

4.1 Experimental results

Experiments were performed to compare the effective range of a UGV with and without the Deployer system. The tests were conducted using the iRobot EOD PackBot (Figure 4).

Figure 4. Deployer module with two Relay Bricks, mounted on the EOD PackBot.

Two experiments were conducted to demonstrate the effectiveness of the relaying system. The first experiment was conducted in an outdoor environment and the second in a mixed indoor/outdoor environment.

4.1.1 Outdoor Experiment

The decision to deploy a Relay Brick is made when the highest link quality (ignoring the active Relay Brick inside the Deployer) falls below the pre-specified threshold value. The threshold value is chosen as a trade-off between link reliability and overall effective travel distance. The lower the threshold, the further the distances between deployed relay nodes. However, the chances of a Relay Brick being deployed too late to maintain the link also increases.

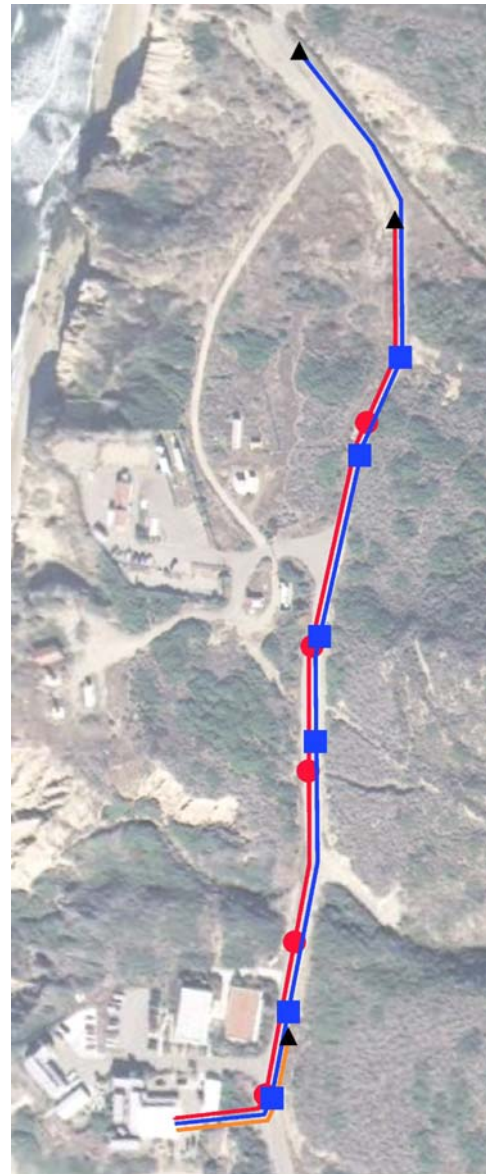Figure 5 shows an overhead view of the outdoor experiment area.

Figure 5. Outdoor experiment area.

The black triangles represent the location of the robot after all available Relay Bricks had been deployed and the link with the base station was lost. The orange line represents the travel path without any deployed Relay Bricks. The line with red dots represents the travel path with the threshold set to 40. The line with blue squares represents the travel path with the threshold set to 45. Respective dots and squares represent deployed Relay Bricks.

Without the benefit of the ADCR system, the PackBot was only able to travel approximately 80 m (NLOS) before losing communications with the base station. With five Relay Bricks launched from the Deployer (one brick failed) and the threshold set to 40, the robot was driven to approximately 450 m north of the base station over NLOS terrain (there are several dips along the winding path). With six Relay Bricks and the threshold set to 45, the robot reached approximately 540 m north of the base station. It is projected that with a six Relay Brick and a threshold setting of 40 the robot could have been maneuvered approximately 560 m.

The distances between adjacent nodes for both threshold settings are shown in Table 1.

Table 1. Distances (in meters) between adjacent nodes

Adjacent Nodes	Threshold 40	Threshold 45
Base – 1	51	49
1 – 2	67	41
2 – 3	79	121
3 – 4	51	44
4 – 5	105	86
5 – 6/Robot	105	44
6 – Robot	N/A	156

As expected, the distance between adjacent nodes is longer with the lower threshold value. The exception is between nodes 2 and 3. This is due to the geography of the area. A significant hill exists between the general locations of the second and third deployed nodes. Under case 40 the second node is deployed farther away from the first, which placed it closer to the bottom of the hill. As the robot traveled uphill it lost LOS with the second node much faster, deploying the third node sooner. In contrast, under case 45, the second node is deployed at a shorter distance from the first, allowing the robot to maintain a better LOS as it traveled over the hill, causing a delayed released of the third node.

4.1.2 Indoor/Outdoor Experiment

Figure 6 shows the area used for this experiment. The UGV begins outside and is immediately maneuvered into an underground structure. The structure is a WWII reinforced concrete bunker with thick walls, minimizing radio wave penetration. A large hill exists over the top of the structure. The height of the hill tapers off significantly towards the southern point of the perimeter.

The red dots and blue squares indicated locations of deployed Relay Bricks with a threshold setting of 40 and 45, respectively. The black line indicates the travel path through the underground structure and outside around the hill. The orange line represents the travel path of the robot without the benefit of the Relay Bricks. The final resting location of the robot with and without deployed Relay Bricks are indicated by black triangles along respective paths.
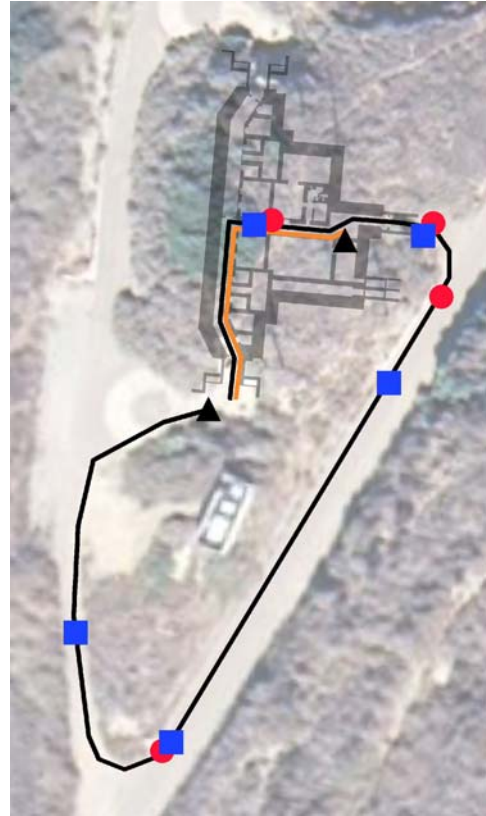

Figure 6. Indoor/Outdoor experimental area.

The first Relay Brick under both threshold cases was released inside the structure just around the corner into an adjoining corridor. Under case 40 the Relay Brick was deployed a couple of meters away as compared to case 45, as expected. The second Relay Brick under both cases was released just outside the structure in approximately the same location. A sharp right turn placed the robot onto a paved road alongside a 1 m tall concrete wall. The third Relay Brick was deployed as shown. Under case 40 the third Relay Brick was deployed farther away then that shown under case 45, however, a loss of link required that node to be moved back to the location indicated in the figure. Continuing down the road the robot maintained a well established LOS with the third Relay Brick. As the strongest signal diminished the fourth Relay Brick was deployed. A U-turn placed the robot onto a dirt road, heading back towards the base station. Under case 40, observing the link quality showed that a fifth Relay Brick was about to be launched, however, as the robot approached

the base station it established a strong link with the base station radio, eliminating the need in deploying a fifth Relay Brick. Under case 45, however, the fifth Relay Brick was deployed.

4.2 Status

Four prototype systems have been developed. One system will be delivered to the Naval Explosive Ordnance Disposal Technology Division (NAVEODTECHDIV), for further evaluation on a Man-Transportable Robotic System (MTRS) PackBot. Two systems will go to the Army Tank Automotive Research, Development and Engineering Center (TARDEC), for use on the Tactical Amphibious Ground Support (TAGS) and Remotec Wolverine platforms. The fourth system is for in-house research, to be used on the Urban Robot (URBOT).

4.3 Future Work

Work is underway to further modify the system and prepare it for in-theater operations. The Relay Brick and Deployer mechanical housings are being redesigned to be smaller and more rugged. The Relay Brick antenna lift mechanism is similarly being redesigned to be simpler and more effective for field use. Since components of the CANR have become obsolete, the radio is being replaced with a higher data rate and higher output power radio. The new radio, however, is smaller in size, consumes less energy, offers enhanced security features, and operates in a military band. The system function is being modified to allow several UGVs, each carrying a Deployer system, to opportunistically use each other's deployed Relay Bricks.

Other plans include developing methods to automatically retrieve deployed Relay Bricks and developing a robust user interface that provides network and system status information, as well as allow the operator to command the release of a Relay Brick at any time. The latter is useful in situations where the operator's tactical location will need to change, and prematurely dropping a Relay Brick may be strategically beneficial from the newer position of the operator. Finally, the availability of analog-to-digital converters and various communications bus interfaces will allow simple additions of various sensors to the Relay Bricks, turning them into stand-alone networked surveillance sensors.

5. Conclusion

High frequency, wireless digital communications used by tactical robots operating in urban environments require a LOS to be maintained with the control station, which may be impossible to achieve. The proposed solution to this problem is to use a radio relaying system. The proposed system includes several relay radios, known as Relay Bricks that are carried in a Deployer module, which in turn is carried by the mobile robot as a payload. By monitoring the network, the Deployer will release a Relay Brick before

the link between the control station and the robot is broken, in order to maintain the communications link. This occurs transparently and without dependence on the user. The system is designed for ease of use and minimal effort on the part of the user for initial setup and final collection and reuse of the Relay Bricks.

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