Evolution of a radio communication relay system

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ABSTRACT

Providing long-distance non-line-of-sight control for unmanned ground robots has long been recognized as a problem, considering the nature of the required high-bandwidth radio links. In the early 2000s, the DARPA *Mobile Autonomous Robot Software (MARS)* program funded the Space and Naval Warfare Systems Center (SSC) Pacific to demonstrate a capability for autonomous mobile communication relaying on a number of *Pioneer* laboratory robots. This effort also resulted in the development of ad hoc networking radios and software that were later leveraged in the development of a more practical and logistically simpler system, the *Automatically Deployed Communication Relays (ADCR).* Funded by the Joint Ground Robotics Enterprise and internally by SSC Pacific, several generations of *ADCR* systems introduced increasingly more capable hardware and software for automatic maintenance of communication links through deployment of static relay nodes from mobile robots. This capability was finally tapped in 2010 to fulfill an urgent need from theater. 243 kits of ruggedized, robot-deployable communication relays were produced and sent to Afghanistan to extend the range of EOD and tactical ground robots in 2012. This paper provides a summary of the evolution of the radio relay technology at SSC Pacific, and then focuses on the latest two stages, the *Manually-Deployed Communication Relays* and the latest effort to automate the deployment of these ruggedized and fielded relay nodes.

Keywords: communication, radio, relay, unmanned ground vehicle, robot, teleoperation, ad hoc mesh network

1. INTRODUCTION

Modern unmanned ground vehicles (UGVs) use mostly high-bandwidth digital radio links, which are by nature high-frequency, typically around 2 GHz or above. These links operate roughly on line of sight, which presents numerous problems for teleoperation, especially for the man-portable class of UGVs. The low height of their antennas means dips and rises in the terrain often block line of sight to the operator or significantly reduce the Fresnel-zone clearance, thus breaking the communication link. Operation in urban environments exacerbates the problem.

Starting in the early 2000s, the Unmanned Systems Group at the Space and Naval Warfare Systems Center Pacific has been engaged in a number of projects to address this issue. *The Autonomous Mobile Communication Relays (AMCR)* project demonstrated the use of autonomous relaying slave robots whose sole purpose was to strategically position themselves to maintain the communication link between a controller and a lead robot. This effort was followed by a number of projects that increasingly moved toward logistically simpler but more rugged solutions with the ultimate aim of fielding a solution to the Warfighter, which was finally achieved in 2012.

This paper provides a history of these projects, with focus on the most recent developments and the lessons learned.

2. AUTONOMOUS MOBILE COMMUNICATION RELAYS (AMCR)

Funded by the Defense Advanced Research Projects Agency (DARPA) under the *Mobile Autonomous Robot Software (MARS)* program in fiscal years (FYs) 2001-04, *AMCR* demonstrated communication relaying by autonomous slave robots[1,2] using wireless ad hoc networking technology developed by BBN Technologies under a separate *MARS* project. The slave robots (*Pioneer 2-DXs*) were equipped with lidar and sonars for obstacle avoidance, and followed the robots ahead in a convoy using laser-retroreflective barcodes (see Fig. 1). Each slave robot monitored the quality of the

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communication link to the robot behind it, and stopped to become a stationary relay node when a link-breakage-prediction algorithm determined that the link was about to fail. An iRobot *ATRV* and a Segway *RMP* were used alternately as the remotely-controlled lead robot.

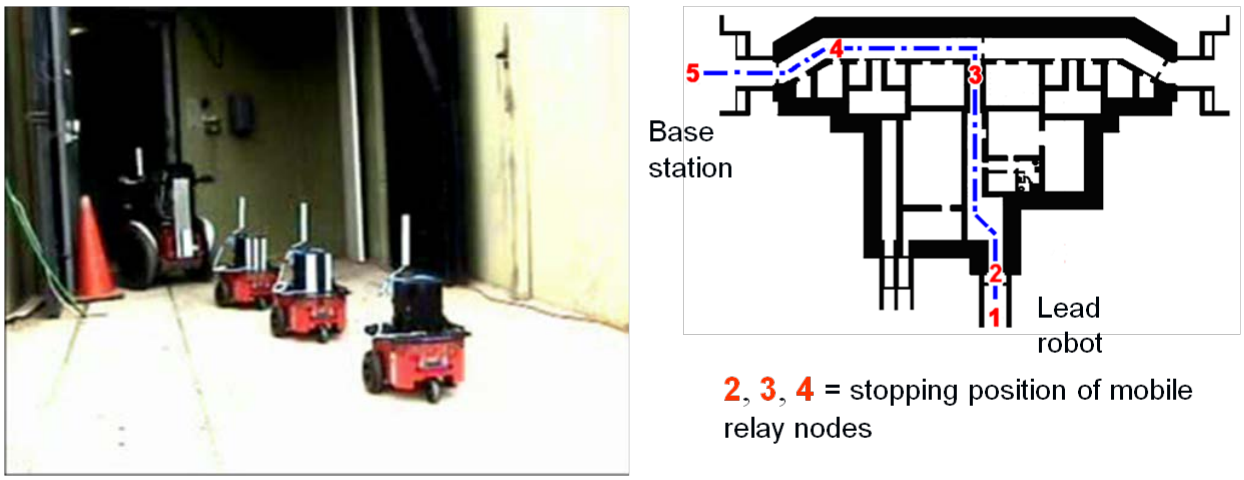

Figure 1. An *AMCR* demonstration, with the robots about to enter an underground World War II gun battery (left), and the locations where the slave robots stopped to become stationary relay nodes (right).

SSC Pacific developed an ad hoc networking radio under this project that combined an in-house developed radio interface board, an onboard computer, an 802.11b PCMCIA radio card, and BBN Technologies' *Hazy-Sighted Link-State* ad hoc networking software. Named the *Compact Ad Hoc Networking Radio (CANR)*, 100 of these radios were produced and distributed to other *MARS* performers for use on their autonomous robot projects.

3. AUTOMATICALLY-DEPLOYED COMMUNICATION RELAYS (ADCR)

Using the ad hoc networking radio technology developed under *AMCR*, SSC Pacific started the *ADCR* project with the goal of producing a system that was more practical. Funded by the Office of the Secretary of Defense' Joint Robotics Program (now Joint Ground Robotics Enterprise—JGRE) during FY05-06, *ADCR* produced a plug-and-play radio repeater system for the iRobot *PackBot* family of robots.[3] The system included a robot-mounted *Deployer Module* that would deploy relay nodes as needed. The *Deployer Module* monitored the signal strength to the closest deployed relay node along the network route leading back to the operator control unit (OCU). Using the same predictive filter that commanded the *AMCR* mobile relays to stop, the *Deployer Module* would instead eject a relay node whenever the link was about to break.

Each first-generation *Deployer Module* took two slots in the *PackBot* payload bay and housed six relay nodes. To prevent interference between nearby relay nodes, only one node was active at any time while still inside the *Deployer Module*. The *Deployer Module* made sure that the node had joined the network before ejecting it and activating the next node, getting ready for the next deployment event. The relay nodes (called "bricks" colloquially) were self-righting. After ejection, a microcontroller in the relay node waited a few seconds (to ensure the brick came to rest), and then issued a command for the doors to open, thereby flipping the brick upright (regardless of how it landed) and releasing a folded spring-loaded antenna. Figure 2 shows the first-generation *ADCR Deployer Module* on a *PackBot* and a deployed relay brick.

Although this *ADCR* design was licensed to three manufacturers, none were produced commercially.

Figure 2. A first-generation *ADCR Deployer Module* on a *PackBot* and a deployed relay node.

4. SECOND-GENERATION ADCR

One deficiency of the first-generation *ADCR* was the limited bandwidth offered by the onboard 802.11b radios. The effort to develop the second-generation systems, conducted during FY07-08 and also supported by the JGRE, produced an improved prototype system. The *Deployer Module* was smaller, taking only one-third of the *PackBot* payload bay. This was made possible by the much thinner relay nodes, which also made self-righting unnecessary. Instead, an accelerometer in the relay node detected which of the two faces the brick had landed on. A microcontroller then raised the dual-diversity antennas appropriately. Unlike the first-generation, this new antenna design could ensure that the deployed antennas were always vertical regardless of the ground slope (assuming that the robot was going up or down a hill and not sideways on its slope when it deployed the relay node—the antennas only had one degree of rotational freedom).

For higher bandwidth, the new radios used hardware developed by Rajant (funded separately by the National Center for Defense Robotics) to support an 802.11g radio card and the BBN Technologies ad hoc networking software. Figure 3 shows the second-generation *ADCR* system.

Figure 3. A second-generation *ADCR Deployer Module* on a *PackBot* and a deployed relay node.

5. AUTOMATIC PAYLOAD DEPLOYMENT SYSTEM (APDS)

While demonstrating the *ADCR* system to the US Marine Corps I Marine Expeditionary Force (I MEF), the SSC Pacific team received numerous suggestions on other payloads that could be delivered by the *ADCR Deployer Module*. These suggestions led to the development of *APDS* in FY09-10,[4] also funded by the JGRE. In order to support as many different types of payloads as possible, *APDS* nodes employed a very modular design.[5] This modularity also extended to the *Deployer Module*, making it easily adaptable to different types of robots.

The *APDS Deployer Module* could accept three different payload sizes, from single to triple height (see Figure 4). Each payload was composed of a payload carrier (which contains the actual payload) and a snap-on payload adapter that communicated to the *Deployer Module* using an infrared interface. This allowed third-party developers to build their own payloads, which only had to conform to a set of SSC Pacific interface specifications. The infrared communication allowed the *Deployer Module* to detect what type of payload it carried and adjust its behaviors accordingly. For example, the *Deployer Module* would know that the next payload in line to be dropped was a passive payload containing supplies, and would skip over it to deploy a radio relay payload if it sensed an impending break in communications.

Similarly, the *Deployer Module* also had a snap-on adapter specific to each type of robot. Thus each robot manufacturer could design a specific *Deployer Module* adapter to use the *APDS* on their robots.

The system also included a base station unit that connected to the OCU via an Ethernet cable and contained a radio similar to those found in the relay nodes and the *Deployer Module*. The base station unit had its own video screen to display status of the payloads and to allow the operator to manually control the deployment of various payloads as needed. Three example payloads were developed: (1) an IR illuminator that could be deployed to illuminate locations of interest at night, (2) a leave-behind video sensor that used the network to transmit its video data back to the base station unit, and (3) an empty triple-height payload that could be used to carry medical supplies, food, or ammunition to the Warfighter at the front line. A marsupial robotics capability has been demonstrated by deploying a magnetic-wheel micro-UGV using the empty payload carrier.

Figure 4. The *APDS*, showing various components.

6. THIRD-GENERATION ADCR

The third-generation *ADCR* effort was a technology improvement internally funded by SSC Pacific's *Naval Innovative Science and Engineering (NISE)* program during FY10-11. The radio hardware was replaced by commercial-off-the-shelf processor/router boards (GateWorks *GW2350*) and Mini PCI 802.11g radios. However, the most significant accomplishment from this effort was the switch to internally-developed ad hoc networking software targeting teleoperation.

Teleoperation of mobile robots requires unique network characteristics that are different from those for static nodes or autonomous robots, to include: minimal or no link-breakage, fast convergence to a new route after a link failure, and a higher throughput with low latency across multiple nodes to accommodate several video streams. We conducted comparisons of several open-source ad hoc networking architectures, picked the most promising architecture (*Babel*), and optimized it for the above requirements.[6] We also started work on a new link-quality estimation technique. However, this work was interrupted by emergent in-theater requirements (which started the *Manually Deployed Communication Relays* project below), and was finished later under the fourth-generation *ADCR* effort.

7. MANUALLY-DEPLOYED COMMUNICATION RELAYS (MDCR)

In late FY10 we received a request from the Naval Explosive Ordnance Disposal Technology Division (NAVEODTECHDIV), responding to two Joint Urgent Operational Need Statements from US Central Command, to provide a relay system for evaluation at the Joint Counter-IED Facility at the Naval Air Warfare Center in China Lake, CA. We provided two repackaged relay nodes (the automatic deployment capability was not required), which were tested along with several other solutions from other laboratories and commercial vendors. Our system was picked for further development. Subsequently, with funding from the Navy Expeditionary Combat Branch (OPNAV N857) and managed by NAVEODTECHDIV, we designed and built 15 prototype *MDCR* kits for operational assessment at Fort Leonard Wood, MO, and in Afghanistan. Five kits each were built for the iRobot *500 PackBot*, *510 PackBot/FasTac*, and *310 SUGV/MiniEOD*. (A prototype system was also developed for the QinetiQ *Talon* robot as part of the initial evaluation but was not selected for further development. This *Talon* system used the same relay nodes as the *PackBot* systems, and all robots and their relays would operate in the same mesh network.)

After the prototype systems passed the operational assessments, we were tasked to develop a level-III (production) technical data package (TDP) and two end-of-line test fixtures for semi-automated functional verification of production units as they exit production lines. Using this TDP, the Robotic Systems Joint Project Office fielded 243 kits in Afghanistan in the second half of 2012, built by the Tobyhanna Army Depot.

Each *MDCR* kit includes two ruggedized relay nodes, to be carried and deployed using deployment forks attached to the flippers of the robots, end-point radios for the robots and OCUs, and miscellaneous hardware and manuals (see Figure 5). The *MDCR* relay nodes are waterproof and use standard military *BB-2557* rechargeable batteries. The radios used are compatible with coalition *Counter-Remotely-controlled-IED Electronic Warfare (CREW)* jammers. The antennas are flexible and foldable. (Earlier prototype antennas were not foldable and proved to be a weak point in the system.) Each deployment fork was designed to connect to and disconnect from the robot flipper with the use of a quick-release pin. An angular attachment offset between the forks allows the relay nodes to be deployed and picked up one at a time (see the left image in Figure 5).

Each relay node has an LED indicator that tells the operator through its solid or blinking status whether the unit is offline, in the mesh network, or is trying to join the network. The *Babel*-based ad hoc networking software developed and optimized for teleoperation during the third-generation *ADCR* effort was used without the automatic deployment function. The entire system was designed to be plug-and-play on each type of robot it was built for—no modification of the robot or controller software was required.

Figure 5. *MDCR* relays carried by an iRobot *510 FasTac* (left) and an *MDCR* kit (right).

8. FOURTH-GENERATION ADCR

With the completion of *MDCR*, we returned our focus to *ADCR*, but this time with the goal of providing more autonomy for the fielded *MDCR* systems. With FY12 internal *NISE* funding, we demonstrated a new system that could deploy the *MDCR* relay nodes either automatically or semi-automatically. Motorized deployment forks were designed that were mounted on the rear of the robot (an iRobot *510 PackBot* was used as the test platform—see Figure 6). A dongle was designed for the OCU to provide buttons for switching between automatic and semi-automatic deployment modes and for controlling the deployment of individual relay nodes. (The addition of the dongle ensured that the system remained plug-and-playable, with no modification to robot or OCU software.) The link-quality estimator that began under the third-generation *ADCR* project was completed. The estimator provides a "weak link" warning based on received signal strength indicator (RSSI) data and an "imminent failure" alert based on trends in the video data throughput. Through extensive testing, we noted that the video data throughput remained fairly constant long after that RSSI value had decreased. Then at the point where video glitches were beginning to appear, the averaged video data throughput dropped fairly linearly while its variance increased significantly. We designed two linear classifiers to detect this condition, one based on the throughput variance, the other on the averaged throughput trend. Supervised learning algorithms were used to train these classifiers. An "imminent failure" alert is issued when both classifiers detect the condition for three consecutive time samples.[7]

Figure 6. The fourth-generation *ADCR* system on an iRobot *510 PackBot*. The left node is being deployed.

For this design, the OCU end-point radio performed the link monitoring function instead of the *Deployer Module* as in previous generations. This was necessary in order to monitor the throughput of the received UDP video data. In the automatic mode, the imminent-failure alert triggers the automatic deployment of a relay. In the semi-autonomous mode, a link-quality indicator LED on the dongle turns from green to yellow to give the weak-link warning and inform the operator to start looking for a good location to deploy a relay node. This LED turns red to indicate the imminent-failure condition, alerting the operator to deploy the relay immediately. We believe that this mode would be favored by the user in the field. It allows the user to control exactly where a relay node is placed. This location can depend on a number of factors unknown to the system, for example: the overall mission, upcoming maneuvers, the terrain ahead, visibility and ease of locating the relay node for later retrieval, etc.

9. LESSONS LEARNED

In this section we will discuss some lessons learned as well as notes on deficiencies we saw in the design of other relay systems that we have seen in field tests. These should be kept in mind when designing a radio relay system.

One of the common weaknesses we have seen in other relay systems, which caused them to fail in field tests, is the use of high-gain antennas. While high-gain antennas may seem desirable for range extension, this gain typically is achieved by focusing the radiation pattern. In the case of an omnidirectional antenna, the radiation pattern "donut" is flattened. This causes connectivity problems when two neighboring nodes are not at the same elevation, or one is tilted due to uneven terrain.

Another factor to take into account is the height of the antenna on the robot. The height of the relay node antenna (when placed on the ground) must be equal to or greater than this height. Otherwise, since the robot or *Deployer Module* would only drop a relay node when its received signal strength has degraded, the deployed relay node with a lower antenna would encounter an even lower link quality and might not be able to join the network at all.

Also, RSSI does not correspond well with link quality. We have observed that throughput data often remains constant well after RSSI has started to decrease. Monitoring the throughput itself is a more effective method for determining when to deploy a relay node.[7]

The high throughput required to transfer multiple streams of video data from a remotely controlled vehicle (often outfitted with multiple cameras) limits the practical number of relay nodes. For our systems, we have noticed that problems controlling the vehicle begin to appear after three relays are in the route. This can be mitigated by reducing video resolution and/or dropping color information from the video streams. Another solution is to use dual-frequency radios to allow simultaneous transmission and reception of data at each node, increasing the overall throughput of the mesh network.

"Route flapping" is a potential problem when the routing algorithm switches between two routes of nearly equal "cost" (which could be a function of link quality, number of intermediate nodes, etc.). The constant switching between two routes could bring the network to a halt. One way to prevent this is to use some measure of hysteresis and "good enough" metrics so that a new route is not selected as long as the current route is still good enough to carry the required network traffic.[6]

When several nodes are in close proximity, they also tend to jam each other so that none can enter the network. In the first- and second-generation *ADCR* systems only one stowed node inside the *Deployer Module* was active at any given time. The system ensured that the active node had successfully joined the network before deploying it and activating the next node. In the *MDCR* and fourth-generation *ADCR* designs, both relay nodes were active while being carried by the robot. However, the angular offset between the two antennas allowed both to be in the network. We have observed that placing the two nodes on a level table top at the same separation distance caused them to block each other from entering the network.

10. CONCLUSIONS

Our experience with these projects has shown that the path from research-and-development to fielding is not always a straight line. Our first project, *AMCR*, demonstrated the most advanced machine intelligence and autonomy. However, to bring the technology to the Warfighter, other real-world concerns came into play, including logistics, ruggedness, operational simplicity, and user acceptance. *ADCR* was much simpler, with only a portion of the autonomy retained but more logistically realistic. The design that was finally fielded, *MDCR*, had no autonomy except for network route selection. The fourth-generation *ADCR* attempted to reinsert autonomy into the fielded systems. We believe that its semi-automatic deployment mode is likely the best solution that will be acceptable to the user. It combines user input (which makes use of human perception and decision-making abilities) with the radio's link-quality monitoring capability and allows for safe operation in the widest variety of terrain.

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Note: all the above publications can be downloaded from the SSC Pacific Unmanned Systems publication archive, at: *http://www.public.navy.mil/spawar/Pacific/Robotics/Pages/Publications.aspx*.