TECHNICAL REPORT 2042
April 2014

Unmanned Ground Vehicle Communications Relays

Lessons Learned

Hoa Nguyen
Narek Pezeshkian
Aaron Burmeister
Abraham Hart

Approved for public release.

SSC Pacific

TECHNICAL REPORT 2042
April 2014

Unmanned Ground Vehicle Communications Relays

Lessons Learned

Hoa Nguyen
Narek Pezeshkian
Aaron Burmeister
Abraham Hart

SSC Pacific
San Diego, CA 92152-5001

SSC Pacific
San Diego, California 92152-5001

Kurt. J. Rothenhaus, CAPT, USN
Commanding Officer

C. A. Keeney
Executive Director

ADMINISTRATIVE INFORMATION

The work described in this report was performed for Intelligent Ground Systems (IGS), U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) by the Unmanned Systems Science and Technology Branch (Code 71710), Advanced Systems & Applied Sciences Division, Space and Naval Warfare Systems Center Pacific (SSC Pacific), San Diego, CA.

Released by
T. Pastore, Head
Unmanned Systems Science
and Technology Branch

Under authority of
M. Machniak, Head
Advanced Systems and
Applied Sciences

SB

EXECUTIVE SUMMARY

Space and Naval Warfare Systems Center Pacific has been developing mesh-networking communication-relaying technology to mitigate the line-of-sight problem associated with modern high-frequency wireless communications for more than 10 years. This report documents the lessons we have learned during the development of these systems and important principles critical to future communication-relay development efforts. These topics are summarized below, organized into five functional groups: radio-frequency principles, wireless networking, mechanical design, electronic design, and software.

RADIO-FREQUENCY PRINCIPLES

Low-gain omnidirectional antennas should be used for a relay system to be versatile and able to work in a wide variety of environments with no a priori terrain and placement information.

The height of the relay-node antenna when placed on the ground must be equal to or greater than the height of the antenna on the robot. Otherwise, the deployed relay node with a lower antenna would encounter lower received signal strength than the robot and might be unable to join the network.

When two nodes are in close proximity, the receiver front end of one node tends to get saturated by the strong signal emitted by the nearby node's transmitter. This may lead to mutual jamming so that neither can enter the network. This often means that only one node should be on at a time while being transported by the robot.

WIRELESS NETWORKING

The Receive Signal Strength Indicator (RSSI) does not correspond well with link quality. Data throughput often remains constant (and video data retains its clarity) well after RSSI has started to decrease. Monitoring the throughput itself is a more effective method for determining when to deploy a relay node.

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 in the data route. This limit is about three for 802.11g wireless networks. Techniques for increasing this limit include reducing the video resolution, eliminating the color component, or using multi-frequency radios.

Due to the delay incurred in establishing a new route, 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 can still carry the required network traffic.

MECHANICAL DESIGN

We analyzed nine types of antenna masts and presented their suitability for various missions: spring hinge, motorized 1 degree of freedom (DOF), telescoping, telescoping spring, weeble wobble, spring-steel foldable, static mast, inflatable mast, and *ZipperMast*™. Of these designs, the spring-hinge and spring-steel foldable masts are most suitable for relay nodes to be deployed from moving unmanned ground vehicles.

Depending on the size and shape of the relay nodes, the deployment method, and the antenna design, a self-righting capability may be required by the relay nodes. We analyzed the usability of three designs: spring-loaded flap, opening book, and tri-cylinder. The spring-loaded flap design was used in the first-generation Automatically Deployed Communication Relays (ADCR) system.

If the relay nodes are not assembled in a moisture-free environment, condensation will build up when the units are subjected to cooler temperatures. Desiccant packs will need to be included inside the nodes to mitigate potential humidity issues. Alternatively, conformal coating of the electronic circuit boards can be used to prevent shorts due to condensation.

ELECTRONIC DESIGN

The type of coaxial cable used for the antenna can affect the overall gain by 1 to 2 dB. The design of the antenna must keep the mast height beyond the minimum dictated by Fresnel-zone attenuation while minimizing the attenuation and maintaining enough flexibility to accommodate the bending required by the mechanical design.

Since it is desirable to have only one relay node active at any time while they are still being carried by the robot (to avoid the previously mentioned mutual jamming phenomenon), a method must be developed to allow the robot or robot-mounted relay-deployment module to communicate with and control each stowed relay node. We examine four such interfaces: direct electrical contact, radio-frequency identification (RFID), magnetic coupling, and infrared data association (IrDA). The magnetic coupling and IrDA methods were used in various generations of the ADCR systems.

An Ethernet link is normally used to communicate between the robot and the relay-deployment module it carries. If the robot is one of the older analog systems, then a video/audio codec board can be used to convert the analog signals to Internet Protocol (IP) Ethernet data.

SOFTWARE

We experimented with three open-source mesh networking architectures: *BATMAN*, *OLSR*, and *Babel*, and chose *Babel* as the most promising architecture to optimize for mobile unmanned ground vehicles (UGVs).

During network testing, we discovered that the high video-data throughput from the remotely controlled robot can cause the Babel network management algorithm to think that a route has degraded, leading to the previously mentioned “route flapping” problem. The solution is, again, to use hysteresis and a “good enough” measure.

Finally, to provide a relaying system that is plug-and-playable, not requiring software modification or configuration on the robot or operator control unit (OCU), a virtual private network (VPN) can be set up. The drawback, however, is that the two end radios must be paired. Data generated by one radio can only be received by the other in the pair (while the intermediate relay nodes can be any compatible mesh node).

CONTENTS

EXECUTIVE SUMMARY iii

1. INTRODUCTION 1

2. LESSONS LEARNED 1

2.1 RADIO-FREQUENCY PRINCIPLES 1
2.1.1 Antenna Gain 1
2.1.2 Antenna Height 2
2.1.3 Inter-node Jamming 3
2.1.4 Input Filtering 4
2.2 WIRELESS NETWORKING 5
2.2.1 Link Quality 5
2.2.2 Throughput 5
2.2.3 Route Flapping 6
2.3 MECHANICAL DESIGN 6
2.3.1 Antenna Mast 6
2.3.2 Relay-node Enclosure 9
2.3.3 Deployment System 11
2.3.4 Temperature and Moisture Considerations 15
2.4 ELECTRONIC DESIGN 15
2.4.1 Antenna Design 15
2.4.2 Stowed Relays and Deployer Interface 15
2.4.3 *Deployer* and Robot Interface 17
2.5 SOFTWARE 17
2.5.1 Mesh Networking 17
2.5.2 Virtual Private Network 18
2.5.3 Configuration Management 18

3. CONCLUSIONS 19

REFERENCES 20

Figures

1. A toroidal antenna pattern for an onmidirectional dipole (left), and for a higher-gain dipole (right) 1
2. Graphical comparison of total antenna gains on level terrain showing the beneficial effect of higher gain 2
3. Total antenna gains when the two radio nodes are vertically offset. This scenario is encountered when one node is on the road and the other node is down near the entrance to a culvert, for example 2
4. Fresnel zone calculations 3
5. Two active MDCR nodes on an iRobot® PackBot® 510, showing the angular offset between the two antennas 4
6. Determination of signal strength warning and imminent failure alert in the fourth-generation ADCR system [7] 5
7. Spring-hinge antenna mast on self-righting relay node 7
8. Motorized antenna mast stowed (left) and deployed (right) 8
9. A spring-steel foldable antenna (left) and one folded back (right), demonstrating its flexibility 8
10. Static masts used on an early MDCR prototype 9
11. The Tethers Unlimited Self-Righting Peeping Tombot [9]. 11
12. First-generation ADCR system on an iRobot® PackBot® 12
13. Second-generation ADCR system on an iRobot® PackBot® 12
14. Fourth-generation ADCR system on an iRobot® PackBot® 13
15. Second-generation ADCR deployment-module components 14

Tables

1. Antenna heights for communication at 1-km range 3
2. Antenna mast comparison 6
3. Self-righting relay node concept comparison 10
4. Deployment system features 13

1. INTRODUCTION

The need for a high-bandwidth communication link to carry multiple video channels from a mobile robot back to a control station requires using high-frequency RF communication links. These links by nature are mostly line of sight, often limiting the flexibility of movement of the robots. Space and Naval Warfare Systems Center Pacific (SSC Pacific) has been developing relaying technology to mitigate this problem for many years. The Autonomous Mobile Communication Relays project [1], started in the early 2000s, demonstrated the capability of autonomous slave robots to provide communication relaying capability for a lead robot exploring an unknown environment. Several generations of Automatically-Deployed Communication Relay (ADCR) systems [2–5] simplified this solution logistically by developing a robot-mountable *Deployer* module that deploys static relay nodes when and where needed. To meet specific in-theater requirements, we designed the Manually-Deployed Communication Relay (MDCR) system [6], 243 of which were fielded by the Robotic Systems Joint Project Office in 2012. A fourth-generation ADCR system was developed in 2013 to automate the deployment of these fielded and proven MDCR relay nodes [7, 8].

This report documents the lessons we have learned during the development of these systems and important principles critical to future communication relay development efforts.

2. LESSONS LEARNED

The discussions in this section will be grouped into five functional categories: radio-frequency principles, wireless networking, mechanical design, electrical design, and software design.

2.1 RADIO-FREQUENCY PRINCIPLES

2.1.1 Antenna Gain

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, without the use of an electronic amplifier this gain can only be achieved by focusing the radiation pattern. The antenna pattern of a dipole antenna is a toroid, as shown in Figure 1 (left). When the antenna is receiving, this is the pattern of directional sensitivity. When it is transmitting, this represents the signal strength in various directions. A high-gain antenna focuses this pattern. In the case of the dipole antenna, it becomes a flattened toroid as depicted in Figure 1 (right).

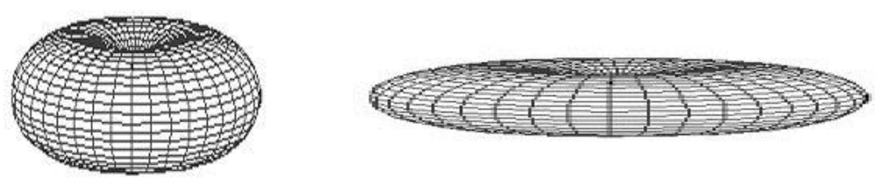


Figure 1. A toroidal antenna pattern for an omnidirectional dipole (left), and for a higher-gain dipole (right).

The use of higher gain dipoles increases the range between radio nodes when they are on the same level plane. Figure 2 depicts this increase in gain or signal strength using a vertical slice of the antenna patterns. The combined length of the dashed lines represents the total gain (sensitivity or signal strength) of the two-node system.

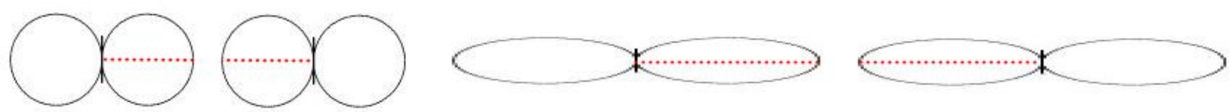


Figure 2. Graphical comparison of total antenna gains on level terrain showing the beneficial effect of higher gain.

However, higher gain can cause connectivity problems when two neighboring nodes are not at the same elevation. Figure 3 depicts this scenario. Note that the combined length of the dashed lines is now shorter for the higher-gain antennas. This phenomenon may also be encountered when the two nodes are at the same level but one or both are tilted due to uneven terrain.

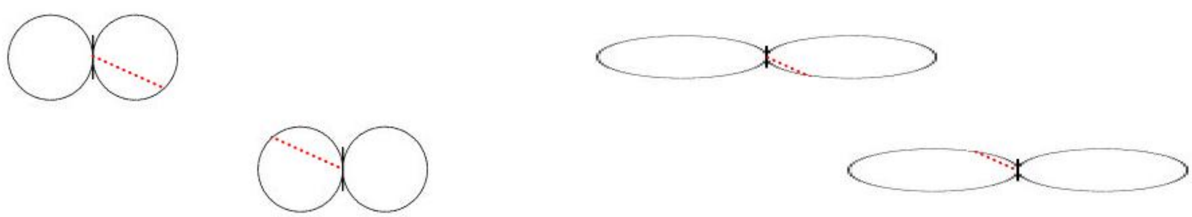


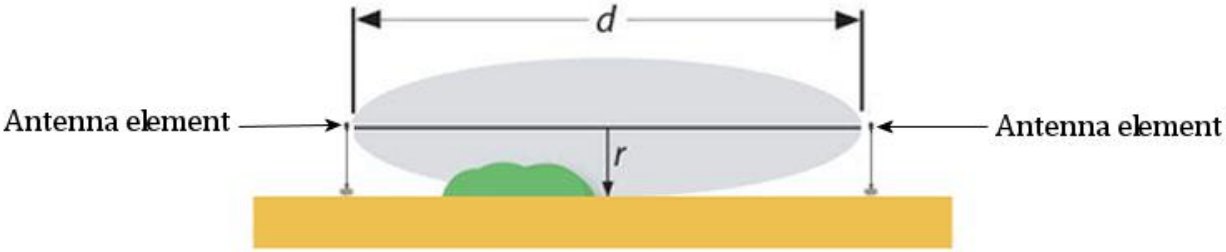
Figure 3. Total antenna gains when the two radio nodes are vertically offset. This scenario is encountered when one node is on the road and the other node is down near the entrance to a culvert, for example.

For a relay system to be versatile and work well in various environments, low-gain antennas are generally best. SPAWAR's MDCR relays and end-point radios use standard half-wave dipoles with 2.1-dBi gain. We have seen other relay systems using 6-dBi high-gain antennas fail the culvert test at Naval Air Weapons Center China Lake.

2.1.2 Antenna Height

The concept of Fresnel zone clearance is very useful in determining the transmission strength between two relay nodes. The (first) Fresnel zone is an ellipsoid connecting the two antennas. Objects (or even the ground) that obstruct part of this zone will produce interferences that reduce the received signal level. As a rule of thumb, a maximum of 40% obstruction is tolerable, but 20% or less is desirable for good communication through the Fresnel zone. Figure 4 depicts the Fresnel zone between two antennas, and the calculation of the zone radius (r), which increases with longer range and/or lower frequency.

Table 1 shows the antenna heights required for unobstructed (by the ground), 20% obstructed, and 40% obstructed communication through the Fresnel zone for a 1-km range at 2.4- and 4.9-GHz frequencies.



$$r_{(\text{in m})} = 17.32 * \sqrt{\frac{d_{(\text{in km})}}{4f_{(\text{in GHz})}}} \quad \text{or} \quad r_{(\text{in ft})} = 72.05 * \sqrt{\frac{d_{(\text{in miles})}}{4f_{(\text{in GHz})}}}$$

Figure 4. Fresnel zone calculations.

Table 1 shows the antenna heights required for unobstructed (by the ground), 20% obstructed, and 40% obstructed communication through the Fresnel zone for a 1 km range at 2.4 GHz and 4.9 GHz frequencies.

Table 1. Antenna heights for communication at 1-km range.

Frequency	40% Obstruction	20% Obstruction	No Obstruction
2.4 GHz	0.9 m (2' 11")	2.8 m (9' 4")	5.6 m (18' 4")
4.9 GHz	0.6 m (2')	2.0 m (6' 6")	3.9 m (12' 10")

We can see from Table 1 that the best case for communication (no obstruction) requires unrealistically tall antennas for unmanned ground vehicles, and most fielded UGV communication systems are operating in the 20% to 40% obstruction range. In this mode, any increase in antenna height will result in increased signal strength at the receiver.

This means that attention must be paid to the height of the antenna on the robot compared to that of the relay nodes. Assuming omnidirectional antenna patterns, the height of the relay-node antenna when placed on the ground must be equal to or greater than the height of the antenna on the robot. Otherwise, the deployed relay node with a lower antenna would encounter lower received signal strength (due to more Fresnel-zone obstruction) than the node on the robot and might be unable to join the network. In other words, because the robot adds height to its antenna, the same antenna shaft cannot generally be used on the robot and on the relay nodes.

MDCR uses a different antenna shaft on the robot than the ones used on the relay nodes, so that all antennas are at the same level after the nodes are deployed on flat terrain.

Note: This effect contributes to the often-reported field observations that a 4.9-GHz radio system has about the same range as a 2.4-GHz radio system for unmanned ground vehicles, even though in free space a higher frequency signal would attenuate faster and would be expected to have a shorter range. The mitigating factor here is that for the same antenna height, the 4.9-GHz system has a flatter Fresnel zone that is less obstructed by the ground than a comparable 2.4-GHz system.

2.1.3 Inter-node Jamming

When two nodes are in close proximity, the receiver front end of one node tends to get saturated by the strong signal emitted by the nearby node's transmitter. This may lead to mutual jamming so that neither can enter the network. In our experience, active MDCR nodes (operating at 4.9 GHz) must be kept at least approximately 1 m (40”) from each other to ensure no mutual jamming. For this reason, 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 *Deployer Module*. In the *MDCR* design, both relay nodes had to be active while being carried by the robot. However, the angular offset between the two deployment forks, which was designed to allow the nodes to be deployed one at a time using the synchronized flippers, also produced an angular offset and a larger separation between the two relay node antennas (see Figure 5). This helped to reduce the inter-node antenna gain (see Section 2.1.1), allowing both nodes to be in the network while being carried by the robot. We have observed that placing the two nodes on a level table top at the same distance apart prevented them from entering the network.

Figure 5. Two active MDCR nodes on an iRobot® *PackBot® 510*, showing the angular offset between the two antennas.

2.1.4 Input filtering

We have observed that input filtering is the best defense against unintentional radio-frequency (RF) jamming to preserve the link between the OCU and the robot. (Other electromagnetic interference-mitigating techniques, such as RF shielding of the electronics, beam forming of the antenna pattern, etc., are not as effective.) Coalition RF jammers often have an unintentionally wide spectral output (or harmonics) that raises the noise floor across the input frequency band of the radio pre-amplifier (which often has a much wider input bandwidth than the intended communication signal). This interferes with the repeater’s operation even when the operational frequency is not being targeted for jamming. Since, in most cases, the jammer and the robot OCU are in close proximity, input filtering is desirable for the OCU-side radio. The robot is usually deployed farther from the jammer than the OCU and continues to be driven farther away. Hence, unintentional jamming is less of an issue for it and the relay nodes it is carrying.

We used a commercial bandpass filter on the OCU-side MDCR end-point radio to mitigate jamming issues. The center frequency and bandwidth of the bandpass filter were chosen to match the relay network’s frequency characteristics. The bandpass filter helps to attenuate the noise outside the frequency band of interest, improving the overall signal-to-noise ratio of the received signal.

2.2 WIRELESS NETWORKING

2.2.1 Link Quality

We have found that RSSI does not correspond well with link quality. Data throughput often remains constant (and video data retains its clarity) well after RSSI has started to decrease. Monitoring the throughput itself is a more effective method for determining when to deploy a relay node. At the point where video glitches begin to appear, the averaged video data throughput drops linearly while its variance increases significantly. For our fourth-generation ADCR system, we use the RSSI data to provide a “weak-link” warning. However, the “imminent-failure” alert is based on two linear classifiers designed to detect the throughput drop-off. One classifier is based on the throughput variance, the other on the averaged throughput trend. Supervised learning algorithms were used to train these classifiers. The “imminent-failure” alert is issued when both classifiers detect the trigger conditions for three consecutive time samples [7].

Figure 6 shows a 2-min recording of RSSI (green line) and video throughput (blue line) illustrating typical trends of both as the video quality diminishes until total link loss due to the robot moving out of range of the control station. The first solid black vertical line represents the time when video glitches start to appear, and the second solid black vertical line is the time when video data is no longer useable. Using linear classifiers, the relay system automatically issues a warning (vertical yellow line, based on RSSI value) and an imminent link-failure alert (vertical red line, based on video throughput trend and variance). The RSSI and throughput lines were averaged. The throughput actually exhibits much larger variances as it drops.

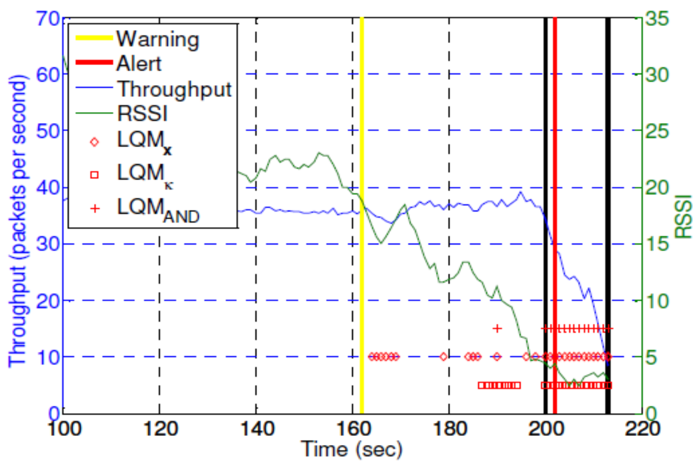


Figure 6. Determination of signal strength warning and imminent failure alert in the fourth-generation ADCR system [7].

2.2.2 Throughput

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. The required throughput, type of data, mesh topology, and the data usage determine the maximum number of relay nodes that can be used in a data-traffic route. For our systems, we have noticed that problems with remotely controlling the vehicle in real time begin to appear after three relays are present in a linear route. This can be mitigated by reducing video resolution, number of cameras, and/or dropping color information from the video stream. Another solution is to use dual-frequency radios to allow simultaneous transmission and reception of data at each node, increasing the overall throughput capacity of the mesh network.

2.2.3 Route Flapping

"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.). Due to the delay incurred in establishing a new route (no matter how small), 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 can still carry the required network traffic. This was implemented in our MDCR and fourth-generation ADCR systems.

2.3 MECHANICAL DESIGN

2.3.1 Antenna Mast

Several key attributes are desired in a relay-node antenna mast deployed from a UGV. As discussed previously in Section 2.1.2, appropriate antenna height is considered critical. Additionally, resistance to impact loads and durability are also very important. Deployment of the relay node may be while the UGV is in motion and may include a free fall to the ground. For this reason, the relay node and antenna must be constructed to mitigate the destructive effects of ground impact. An antenna mast can be constructed to withstand the impacts or stowed within an outer shell that protects it until after the node has been placed. The antenna can then be deployed.

Deployable antenna masts are usually more complex because they need to transform from a compact shape inside the relay node enclosure into a long straight vertically oriented mast. Many different concepts of deployable antenna were examined to understand their utility. Table 2 includes a list of different antenna-mast concepts that were explored for use as relay nodes. Each concept has been rated in a variety of characteristics on a scale of 1 to 3, with 1 the worst and 3 the best. This table is not an endorsement of any one concept but attempts to give a general characterization of different design approaches.

Table 2. Antenna mast comparison.

Description	Complexity	Durability	Height	Impact Resistance	Cost	Weight
Spring hinge	2	2	2	3	2	3
Motorized 1 DOF	1	2	2	1	1	2
Telescoping	1	1	2	2	1	1
Telescoping spring	1	1	2	1	1	2
Weeble wobble	3	3	1	3	1	3
Spring-steel foldable	2	3	3	3	2	2
Static mast	3	3	3	1	3	2
Inflatable mast	1	1	2	3	2	2
ZipperMast™	1	2	3	2	1	1

A spring-hinge antenna mast was used in our first-generation ADCR relay nodes (Figure 7). The antenna mast is made of three aluminum links, a radiating element, and four spring hinges. The mast is folded and stored in a cavity in the relay node for protection until the relay node has come to rest on the ground surface. This type of antenna mast proved effective for deployment from vehicles the size of a iBot® Packbot® UGV. The antenna mast was approximately 18 in tall and could be folded into a relay node less than 8 in long. This design could be scaled to larger systems. The relay enclosure protected the antenna effectively before mast deployment. However, the complexity of the mast reduced its durability.

Figure 7. Spring-hinge antenna mast on self-righting relay node.

A motorized antenna mast with 1 DOF was demonstrated on the second-generation ADCR system (Figure 8). The relay node was deployed and the antenna masts were then actuated to a vertical position by a motor (Figure 8, right). An accelerometer was used to find the vertical orientation regardless of which side the node landed on or whether the relay node had landed on level ground. This type of antenna-mast deployment required fewer parts than the spring mast but the antenna masts were not protected well from impacts with the ground. Many antenna masts broke during relay node placement. Unless a method is found for protecting the antenna masts during deployment, this design will not work well for nodes that must be dropped from a moving robot or from a considerable height. Furthermore, because the antenna masts are relatively long, a motor gearbox with adequate torque for deployment actuation must be selected.

A telescoping antenna mast consists of rigid tubes of decreasing diameter nested within one another similar to an extendable automobile antenna or tripod leg. A telescoping mast can be actuated using air pressure or a by a flexible linear gear and motor. The linear sliding motion of the nested links is prone to jamming in dirty and rugged environments where UGV systems are often used. Dings or bends in the links can easily jam motion making this approach difficult for automated deployment from a UGV. Management of the coaxial cable within the mast can prove problematic during extension and retraction.

A spring-loaded linear telescoping mast with stacked links was developed as a conceptual prototype under the ADCR project. The prototype was very compact but also very complex and prone to jamming. This type of design is not recommended for use with UGVs.

A weeble-wobble type mast consists of a base with a spherical base that is weighted at the bottom and a lightweight vertical mast. This type of design is similar to the children's toy, *Weeble*. This design is simple but must be large and heavy to have the geometric proportions required to position the antenna high above the ground. This type of mast will remain vertical only on hard, flat, and level surfaces. Rough, soft, or uneven surfaces will keep this design from righting correctly. This type of mast is also susceptible to wind.

Figure 8. Motorized antenna mast stowed (left) and deployed (right).

A spring-steel foldable antenna (Figure 9) was used with the MDCR system. The antenna mast is rugged and flexible. It can be bent 180º at one point and still return to its original position. It is constructed from two long strips of spring steel, each with a parenthesis shaped cross section (similar to a tape measure). The two pieces of spring steel are held together with an outer sheath and the coaxial cable for the antenna runs between the pieces of spring steel. This type of antenna mast, designed for use with UGVs, is rugged, reliable, and can be configured to reach a beneficial height. For this type of mast to be bent for storage or pre-deployment, however, the two pieces of spring steel must slide relative to each other. This works well for one bend in the mast but cannot accommodate more, which limits how compact this type of antenna can be when stored.

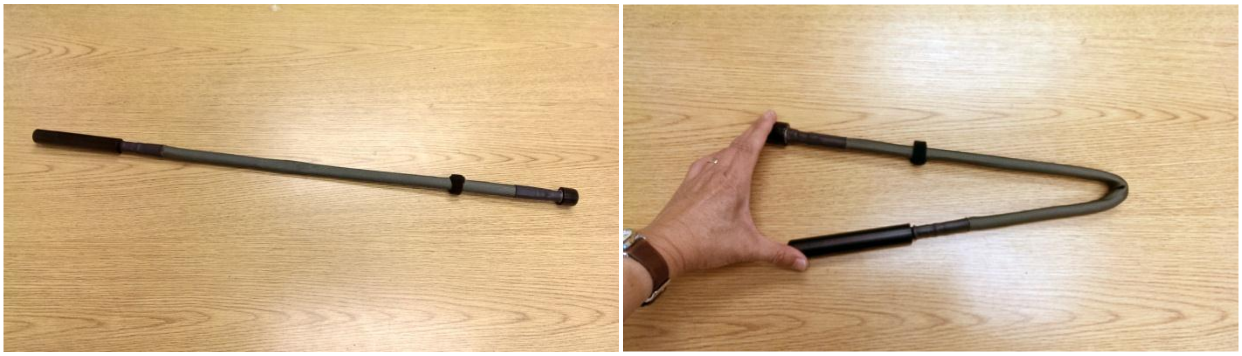


Figure 9. A spring-steel foldable antenna (left) and one folded back (right), demonstrating its flexibility.

Inexpensive and simple, a static mast is the simplest type, but hard to protect during deployment from the UGV. It also takes up a significant amount of space on the UGV and requires careful placement to maintain the antenna in a vertical position during deployment. This type of antenna was tested on the MDCR system (Figure 10) but abandoned in favor of the spring-steel mast design in the production systems, as the rigid nature of the antenna mast led to many broken masts during handling and testing. This type of mast cannot be deployed at speed and requires a relatively complex deployment method to reliably place the relay node in a vertical orientation.

Figure 10. Static masts used on an early MDCR prototype.

It is conceivable that an inflatable mast utilizing a $C0_2$ cartridge, pressure regulator, and valve could be used to apply and maintain pressure in an appropriately sized mast for a UGV relay node. The mast however would only remain extended as long as the $C0_2$ cartridge can supply gas to the mast. The length of the time the mast can remain deployed is dependent on the pressure and volume of gas in the cartridge and the leak rate out of the mast. Additional experimentation would be required to assess the suitability of this approach for use with relay nodes.

ZipperMast™ is a system developed by Geosystems Inc. and is deployed by motors that drive three coiled pieces of spring steel into an extended mast with a triangular cross section. The mast is very suitable for systems that require a relatively long mast. However, the complexity, size, and cost of the system make it unsuitable for a UGV relay-node system that must be small and requires a relatively short mast.

2.3.2 Relay-node Enclosure

A relay-node enclosure must contain the radio, battery, and electronics and provide for antenna deployment. It must also be designed to meet the shock, vibration, ultraviolet, thermal, and ingress protection requirements of the application. Interface requirements may also need to be considered, such as recharging, power switch, battery level, relay retrieval, remote power toggling, and channel selection.

Shock isolation is an important consideration when designing a relay node that will be dropped from a fast-moving UGV or from a considerable height. Testing done on the ADCR project showed that internal electronics in an ABS enclosure dropped from a iBot® *PackBot*®-mounted *Deployer* experienced high-impact forces. During testing of prototype relay nodes, both Mini-PCI and PCMCIA radios were dislodged from their card slots due to deployment-induced impacts. For this reason, internal electronics may need to be mounted on shock and vibration isolators. When selecting shock isolators, it is important to verify that relative motion of isolated components under maximum loading will not cause them to collide with non-isolated components. This type of interaction led to the failure of some electrical connectors on an early ADCR prototype.

Depending on ambient heat conditions and heat generation of the radio and support electronics, an appropriate heat-dissipation strategy should be evaluated.

Self-righting of a relay node may be required to allow proper deployment of the antenna mast. Several self-righting concepts have been explored. Table 3 captures the concepts explored and gives subjective ratings in key areas where 1 is worst and 3 is best.

Table 3. Self-righting relay node concept comparison.

Self-righting Concept	Righting Reliability	Stability	Complexity	Impact Resistance	Cost
Spring-loaded flap	2	2	2	2	2
Opening book	3	3	3	2	3
Tri-cylinder	2	3	2	2	1

The first-generation ADCR used a spring-loaded-flap system (Figure 7) to right a brick-shape relay node. The relay node geometry and proportions were such that it was unlikely for the node to land on one of the two smaller ends. A motorized latch held the flaps in place until the node came to rest on the ground, after which the motor was actuated and the flaps rotated outward, righting the node, regardless of which of the four longer faces the node had landed on. This righting method worked well in most terrain. Slopes greater than 20º could be problematic for this design because the righting motion may cause the node to tumble down the slope. Additionally, the self-righting mechanism would occasionally fail on sandy ground when the sand would give as the relay node attempted to right itself. The latch was designed to allow the flaps to be reset without actuating the motor. They could simply be pushed back into place manually and recaptured. Making sure that the torsion springs used in the flaps had enough torque to right the relay node was an important design consideration. Lubricants should also be used to reduce the rotational friction of the latch to minimize the torque requirement of the motor, which would allow a smaller motor to be used. The lubricant must be rated for cold temperatures; otherwise friction will increase at colder temperatures, stopping the motor from rotating. The first-generation ADCR system experienced this problem while tested in an underground coal mine.

If the node is thinner, then a variation is one that resembles a book with the front cover as the righting element. When the relay is dropped from the UGV, it is most likely to land on the front or back surface instead of on one of the smaller sides. When the relay has come to rest, the "book cover" opens. If the relay node has landed on its back, the opening of the front cover simply makes the node more stable. If the node has landed on its front, then it will be flipped over. The antenna mast can then be deployed. The exterior of the node can be designed in a way to absorb impact forces protecting the internal antenna mast, radio, and electronics.

A tri-cylinder design consists of an antenna mast and electronics enclosed within a cylindrical enclosure. Exterior to the cylinder, three legs are folded up parallel and close to the cylinder. The relay node is deployed, comes to rest, and then the three legs rotate outward forming a tripod that rights and stabilizes the cylinder. This design has significant complexity in the actuation of the three legs but can achieve both righting and antenna deployment with one actuation. The *Self-Righting Sensor* by Tethers Unlimited is an example of this type of system (Figure 11).

Figure 11. The Tethers Unlimited Self-Righting Peeping Tombot [9].

2.3.3 Deployment System

Four relay-node deployment systems were developed at SSC Pacific. The first-generation ADCR (Figure 12) deployed brick-like relay nodes with spring-hinged antenna masts (Figure 7). The second-generation ADCR and the APDS deployment systems (Figure 13) shared a common design that delivered thinner relay nodes with motorized antenna masts (Figure 8). The MDCR system employed forks attached to the iRobot® *PackBot*® and *miniEOD* robot flippers (Figure 5 and Figure 10), and depended upon the flippers to place the relay nodes. Finally, the fourth-generation ADCR deployment system (Figure 14) used motorized forks attached to the back of the robot to drop the MDCR relay nodes, freeing up the iRobot® *PackBot*® flippers so that they could be used for their intended purposes. (This design can also be easily adapted to other robotic platforms such as the *Talon.*) All four deployment systems were designed for small UGVs traveling at slow speeds (5 mph or less). Common important features include ability to emplace a relay and manual loading and unloading of relay nodes. A list of features for each deployment system is shown in Table 4.

2.3.3.1 Relay Deployment

All deployment systems require a method for emplacing the relay node on the ground. The first-generation ADCR system (Figure 12) used a compression spring-loaded mechanism. The second-generation ADCR system (Figure 13) used a constant-force-spring-loaded mechanism. MDCR (figure 5) used a fork with magnets to hold the relay node securely, with the node emplacement accomplished by the robot flippers. Finally, the fourth-generation ADCR)Figure 14) used a motorized forked carrier with magnets to emplace the relays. Many other methods are conceivable, such as dropping the relays out of the bottom of a *Deployer* using gravity. The spring-loaded designs had the benefit of allowing relays to be closely packed into a small space on top of the robot. MDCR and the fourth-generation ADCR were much less compact systems but allowed relay nodes to be both emplaced and picked up for repositioning or retrieval.

Figure 12. First-generation ADCR system on an iRobot® *PackBot*®.

Figure 13. Second-generation ADCR system on an iRobot® *PackBot*®.

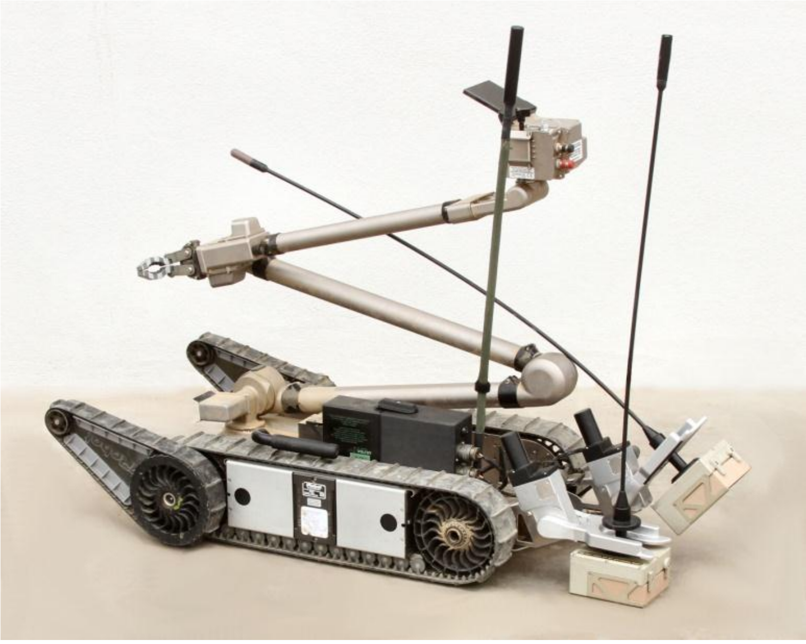


Figure 14. Fourth-generation ADCR system on an iRobot® *PackBot*®.

Table 4. Deployment system features.

Feature	First-generation ADCR	Second-generation ADCR/APDS	MDCR	Fourth-Generation ADCR
Emplace relay	Yes	Yes	Yes	Yes
Manual load/unload relay	Yes	Yes	Yes	Yes
Pick up relay	No	No	Yes	Yes
Turn relay on/off	Yes	Yes	No	No
Program relay while in *Deployer*	No	Yes	No	No
Placement mechanism	Compression spring	Constant-force spring	Robot control	Motorized
Latch mechanism	Spring pin	Rotating latch	Magnets	Magnets

The first- and second-generation ADCR systems both launched the relay node out of a *Deployer* using a spring. For the first-generation ADCR, a compression spring was used. The force provided by a compression spring (F_{CS}) follows Hooke's Law,

$$F_{CS}=kx,$$

where k = spring constant, and x = spring displacement.

The potential energy stored in a compression spring (PE_{cs}) that can be converted to kinetic energy of the launched relay is

$$PE_{CS} = (1/2)kx^2.$$

To have enough energy to launch a relay node, the compression spring must be considerably compressed, resulting in a large force being applied when the relay is fully stowed. A strong latch is required to hold the brick in place.

The second-generation ADCR system used a constant-force spring to launch the relay nodes. A constant force spring does not follow Hooke's Law. Instead, it provides the same output force along its entire range of motion. In most cases, it also has a much longer range of motion than a coiled compression or tension spring. The potential energy output for a constant force spring is

$$PE_{CFS}=xF_{CFS}.$$

The latching force required for a constant-force spring is equal to the output force of the spring. Given the same desired potential energy ($PE_{CFS} = PE_{CS}$) and loading distance (x), a launching mechanism with a constant-force spring will require half the latching force of a compression-spring system.

A linear track is required to guide the motion of the spring and relay node to be launched from a *Deployer* with a constant-force spring. Linear tracks are prone to jamming and must be carefully designed to operate effectively in dirty, dusty, and wet environments.

2.3.3.2 Manual Relay-node Loading and Unloading

The relay nodes should be able to be manually loaded into and unloaded from the deployment system to allow for charging, maintenance, and other logistical considerations. For systems with a motorized mechanical latch such as the first- and second-generation ADCR systems, additional mechanical parts were incorporated to allow an operator to manually back-drive the latch and release the relays. To manually remove relays from an MDCR or fourth-generation ADCR system, a person would simply pull the relay hard enough to overcome the magnets holding it in place on the fork carrier. For ease of operation, deployment systems should be designed to require only one motion for loading. Latches in the second-generation ADCR systems achieved this, allowing an operator to simply push a relay node into the *Deployer* until the rotating latch mechanism deflects and snaps into the catch on the relay (Figure 15).

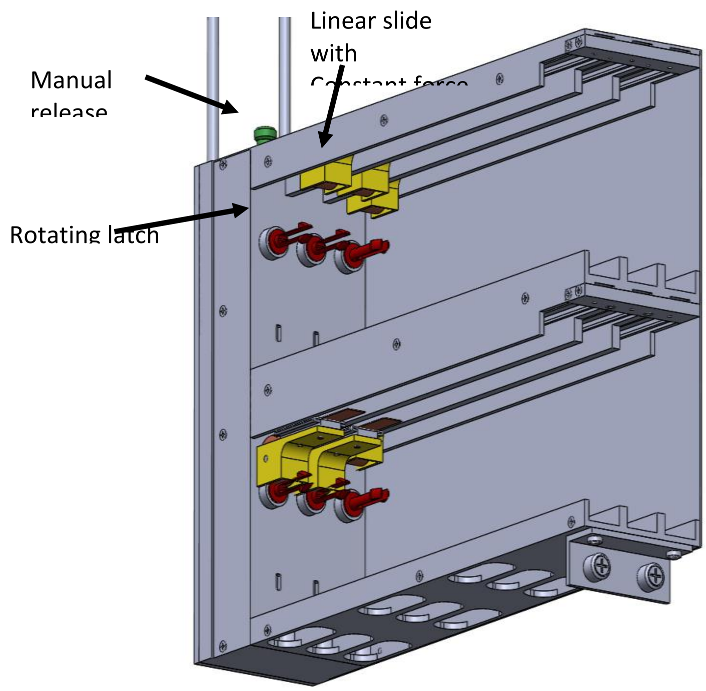


Figure 15**.** Second-generation ADCR deployment-module components.

The first-generation ADCR system used a motor-actuated, quick-release spring pin and catch to retain relay nodes. As a relay node was pushed into the *Deployer*, the end of the pin entered the relay. At the same time, the operator had to pull a lever to manually press the button on the spring pin allowing the relay to be pushed in all the way. The operator then released the lever and the balls on the spring pin extended out and captured the catch on the relay. This method of loading was difficult for the operator, and the linear motion required to engage and disengage the latch was prone to jamming. It is recommended that future deployment systems employing a latch mechanism use a rotational latch similar to second-generation ADCR instead of the linearly actuated latch employed by the first-generation ADCR.

2.3.4 Temperature and Moisture Considerations

To ensure that the MDCR relay nodes function over the specified temperature range, several units were tested in our on-site environmental chamber. The test units were subjected to temperature swings with the units both active (functional test) and inactive (storage test). We observed that condensation built up when the units were cooled (and the air inside cannot hold as much moisture), since they were not assembled in a moisture-free environment. If relay nodes are to be opened for repair or software upgrades, it may not always be possible to re-assemble them in a controlled, dry environment. Therefore desiccant packs were installed in each MDCR node to mitigate potential humidity issues. Conformal coating of the electronic components and circuit boards is another method for preventing shorts due to condensation.

2.4 ELECTRONIC DESIGN

2.4.1 Antenna Design

There are several constraints in designing an antenna mast:

- Minimum mast height – The height of a deployed relay-node antenna must be no less than the height of the robot antenna as measured from the ground (see Section 2.1.2).
- Flexibility – The relay node mast must be flexible enough to allow the carrying robot to travel through low-height tunnels (like culverts) without mobility constrains or antenna damage. Rigid masts will severely limit mobility and may cause the mast to break.
- Attenuation – The attenuation of the coaxial cable running through the mast must be kept to a minimum to maximize transmitted and received signal power.

During development of the MDCR system, several iterations of antenna-mast designs were prototyped and tested on a robot to observe their flexibility during platform motion. We also measured their radiation patterns at our on-site anechoic chamber. Even though the overall length of the antenna mast, and hence, the RF coaxial cable within was relatively short, the type of coaxial cable used affected the overall gain by 1 to 2 dB. The final design kept the mast height beyond the minimum dictated by Fresnel-zone attenuation (see Section 2.1.2) while minimizing the attenuation and maintaining enough flexibility to allow the mast to fully snap back to vertical from a 180-degree deflection.

2.4.2 Stowed Relays and *Deployer* Interface

The robot carries a *Deployer* module that contains the relay nodes to be deployed. Since a relay node takes a finite amount of time to fully boot and enter the network, it is of utmost importance to have a relay node that is fully booted and in the network before deployment is needed. This prevents any network interruptions because of deployment. To meet this requirement, one option is to activate all relay nodes prior to driving the robot down range.

This option has two drawbacks:

- Due to the close proximity of all their antennas, the relay nodes will mutually interfere and prevent themselves from entering the network (see Section 2.1.3). This is manageable when there are no more than two relay nodes by placing the antennas at an angular offset from one another to reduce co-interference. This angular-offset approach was successfully used in the MDCR system.
- Battery power of the active but unused relay nodes will be wasted during the mission.

A second option is to always have only one active relay node in the *Deployer*. As soon as the active relay node has been deployed, the next one in the *Deployer* will turn on and become ready for deployment. Since the boot time of a relay node is normally shorter than the time between two consecutive deployments, this approach guarantees no network interruption due to deployment. This option eliminates the disadvantages of the first approach but introduces a new requirement: a means to selectively activate individual relay nodes stowed in the *Deployer*, which requires a communication interface between the *Deployer* and the stowed relay nodes.

Below is a short list of various interfaces we have considered and those that have been selected for use in various iterations of the ADCR system.

- Direct electrical contact – One approach is to have a direct electrical data connection between stowed relay nodes and the *Deployer*. Although this appears to be a simple approach it does introduce serious challenges in keeping the contacts from shorting (due to wet or rainy conditions) and keeping them clean (due to dust and gunk build up).

- Radio-frequency identification (RFID) – We have considered using RFID technology to allow the *Deployer* to communicate with its stowed relay nodes, but this approach has two major issues:

    - It is prone to signal jamming.

    - It is difficult to localize. It is essential for the Deployer to know which relay node is active so that it can be deployed. The ID of the active relay node can be easily obtained, but not its exact location in the Deployer to a high degree of accuracy.

- Magnetic coupling – The requirement to activate a relay node can be communicated from the *Deployer* to the relay node using only one bit of information. In the first-generation ADCR system, we placed electromagnets behind each chamber of the *Deployer*. Within each relay node we placed a Hall-effect sensor, which was interfaced to a micro-power always-on circuit. To activate a relay node, the *Deployer* would pulse the appropriate electromagnet. The Hall-effect sensor would sense the ensuing magnetic field and trigger the micro-power circuit to enable the main power switch of the relay node. This approach is very robust to environmental conditions and entirely sealed within the *Deployer* and relay-node enclosures, however, the major drawbacks are:

    - Electromagnets are generally larger, more expensive, and heavier than other options

    - Inappropriate for high data-rate communications

    - No feedback from relay node to *Deployer* to indicate successful power-up

- Infrared data association (IrDA) – The development of improved versions of the ADCR system (and specifically the Automatic Payload Deployment System [4, 5]) demanded a communications link between the *Deployer* and its stowed relay node that can support relatively high data rates. As a result, we integrated an IrDA transceiver in each relay node and each bay of the *Deployer*. This allowed the *Deployer* to transmit and receive full packets of data, thus providing a great deal of flexibility in detecting not just relay-node payloads but other payload types as well, like camera nodes, illuminator nodes, and carrier nodes (to carry supplies, food, ammunition, etc.). We have found that IrDAs are very robust to dirty conditions. We have performed experiments where we have severely scratched the surface of the transparent plastic cover using sandpaper and discovered that messages were still transmitted and received successfully. Some design requirements are needed to ensure successfully operation with IrDAs:

- "Blinders" were required for each bay of the Deployer to prevent crosstalk between adjacent chambers. These were simply long hollow square structures that prevented the infrared light of one chamber from shining onto another.
- To save battery power, each relay node must only consume micro levels of power while waiting to receive a message over its IrDA interface before fully waking and booting.

2.4.3 *Deployer* and Robot Interface

Since the repeater system replaces the native communication system of the robot, the *Deployer* must have a way to interface to the robot. We have historically used a 10/100 Ethernet interface since it is fast and robust enough to support high data rates, easy to work with, and is usually available as an external connector on robotic platforms. However, Ethernet is not a strict requirement. We have demonstrated our repeater system on an older QinetiQ *Talon* robot that does not support Ethernet. It has just analog audio, video, and serial communications. In this case we embedded an audio/video codec in the *Deployer* to act as the bridge between the robot's analog audio/video and serial interface and the *Deployer* radio's Ethernet interface. Of course, the same codec was used on the controller side to bridge the OCU-side radio to the controller.

2.5 SOFTWARE

2.5.1 Mesh Networking

We experimented with three open-source mesh networking architectures: *BATMAN*, *OLSR*, and *Babel*. On-robot experiments revealed that *Babel* provided network route switching more quickly and accurately than *OLSR*. *BATMAN* was unable to successfully run. *Babel* allowed the robot and OCU to connect, although mesh transitions took minutes. *OLSR* had difficulty connecting the OCU and robot—sometimes the network would never converge on a route. Based on these experiments, we chose to proceed with optimizing *Babel* for our application [6].

During testing, we found that the *Babel* network service randomly crashed. This issue was resolved by making the code aware of the "endianness" used by the Intel *ixp400* on the Gateworks *2350* network processor. Testing in the laboratory and at Naval Air Weapons Station China Lake showed that the ADCR/MDCR radio system based on *Babel* had potential, but it still needed more development. The connection between the OCU and robot was flakey and the route convergence time took too long.

Further testing found that the data traffic from the robot was affecting the link-quality-estimation metric used by *Babel*. Analysis of the mesh found that the robot traffic was saturating the link, causing the link estimation method of *Babel* to think that the signal had degraded. This in turn was causing the network to flip-flop between two or more routes (briefly discussed in Section 2.2.3). A solution was devised that classified all links that could handle robot traffic as having the same weight (a perfect link) as any other link that could handle robot traffic. It then penalized all links that could not handle robot traffic by arbitrarily doubling (for the worst) the link quality metric. (This is called the “good-enough” metric). Experimentation provided a good threshold for the "good enough" level. This parameter was determined by finding a suitable link quality value right on the edge of losing communication, then adding a safety margin. This change resulted in a very stable network. However, at this point *Babel* still suffered longer-than-desired route-switching times of about 30 to 60 seconds. Analysis of the *Babel* source code isolated the problem to the long intervals between the “hello” messages that are automatically sent to monitor the network status. Software modifications were made to enable sub-second “hello” intervals. Experimenting with different values of “hello” intervals showed that 10 “hellos” a second gave near real-time network convergence and transition while not saturating the mesh with overhead traffic.

2.5.2 Virtual Private Network

One of the common issues with the initial prototype systems was that the robot and OCU needed to be reconfigured for every test. This was an unfriendly, unreliable, and time-consuming process. Additionally, this is unacceptable for a system to be fielded. We needed our systems to be plug-and-playable, with no configuration needed on the target robot or OCU. This started a search of various technologies to make connecting the robot and OCU over a mesh simpler, and resulted in our use of VPN technology, specifically an open-source VPN package, *OpenVPN*. This technology provides a wrapper around the network messages, providing a plug-and-play solution. The radios do not need to know which robot or OCU generates or receives the traffic data; hence, no robot or OCU configure-tion is needed. The drawback, however, is that the two end radios must be paired. Data generated by one radio can only be received by the other in the pair, while the intermediate relay nodes can be any compatible mesh node.

To provide the most effective robot-data transfer, the following operations must be performed in *OpenVPN*:

- Set the Maximum Transmission Unit (MTU) to 1600. This is because each VPN endpoint has an MTU of 1500 (the default for Ethernet) and the VPN process adds just under 100 bytes to each packet.
- Configure the VPN to be a User Datagram Protocol (UDP) point-to-point mesh with a tap (layer 2) interface. While using the Transmission Control Protocol (TCP)/Internet Protocol (IP) would increase the reliability of packets getting to their destination (through automatic re-tries), this is actually detrimental to the remote control of mobile robots, where real-time control is critical.
- Disable all special security and redundancy options to ensure minimum data latency.
- Bridge each end-point to a physical port using the standard Linux interface bridging utility.

The end result of using the VPN in this manner is that it can be thought of as a virtual cable between two physical points. No special configuration is necessary for it to work with any robotic system.

2.5.3 Configuration Management

During our software development effort we found that configuration management was paramount. Each software component (*OpenWrt*, *babeld*, and MDCR/ADCR source code) was managed using a software versioning repository. We used *Subversions (SVN)* to manage our own modified versions of *OpenWrt*, *babeld*, and the MDCR/ADCR support scripts. The development environment was a stock *Ubuntu* Linux version installed onto a *VirtualBox* virtual machine.

3. CONCLUSIONS

We have presented here a number of important principles and lessons learned from over 10 years of developing RF networked communication-relaying systems. The topics were organized into five major areas: radio-frequency principles, wireless networking, mechanical design, electronic design, and software. While not exhaustive, they should help developers of future RF network communication-relay systems.

REFERENCES

[1] H. G. Nguyen, N. Pezeshkian, M. Raymond, A. Gupta, and J. M. Spector. 2003. "Autonomous Communication Relays for Tactical Robots." IEEE 11th International Conference on Advanced Robotics (ICAR 2003), June 30 to July 3, 2003, Coimbra, Portugal.

[2] H. G. Nguyen, N. Pezeshkian, A. Gupta, and N. Farrington. 2004. "Maintaining Communication Link for a Robot Operating in a Hazardous Environment." ANS 10th International Conference on Robotics and Remote Systems for Hazardous Environments, March 28–31, Gainesville, FL.

[3] N. Pezeshkian, H. G. Nguyen, and A. Burmeister. 2007. "Unmanned Ground Vehicle Radio Relay Deployment System for Non-line-of-sight Operations." *Proceedings of the 13th IASTED International Conference on Robotics and Applications*, August 29–31, Wuerzburg, Germany.

[4] N. Pezeshkian, H. G. Nguyen, A. B. Burmeister, K. F. Holz, and A. Hart. 2010. "Automatic Payload Deployment System," *SPIE Proceedings 7692: Unmanned Systems Technology XII*, April 5–9, Orlando, FL.

[5] N. Pezeshkian, H. G. Nguyen, A. B. Burmeister, K. F. Holz, and A. Hart. 2010. "A Modular Design Approach for the Automatic Payload Deployment System." AUVSI Unmanned Systems North America, August 24–27, Denver, CO.

[6] A. Hart, N. Pezeshkian, and H. Nguyen. 2012. "Mesh Networking Optimized for Robotic Teleoperation." *SPIE Proceedings 8387: Unmanned Systems Technology XIV*, April 25–27, Baltimore, MD.

[7] N. Pezeshkian, J. D. Neff, and A. Hart. 2012. "Link Quality Estimator for a Mobile Robot." 9th International Conference on Informatics in Control, Automation and Robotics (ICINCO), July 28–31, 2012, Rome, Italy.

[8] H. G. Nguyen, N. Pezeshkian, A. Hart, A. Burmeister, K. Holz, J. Neff, and L. Roth. 2013. "Evolution of a Radio Communication Relay System," *SPIE Proceedings 8741: Unmanned Systems Technology XV*, May 1-3, Baltimore, MD.

[9] Tethers Unlimited, "SensorPod™ Emplacement Technologies," URL: http://www.tethers.com/sensorpod/emplacement.htm, retrieved September 10, 2013.

Note: References 1 through 8 can be downloaded from the SSC Pacific Unmanned Systems publication archive, at http://www.public.navy.mil/spawar/Pacific/Robotics/Pages/Publications.aspx.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-01-0188

1. REPORT DATE *(DD-MM-YYYY)*
April 2014

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Unmanned Ground Vehicle Communications Relays

Lessons Learned

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS
Hoa Nguyen
Narek Pezeshkian
Aaron Burmeister
Abraham Hart

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
SSC Pacific
53560 Hull Street
San Diego, CA 92152–5001

8. PERFORMING ORGANIZATION REPORT NUMBER
TR 2042

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Intelligent Ground Systems (IGS)
U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC)
6501 E. 11 Mile Road
Warren, MI 48397-5000

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Space and Naval Warfare Systems Center Pacific has been developing mesh-networking communication-relaying technology to mitigate the line-of-sight problem associated with modern high-frequency wireless communications for more than 10 years. This report documents the lessons we have learned during the development of these systems and important principles critical to future communication-relay development efforts. The topics discussed are organized into five functional groups: radio-frequency principles, wireless networking, mechanical design, electronic design, and software.

15. SUBJECT TERMS

mesh networking	virtual private networks	software development	communications links
radio frequency	stowed relays	mobile robots	lessons learned

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					H.. Nguyen
					19B. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	30	(619) 553–1871

INITIAL DISTRIBUTION

853	Archive/Stock	(1)
843	Library	(1)
71710	H. Nguyen	(1)

Defense Technical Information Center
Fort Belvoir, VA 22060–6218 (1)

SSC Pacific
San Diego, CA 92152-5001