Challenges for deploying man-portable robots into hostile environments

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ABSTRACT

The Man Portable Robotic System (MPRS) project objective was to build and deliver hardened robotic systems to the U.S. Army's 10th Mountain Division in Fort Drum, New York. The systems, specifically designed for tunnel and sewer reconnaissance, were equipped with visual and audio sensors that allowed the Army engineers to detect trip wires and booby traps before personnel entered a potentially hostile environment. The greatest challenges for the project stemmed from the users three main requirements: 1) man-portable (lightweight and small), 2) waterproof (not just water-resistant), and 3) soldier proof (highly rugged and reliable).

The MPRS systems were, of course, plagued by the usual problems in robotics: limited battery power (run-time) and limited communications range. At the Army's request, the systems incorporated no autonomous functionality; however, MPRS did integrate several state-of-the-art components, including a fully digital video system. This paper discusses specific challenges encountered and lessons learned by the MPRS team during recent tunnel and sewer reconnaissance testing at three sites in 2000: Fort Drum (New York), Fort Leonard Wood (Missouri), and Fort Polk (Louisiana).

Keywords: robotics, teleoperation, reconnaissance, surveillance, digital video, JAUGS, MDARS

1. BACKGROUND

In modern-day warfare the most likely battlefield is an urban environment, which poses many threats to today's soldier. One of those threats comes from the tunnel and sewer infrastructure beneath the city. Before a section of the city can be declared safe, the underground tunnel network must be cleared. The laborious process of clearing a tunnel has changed little over the last century. The infantryman must inch his way through a very hostile environment looking for trip wires and land mines as well as watching for possible ambushes. The MPRS Urban Robot (URBOT) was designed to remove the soldier from this dangerous environment. By using a remotely operated vehicle with video and audio surveillance capability, the tunnel can be inspected prior to sending in soldiers to perform the final clearing.

2. DESIGN REQUIREMENTS

The goal of the MPRS program was to develop a lightweight mobile platform for operation in urban environments. The platform had to be capable of negotiating an eight-inch obstacle and yet small enough to be man-portable. The Army definition of man-portable is "less than 40 pounds", or capable of being broken into subassemblies for two soldiers, with each soldier carrying no more than 40 pounds. The system also had to either be invertable or self-righting so that if it were to flip over the mission could continue. The system had to be waterproof due to the likelihood of encountering water in a tunnel system. There was never a requirement for the system to operate while totally submerged because of the wireless nature of the robot, but it was required to run in up to five inches of water continuously. Typical operational scenarios necessitated a communications range of at least 200 meters inside the tunnel and a runtime of at least two hours.

There were also implied requirements that the system was expected to meet. Because the robots were going to be operated in the field by real soldiers, they had to be extremely rugged. It was always assumed that the soldiers would not treat the robots like laboratory equipment. This requirement was in direct conflict with the man-portable criteria. It was a continuous challenge to build a system that was both rugged and waterproof, yet at the same time light enough for two people

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to carry. The Operator Control Unit (OCU) also had to be waterproof since the soldiers would be operating the robot in a wide variety of weather conditions.

3. FIRST PROTOTYPE ROBOT AND OCU

The first-generation MPRS prototype was developed for the U.S. Army Combat Engineers Tunnel and Sewer Concept Experimentation Program (CEP) held at Fort Leonard Wood in the fall of 1999[1]. The purpose of the CEP was to validate the concept of employing teleoperated robots to conduct tunnel, sewer and bunker reconnaissance in urban combat. Several robotic platforms were evaluated, including the MPRS URBOT[2]. The soldiers operating the robots during these exercises were from the 41st Engineer Battalion, 10th Mountain Division, and 577th Engineer Battalion.

3.1. Robot

The first-generation prototype (Figure 1) was based on a modified Foster-Miller Incorporated (FMI) *Lemming* chassis, chosen for its simplicity and symmetry. The symmetry allowed the robot to be invertible, thus removing the requirement for a self-righting mechanism. It also gave the robot equal mobility in both the forward and reverse directions, which is important when inspecting a tunnel that is not wide enough to support a 180 degree turn. The chassis and drive train components of the Lemming were mostly unmodified but the electronics were completely replaced. This division of work between SPAWAR Systems Center San Diego and FMI continued throughout the project. It would have been difficult for one group to do all of the work in the extremely compressed schedule of this project.

A watertight electronics box that contained the processor, motor controller board, video CODEC, WLAN modem and power regulator was added to the chassis. The processor was a 66-MHz PowerPC-based ipEngine from Brightstar Engineering. The ipEngine has an integrated FPGA that provides a vast number of I/O configurations. Part of the FPGA was dedicated to the PID control loop for the drive motors. The video CODEC (from Indigo Active Vision Systems) was used to send real-time digital video and audio from the robot to the OCU over a wireless RF link. The video system employs a hardware-based CODEC that provides between 15 and 20 frames per second. The 2.4-GHz RF link from Breezecom also carried the command and control data so that only one radio link was required.

A watertight sensor suite (or "sensor snout") was added to the chassis which held collision avoidance sensors, pinhole cameras, electronic compasses, halogen headlights, and an ipEngine (Figure 1). The collision avoidance sensors consisted of two arrays of five Sharp near-infrared triangulation ranging sensors and five sonar ranging sensors. The camera array consisted of two forward-looking cameras (one for inverted operation), one upward-looking camera and one downward-looking camera (for inverted operation). All of the cameras were low-light, fixed-focus cameras. Two Precision Navigation electronic compasses (one for inverted operation) provided magnetic heading, pitch, roll, and ambient temperature. The sensor snout was designed as a self-contained modular package that could be replaced with other sensor packages for different types of missions.

Figure 1. Front view of first-generation URBOT.

3.2. OCU

The first-generation OCU consisted of three subassemblies: the electronics box, battery box, and control pendant. The electronics box contained a Breezecom WLAN modem, video CODEC, ipEngine, small Ethernet hub, and a video overlay board. The control pendant used capacitive touch-sensor technology (from Quantum Research) for user input, and incorporated an integrated 2.5-inch LCD video monitor (Figure 2). The capacitive touch sensor allowed the control pendant to be completely waterproof since no mechanical buttons were needed. It also made it possible to operate the system while wearing the bulky gloves of a chemical suit. The LCD screen displayed the live video feed from the robot as well as vehicle status information (heading, speed, pitch, roll, and camera view) overlaid at the top of the screen.

Figure 2. Original control pendant with capacitive touch pad.

4. FINAL MPRS URBOT CONFIGURATION

The CEP at Fort Leonard Wood provided invaluable feedback from the user community. Based on that feedback as well as issues discovered by the design team, a second-generation MPRS robot was developed and subsequently deployed at Fort Drum, NY and Fort Polk, LA during the Joint Combined Forces (JCF) Advanced Warrior Experiment (AWE) in September of 2000.

4.1. Robot

The platform chassis was upgraded from the Lemming to a variant of the six-wheel Foster-Miller *Tactical Adjustable Robot* (*TAR*), with a fixed length of 33 inches (i.e., no longer adjustable) to save weight (Figure 3). The addition of a slightly over-sized center wheel creates a high-center pivot point that allows the robot to turn much more efficiently. This not only reduces the power required to pivot on a high-friction surface, but it also allows much more precise control, which is crucial when the robot is used as the pan axis of the inspection camera.

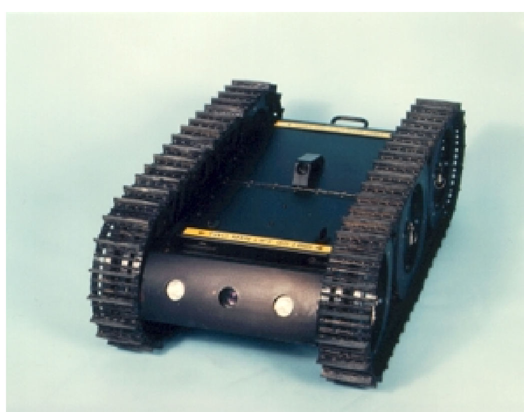

Figure 3. The second-generation URBOT.

Because the system is intended to be man-portable, the wheels and tracks were designed to be easily removed without the use of any tools; the user simply removes the quick-release pins from the axles and slides the wheels off. By removing the tracks, wheels and batteries, the weight of the system can be equally divided among two soldiers.

The original low-cost DC gear motors were replaced with high-performance DC motors. Each motor and optical encoder is encased in a waterproof housing that is connected to a custom-built gearbox, in turn is coupled to the drive wheels through a chain and sprocket assembly (Figure 4).

The tracks (designed and manufactured by Foster-Miller) are made of short, molded plastic sections that are screwed together. For added traction, small rubber cleats are stapled to the plastic track. This design allows for a lightweight track with a very aggressive tread design.

The original one-piece top cover was replaced with a hinged lid and quarter turn latches. The new lid makes it much easier for the user to access the batteries, and it also eliminated the need to disconnect the top camera (Section 4.2.1) every time the lid was removed. The reinforced lid also acts as a restraint to hold the batteries in place.

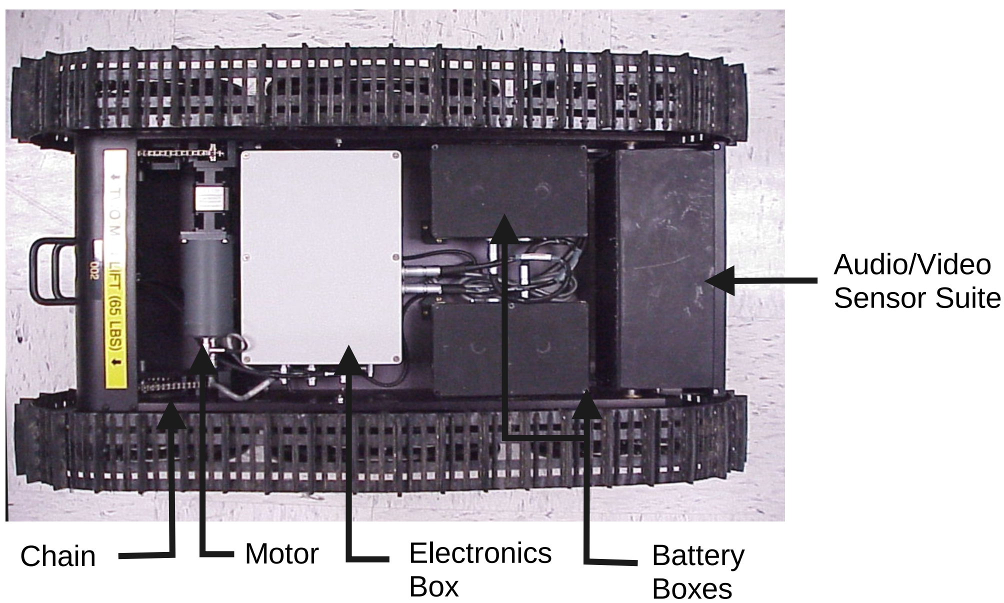

Figure 4. Top view of URBOT with cover removed.

4.1.1 Sensor Snout

Preliminary evaluation during the CEP showed that the user did not require or want any type of computer-aided control (i.e., telereflexive control). Telereflexive control is where the robot assists the operator by avoiding obstacles while maintaining the same general heading that has been commanded[3]. During a tunnel reconnaissance mission, the robot needs to move slowly and stop often, allowing the operator sufficient time to closely examine the video for anything of tactical significance. Accordingly, a purely teleoperated system was requested, giving the user direct control over every aspect of the system. Because there was no need for telereflexive control, the collision avoidance sensor arrays were removed.

It also became evident during the CEP that the success of any robotic inspection vehicle depends on the operator's ability to reliably assess the video. User feedback specifically called out several important points regarding the video: 1) analog video transmitters generally have too much multi-path breakup and signal degradation; 2) digital video systems need to have an update rate of at least ten frames per second; 3) mechanical jitter is a problem while the robot is moving; and 4) a high-resolution inspection camera with the ability to tilt and zoom is a necessity.

Based on this feedback, the sensor snout was redesigned to incorporate a tilt motor (tilt range of ±90 degrees) and a high-resolution zoom inspection camera. The camera selected was a Sony EVI-330T, which has a 24x zoom, auto focus, auto iris, and electronic image stabilization. All of the camera's functions are controlled via an RS-232 port. The electronic compasses were moved to the robot electronics box.

The new snout was designed to be a modular payload that could be replaced with other payload packages in an almost plug-and-play manner. This is possible because each payload package contains an ipEngine that is networked with the ipEngine in the electronics box via Ethernet. The robot uses dynamic registration (see Software section) to recognize what type of payload is attached and what its corresponding functions are.

4.2.1. Cameras

In addition to the inspection camera in the snout, three more cameras were added to the second-generation platform. A pair of fixed-focus auxiliary "drive cameras" were installed on the top and bottom cover panels of the chassis. This mounting configuration provides a removed perspective, allowing the operator to see the forward drive sprockets and any obstacles that protrude into the robot's path. Also, a rear-facing camera with a built-in IR illuminator was added so that the operator can back out of the tunnel if necessary (Figure 5). This camera also aids the operator in attaching the retrieval hook to the rear handle. The retrieval/deployment hook is used to lower and extract the robot through a manhole. The rear camera and its associated infrared illuminator make it much easier for the soldiers to "snag" the robot, especially in the dark.

Figure 5. Rear of the robot showing the carrying/recovery handles, rear-facing camera, and ON/OFF switch.

4.2.2. Batteries

The battery systems, (completely self-contained and watertight), were co-developed by SPAWAR Systems Center and Foster-Miller. Each pack includes three 12V 3500mAHr NiMH flat-pack batteries connected in parallel with a total combined power output of 126 WHr. The pack also contains all of the required charging and discharging circuitry. The batteries are discharged in parallel, but charged individually from a single 24V supply. This allows the batteries to be charged directly from most military vehicles using the standard slave receptacle with the supplied adapter (Figure 6).

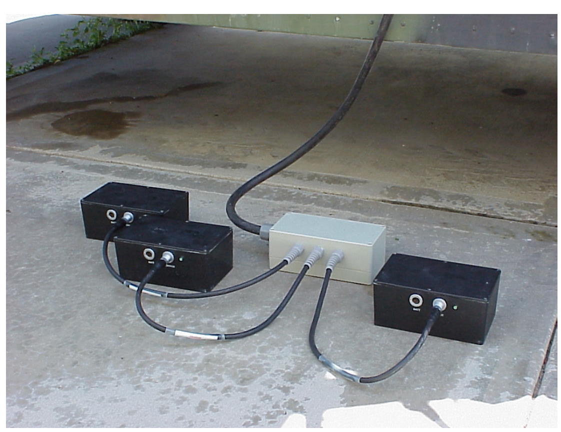

Figure 6. Slave receptacle adapter and three robot battery packs.

The robot uses two of these battery packs: one for the motors and lights (dirty power) and another for the remaining electronics (clean power). The OCU uses one battery pack, which is similar to the robot battery, but includes a built-in 5V regulator so that it outputs both 12V and 5V. To aid the user in differentiating between the robot and OCU batteries, the battery boxes were painted different colors and use a different pin configuration in the output connector.

The run-time varies depending on how the robot is used, but during a standard inspection mission the user can expect to have between two and three hours before the batteries need to be replaced or charged. Mission time will decrease if the robot is driven at high speed for extended periods of time and/or if the lights are kept at a high intensity level.

4.2.3. Wireless Link

The MPRS URBOT employs a single wireless Ethernet link for data, video, and audio. The wireless LAN modems are 2.4GHz Breezecom Pro.11 series radios. These IEEE 802.11 standard radios have a maximum data rate of 3Mbps and a maximum power output of 100mW. To boost the output power, a 500mW bi-directional amplifier is used on the OCU side of the link. There are two interchangeable antennae that the user can employ at the OCU: the standard antenna is an 8.5dB patch, and the second antenna is a 15dB Yagi. The patch is much smaller and easier to manage while the Yagi gives the user extended range. (With the patch antenna the maximum range is approximately 100 yards line-of-sight (LOS); with the Yagi antenna the maximum range is approximately 300 yards LOS.) The primary reason for the limited range is the fact that the robot (and therefore its antennae) sits so close to the ground. The antennae on the robot are mounted next to the chassis behind the middle wheel of the robot (Figure 7). (There are two antennae on the robot because the Breezecom radios use a diversity scheme to help eliminate multi-path effects.) This location is not optimal in terms of RF propagation but was necessary for inverted operation. This mounting configuration also helped the URBOT keep a low profile, which was a very desirable characteristic.

Interestingly, the radios actually perform better inside of the tunnel than in open areas, because the metal in the tunnel walls acts as a wave-guide and focuses the RF energy, even around corners. All of the tunnels that the URBOTs have been employed in to date have been constructed of either corrugated steel or reinforced concrete.

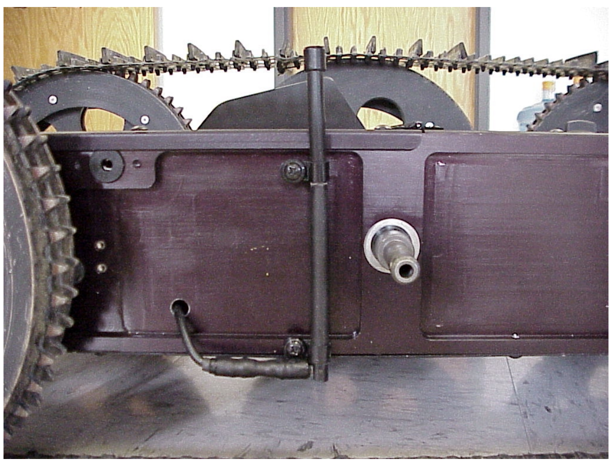

Figure 7. 5dB omni-directional antenna mounted to the robot chassis.

4.3. OCU

The second-generation OCU electronics were not changed significantly from the original design. A canvas backpack (by Camelbak®) was used to carry the electronics box and the battery pack (Figure 8).

The original control pendant with its capacitive touch pad was found to have one major flaw; it was impossible to differentiate the buttons in the dark. Accordingly, the touch pad was replaced with a pushbutton array that provides excellent tactile feedback for unambiguous one-handed operation in total darkness (Figure 9). The pushbuttons are waterproof and large enough to operate with gloves.

Figure 8. OCU pack with pendant, video display and 8.5db patch antenna.

The new control pendant is small enough to be operated with one hand, but one-handed operation comes at a price; it limits the number of buttons that can be accommodated. Because of the limited number of buttons available, a menu-driven approach was taken (Figure 10). With the use of three buttons the operator can bring the menu up, cycle through the menus, and then adjust various parameters such as light intensity, camera selection, zoom, focus, etc. The menus are generated with a simple text overlay board. The overlay board is also used to display various status parameters at the bottom of the screen. Starting from the left: a blinking heart that indicates that a connection has been established between the OCU and the robot; stair steps that indicate the RF signal quality; the heading in degrees; the camera currently being displayed; an odometer; and the amount of time the OCU has been running.

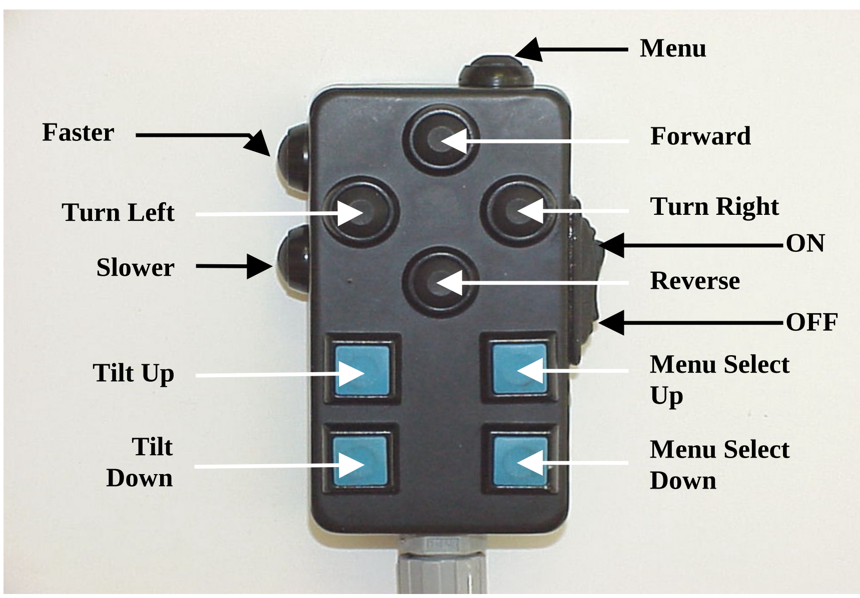

Figure 9. Second-generation control pendant.

It was also discovered that since the soldiers generally work in pairs and need to be able to view the video simultaneously, which was difficult with the small LCD panel. The 2.5-inch LCD panel was therefore replaced by a detached five-inch active matrix LCD panel (Figure 8). The display is housed in a rugged, waterproof enclosure.

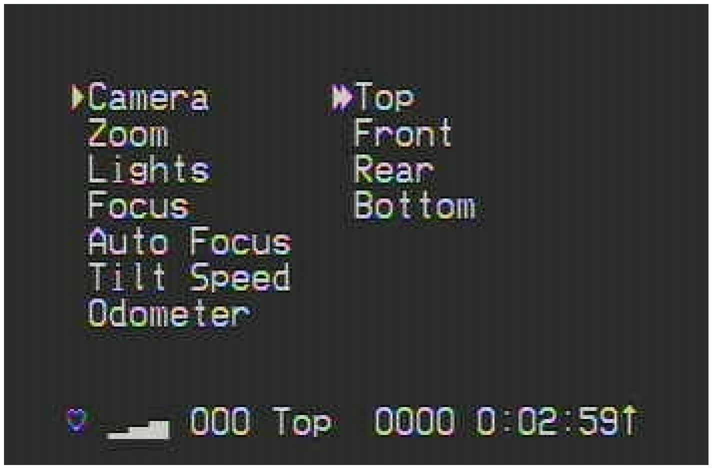

Figure 10. Example of menu on the video display.

The decision to have only one camera in the snout also came at a price; the video appears upside-down when the robot is inverted. To compensate for this, the soldier simply rotates the video display 180 degrees. However, this is not a perfect solution. When the video display is upside-down the video is in the right orientation, but the text overlay is still inverted which obviously makes it difficult to read and to navigate the menus. This problem will be corrected in the near future through a software inversion of the digital data at the CODEC.

4.4. Software

The user requested that the MPRS system be very flexible and modular. This was because there will likely be multiple copies of the system in the field during a battle. If one operator or his OCU was lost it should be possible to control that operator's robot with any other OCU in the field. It was also the intention of the user to employ the URBOT in a variety of missions that may require different sensor packages. To achieve this flexibility a new software architecture was developed.

The MPRS URBOT employs a software architecture that borrows concepts from both the Mobile Detection Assessment Response System (MDARS) Multiple Resource Host Architecture (MRHA) and the Joint Architecture for Unmanned Ground Systems (JAUGS). The hybrid architecture is termed SMART for Small Robotic Technology. It uses the underlying MDARS MRHA message format and a similar approach to function-oriented operation[4]. From JAUGS it borrows the concept of functional agents or components that are responsible for executing predefined operations, such as driving, navigating, communicating, etc[5]. The MPRS SMART software architecture is intended to be efficient, adaptable, and modular; efficient in terms of message processing, adaptable to a variety of applications, and modular in terms of support for adding capabilities in response to new requirements.

4.4.1. Functional Agents

A *functional agent* is a conceptual entity that is capable of performing a specific set of operations. An agent must perform application-specific processing (e.g., monitor sensors, sample input devices, etc.), and it must also process incoming messages received from other agents. An agent is implemented as a process. Multiple agents can execute on a single computer as multiple concurrent processes.

4.4.2. Domains

A *domain* is a logical collection of functional agents that inter-operate. It is a grouping of agents along control boundaries. A domain is typically represented by a complete system such as a robot and its controller(s). Agents represent subsystems such as a drive controller, an operator control unit, or a sensor data collector.

4.4.3. Messages

Messages are requests for information or requests for operation. Standard messages are used for network connectivity, status reporting, and device control. Application-specific messages are used to extend the standard set of operations available to an agent. All agents must process standard SMART system messages (e.g., register, unregister, ping, etc).

4.4.4. Dynamic Resource Discovery

The SMART architecture supports dynamic discovery of resources (i.e., agents). This allows SMART systems to dynamically configure themselves to form networks of inter-operating agents within and across domain boundaries. The process is straightforward and does not rely upon a single "coordinating" entity such as a supervisor or scheduler. This avoids the rather large problem of what to do if the coordinating entity dies. Dynamic resource discovery under the SMART architecture is based upon the concept of a *registration table* that maintains the current known state of the system in terms of available (live) agents.

4.4.5. Registering

At startup, each agent broadcasts its presence to the network.[†] The broadcast message is re-transmitted at regular intervals until it is acknowledged. The broadcast data includes the agent's domain, class, subclass, process ID, and network address. The domain is a logical identifier that is used to associate agents of a system. The class is the general category of an agent such as *controller, driver, navigator, observer*, etc. The subclass is the type of agent within the class such as *differential GPS navigator, skid-steer track driver,* etc. The subclass is used to differentiate between agents of the same class with different capabilities. The process ID is used to identify an agent on a computer executing multiple processes. The network address is a unique identifier that allows the communications network to unambiguously deliver a message to an agent.

When an agent receives a registration request, it adds the registration data to a table. Duplicate entries are simply overwritten. The registration data is used to route future message transmissions to the registering agent. The agent that has successfully received the registration request then sends an acknowledgement to the registering agent. This stops the registering agent from broadcasting the registration request. The acknowledgement message includes the entire registration table of the agent that responds to the registration request. This helps disseminate registration information between agents on the network. As message delivery is assumed to be unreliable, some agents may not receive the broadcast registration requests and the registering agent may not receive all of the acknowledgement messages. By including the entire registration table in the acknowledgement message, the odds are increased that the registering agent will be made aware of all other agents on the network.

4.4.6. Unregistering

When an agent anticipates leaving the network, it sends a broadcast message to all other agents indicating that it is terminating. All remaining agents will remove the terminating agent from their registration tables, and the terminating agent will no longer be reachable. The broadcast message is not acknowledged since the originating agent has terminated.

Occasionally (and especially in environments that do not maintain reliable communications networks), agents will actively inquire as to the status of other co-dependent agents. A ping message is sent from an originating agent to all other agents of interest. If a reply to a ping is not received within a specified time period, then the originating agent will remove the non-responding agent from its registration table.

4.4.7. Defined Agents

There are a number of agents that have been defined for use on the MPRS system. They are the controller, driver, and observer. There are three other predefined agents that are not currently used under MPRS: user, navigator, and monitor. Agents are typically configured to rely upon other agents for services or information in an *a priori* fashion. However, an agent will generally only accept data requests and commands from an agent within their domain. This allows cooperative and subsumptive relationships between agents in a completely dynamic fashion. A driver agent, for example, can be commanded by any other agent in the domain to move the robot to a specified location.

4.4.8. Controller

The controller is responsible for operating the robot and is implemented as a single process running on an embedded processor at the OCU. It is responsible for sampling user input, mapping user input to robot commands, and for periodically querying the robot for status. It also monitors OCU battery voltage, and displays status messages to the user. The controller relies upon the driver and the observer agents.

4.4.9. Driver

The driver is responsible for robot mobility and implements drive (teleoperation) commands sent to it by the controller. It maintains overall robot status, which includes heading, speed, odometry, temperature, operational mode, and alarm status

[†] This assumes the use of some sort of network (not necessarily Ethernet, but a network that supports broadcasting of data).

(low battery, tilt limit, excessive temperature). It is intended to implement a variety of mobility behaviors including teleoperation, reflexive teleoperation (sensor-aided teleoperation), and supervised autonomous operation (directed GPS navigation). On the second-generation URBOT the only behavior implemented is teleoperation. The driver relies upon the observer to supply environmental and navigational information such as temperature, heading, and pitch/roll.

4.4.10. Observer

The observer is responsible for robot sensory input. On the first-generation URBOT it controlled the array of ultrasonic ranging sensors, IR ranging sensors, temperature and heading sensors, and pitch/roll sensors. The sensor data is stored by the observer for transmission to other agents upon request. On the second-generation URBOT the observer is responsible for positioning the tilt housing and controlling the video camera. The observer does not rely upon any other agent (i.e., it is completely independent).

5. LESSONS LEARNED AT THE ADVANCED WARRIOR EXPERIMENT

The second-generation MPRS URBOTs were used in several Army exercises at Fort Drum, NY prior to the AWE as well as at the AWE. At each of these exercises, new issues came to light with respect to how the robot performed in various conditions and how the users perceived the URBOT's role.

5.1. Mechanical

As a whole, the mechanical design worked very well, and proved to be rugged and reliable even in the hands of enlisted soldiers. The system even endured an accidental seven-foot drop test, which occurred because of a poorly designed deployment rope. The deployment rope was configured to allow the soldiers to lower the robot into a sewer system via a manhole. The deployment system consisted of two ropes, one to carry the weight of the robot and a second to release the panic latch once the robot was safely on the tunnel floor. The problem with this approach was that the release rope had to be carefully tended so that it did not become tight and release the robot prematurely in midair. In the end, this system was much too complex. During training the release rope was inadvertently tensioned and the robot dropped seven feet, snout-first, onto a concrete floor. The positive side of this failure was that it tested the robot in a way that would never have been done deliberately. The robot was extracted from the tunnel, powered up, and ran fine. There was almost no visual damage, and on closer inspection the only damage found was a slightly bent snout pivot shaft.

Another minor mechanical problem was the rigidity of the hinged lid. It was discovered that when the robot climbs up a vertical obstacle such as a wall and flips over backwards, the impact of the batteries deforms the lid slightly. This is not a catastrophic failure in that the lid still holds the batteries in place. However, if this were to occur numerous times the lid may eventually fail.

The only significant mechanical problem with the system is the track. Foster-Miller designed the track for the Lemming system, which was a much lighter, less powerful vehicle. The larger, heavier URBOT created stresses on the track that routinely pulled sections apart and ripped the thin plastic webbing. Foster-Miller currently has an updated track design that is a continuous belt made of a much stronger material. Unfortunately, there was insufficient time to upgrade the URBOT system to this new design before the AWE.

Overall the soldiers had very few complaints with respect to the mechanical systems. They did state that the system was too heavy to pack over long distances. The complete system including a spare set of batteries weighs approximately 100 pounds. At 50 pounds per person this is 10 pounds over the design goal. This is almost entirely due to the fact that the soldiers have to carry spare batteries into the field. (The spare batteries are needed because there is no way for the soldiers to charge the batteries during an exercise.)

It was also discovered that the URBOT was not fast enough to keep up with the momentum of an attack. During an attack on a city, momentum is everything; if someone or something cannot keep up it gets left behind. The original design requirement called for a minimum speed of 3 feet per second. The URBOT's top speed is approximately 2.5 feet per second. This was short of the design requirement, and even the original requirement is not nearly as fast as the soldiers would like. The new requirement is for a system that is closer to 10 feet per second. Foster-Miller already has a new motor design (using brushless DC motors) that will increase the maximum speed of the URBOT to approximately 6 feet per second.

5.2. Electrical

The electronic systems also performed very well. It was stated on many occasions that the video system was the best that has been employed on a portable robot to date. The only major drawback to the digital video system is the high bandwidth requirement and hence the requirement for a WLAN modem and the high frequencies employed by these radios. Because of the low-power and high-frequency characteristics of these radios, the communications range is generally limited to LOS. These restrictions can be overcome in some instances by the use of repeaters and high-gain antennas.

The primary problem with the electrical system was the water-tight connectors: there were repeated failures of the connectors throughout the system. This can be mostly attributed to the fact that engineers built many of the cables rather than trained technicians, and in part to the complicated nature of the watertight connectors that were used. Each connector is made of four to five pieces that must be custom ordered to fit the cable. On a project with such a compressed schedule it was difficult to maintain the required tolerances.

Another problem that came to light during the Fort Drum exercises was that there is no power gauge on the battery boxes to indicate the level of charge left in the battery pack. Many of the problems reported by the soldiers were determined to be a result of insufficiently charged batteries. For the AWE, a self-contained battery tester was fabricated so that the soldiers could verify that the batteries were fully charged prior to the mission.

As anticipated, the summer heat in Louisiana was a minor problem during the AWE. At times the ambient temperature reached 115 degrees Fahrenheit and the heat index was over 130 degrees. When the system was run for an extended period in direct sunlight some of the integrated circuits failed. The resolution to this problem was to simply turn the system off and let it cool down for about 30 minutes. This problem was not a surprise since all of the electronics in the system are commercial grade and not rated for such extreme heat conditions.

5.3. Training

The biggest problem encountered during the entire twelve month project did not concern the mechanical or electrical systems, but instead with the "trained" operators. In order for any robotic system (even one as simple as the URBOT) to be successful, the operator of that system must be intimately familiar with how the system works and what its strengths and weakness are. The only way someone can obtain this kind of familiarity is to train with the system repeatedly. Unfortunately, the Army was not able to permanently dedicate personnel to the URBOT initiative, with the result that at every exercise the URBOT operators were soldiers with only a brief introduction to the system. In addition, inadequately trained operators have little or no troubleshooting ability. This meant that when a minor problem arose with the robot, the soldiers just quit using it instead of trying to work through the problem.

5.4. User Wish List

Every time the design team met with the soldiers for either training or an actual exercise there was an enthusiastic stream of suggestions on how the URBOT could be improved. Some of the most frequent and practical suggestions are listed below.

The primary concern to the soldiers was the fact that the URBOT introduced new batteries into what is an already immense variety of batteries that have to be carried into the field. It was repeatedly requested that the URBOT batteries were at least interchangeable (same battery for OCU and robot). Even higher on the wish list was that that URBOT use a standard battery that the Army already carries. This option was investigated but it was found that the Army-issue batteries had nowhere near the energy density that was required for the desired run-time.

Another suggestion that came out of the Fort Drum exercises was that the URBOT have night vision capability. The soldiers not only wanted to use the robot for tunnel inspection but also for building inspection and surveillance. The only way the URBOT can currently be used at night is with halogen headlights, which immediately gives its position away. The addition of a small FLIR camera is being investigated.

Probably the most common request from the enlisted soldiers was for a more lethal robot. They want a robot that can be used not only for reconnaissance, but also to attack the enemy and defend a position. Technically, this would not be a difficult addition (aside from the added weight). The first step to such a system is the addition of non-lethal weapons, which is being pursued by Foster-Miller.

REFERENCES

1. Laird, R.T., Bruch, M.H., "Issues in Vehicle Teleoperation for Tunnel and Sewer Reconnaissance," IEEE Conference on Robotics and Automation, San Francisco, CA, April 2000.
2. Pulaski, G., "Engineer Test Report for Tunnel and Sewer CEP, Draft Version", Battle Lab and Test and Evaluation Coordination Office, Ft. Leonard Wood, MO, March 2000.
3. Laird, R.T., Everett, H.R., "Reflexive Teleoperated Control," Association For Unmanned Vehicle Systems, 17th Annual Technical Symposium and Exhibition (AUVS '90), Dayton, OH, pp. 280-292, July-August, 1990.

4. Everett, H.R., Laird, R.T., Gilbreath, G., Heath-Pastore, T.A., Inderieden, R.S, Grant, K., Jaffee, D.M., "Multiple Resource Host Architecture for the Mobile Detection Assessment Response System," *Technical Document 3026,* Space and Naval Warfare Systems Center, San Diego, CA, August 1998.
5. Unmanned Ground Vehicles/Systems Joint Program Office, "Joint Architecture for Unmanned Ground Systems," Volume II, Redstone Arsenal, AL, September 2000.