

SAND REPORT

2002-1779

Unlimited Release

Printed June 2002

Robotic Mobile Manipulation Experiments at the U.S. Army Maneuver Support Center

Fort Leonard Wood, Missouri
30 October – 8 November 2001

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Prepared by
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**Robotic Mobile Manipulation Experiments at the
U.S. Army Maneuver Support Center**

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Abstract

This activity brought two robotic mobile manipulation systems developed by Sandia National Laboratories to the Maneuver Support Center (MANSCEN) at Ft. Leonard Wood for the following purposes:

- **Demonstrate advanced manipulation and control capabilities**
- **Apply manipulation to hazardous activities within MANSCEN mission space**
- **Stimulate thought and identify potential applications for future mobile manipulation applications**

Provide introductory knowledge of manipulation to better understand how to specify capability and write requirements

Background

Each of the MANSCEN schools – Engineer, Chemical and Military Police - was tasked to identify difficult and hazardous activities within their mission space and bring training aids against which to experimentally apply mobile manipulation robots. Each school was provided two days with the robots, during which the soldiers were trained to use the robots' advanced manual control and automatic control capabilities, and the experimental tasks were carried out. Little or no information was provided to the Sandia National Laboratories (SNL) robotics team prior to arrival at MANSCEN, thereby challenging the flexibility of the robot systems. Detailed descriptions of the tasks and results are provided in the *Description of Tasks and Results* section.

Equipment Description

The Wolverine robot is a commercial product of REMOTEC, similar in size to the RONS vehicle currently deployed with U.S. military Explosive Ordnance Disposal (EOD) forces around the world. Hardware was modified by complete replacement of the control system with a PC-based controller and joint angle sensors. The manipulator is mechanically identical to the most recent RONS upgrade, with five degrees of freedom (DOF) and a redundant linear joint.

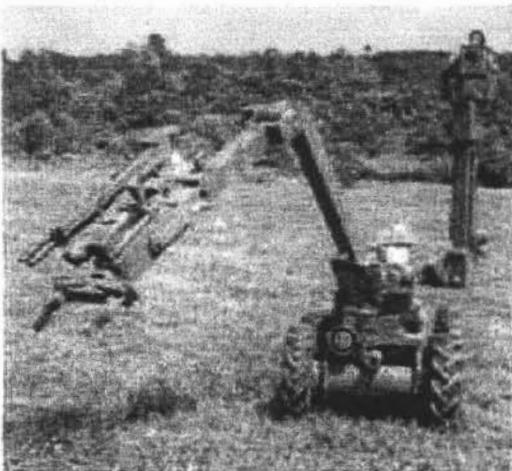


Figure 1: Remotec Andros Wolverine

The Turing robot is built on a chassis similar to the Bison robot deployed by U.K. military EOD forces in Bosnia and Kosovo, with a six DOF experimental manipulator of greater dexterity and speed than the Wolverine.

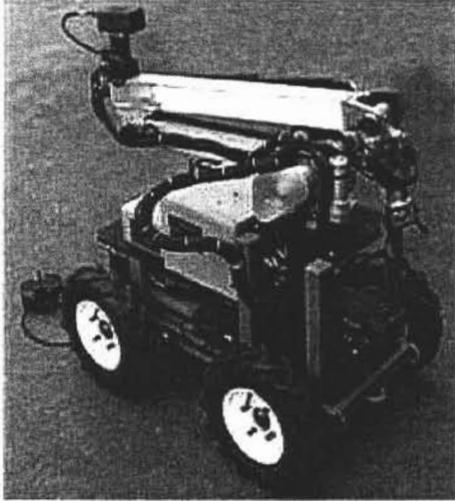


Figure 2: Turing Robot

Visual targeting was installed on both robots, enabling automatic operations against operator-designated targets. Hardware included a pair of calibrated cameras mounted on a pan-tilt unit on the robot. Video images were sent to the operator, who drew on the video screen to convey target information to the robot system.

The control station, located in a trailer that doubles as garage and repair station, consisted of two industrial PC computers, a flat screen video display, a flat screen "soft" control panel, and a variety of selectable input devices. Input devices include joysticks, space ball (a six-DOF single-hand device capable of controlling the entire manipulator), and foot pedals used for steering and acceleration.

The entire system was integrated and enabled using the Sandia Modular Architecture for Robotics and Teleoperation (SMART) tools. SMART enables access to the broadest range of hardware and software technologies while substantially reducing integration time and time-to-field for systems requiring real-time operation. Just one of many SMART capabilities is that it facilitates more efficient use of an existing robot's capability and substantial improvement in ease of control. SMART is also compatible with the Joint Architecture for Unmanned Ground Systems (JAUGS).

Description of Tasks and Results

Combat Engineers

The engineers challenged the system to locate buried mines using a standard hand-held mine detector, cut any trip wires attached to the mines, then remove fuses. In experiments associated with breaching, emplacement of charges, breaching frames, and shotgun aiming was required. The ability to hold and fire weapons was also on the requirement list; holding and aiming was demonstrated. Finally, an experiment in the placement and aiming of an explosively formed penetrator was performed.

Mines

Locate Buried Mine

This was accomplished using a hand-held mine detector to sweep an area to locate mines, unexploded ordnance (UXO), and a proofing wire. With no modification, and mounted on the Wolverine robot with tape, the mine detector was useable with the audio signal passed from the headset, to robot microphone, and on to the operator. Items as small as a 2cm length of wire were detectable. Multiple mines and metal objects, such as a 20mm shell, were also detected.

Future demonstration: Automatic sweeping patterns that could be readily programmed. Sensors to maintain distance from the ground would be desirable. Non-intrusive sensors, such as laser ranging, may be best to prevent interference with magnetometry, but such light-based sensing may be limited in tall grass and shrubs.

Defuse Anti-Tank Mine

Using the Turing robot, engineers removed the fuse of a training device in approximately 40 seconds of coming within reach of said device. On the second attempt, the gripper was forced down between fuse and mine body, wedging fast and burning out a small rotation motor in the wrist. Turing resumed operation after a three-day wait for replacement parts.

Future demonstration: Use of a force-torque sensor to prevent over-torque of devices and robotic equipment. Specialized tooling may be necessary to clear soil and debris from around fuses.

Defuse Anti-Personnel Mine

Using the Wolverine robot, engineers were able to remove a fuse from an anti-personnel (AP) mine by reaching over the fuse, under the tilt mechanism, and with blocks taped to the gripper, rotate it free. The blocks were necessary, as the gripper configuration did not allow sufficient clearance around the triggering mechanism.

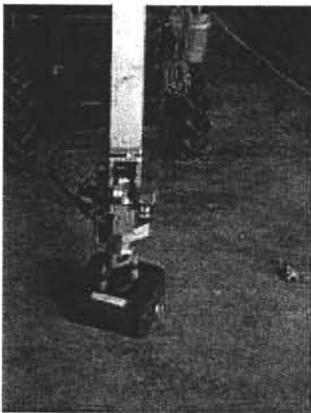


Figure 3: Anti-tank mine defused



Figure 4: Anti-Personnel mine defused



Figure 5: Mine sweeping

Trip Wires

Using the Wolverine robot, engineers removed 15 trip wires using hand-held cutting tools taped to the gripper. Two mines were buried in soil, with lightly camouflaged trip wires reaching away from the fuse. These wires could be seen clearly through the robot color zoom camera. In many trials, each wire was cut within minutes. According to the engineers observing, most of these cuts would not have detonated the mine.

In one experiment, visual targeting was used to mark all of the wires attached to the fuse. The operator could then command the robot to approach within approximately eight inches automatically, and take over manually for the cut. The operator had difficulty with depth perception related to the wire cutting, thus slowing the general process.

Laser-line cross hairs, normally used for bore sighting, were tested for the ability to see trip wires in air. Shiny wires can be seen as red dots in the air disconnected from the remainder of the projected line in indoor light. Rusted wires can also be seen. In darkness, trip wires stood out clearly in the robot video cameras. Scanning the laser showed the wires as points moving linearly toward or away from each other in space.



Figure 6: Devices for test include mines, UXO and fuse igniters



Figure 7: Mines buried with trip wires



Figure 8: Trip wires cut by robot



*Figure 9: robotic countermine activities at the Operational Control Unit (OCU)
(Conducted by SFC O'Donoghue)*

Future demonstration: The trip wire visibility in this experiment indicates that use of a laser scanning system such as SNL's Laser Mapper (LAMA) system (part of which is already built into the demonstrated robots' targeting system) could be used to automatically identify linear segments of trip wires in both daylight and darkness. Higher accuracy sensing and manipulator systems could produce an automatic wire cutting capability, eliminating the difficulty with operator depth perception. Visual servoing

technology, currently under development at SNL, could be used to guide the cutters onto the wire. Alternatively, the stereo camera system could be utilized to bring back stereo imaging for the operator's eyes.

Charge Placement

Placement of Explosive Charge

An EOD-type general disrupt device (mineral water bottle charge) was emplaced near multiple objects using manual and automatic techniques. Automation provided the tool change capability, retrieving the charge from a storage location by a button push.

Automation was also used after the operator visually targeted the package to be destroyed, illustrated in Figure 8. The robot placed the charge in the optimal position automatically upon operator command. Shock tube for initiation was payed out as the robot backed away from the device.

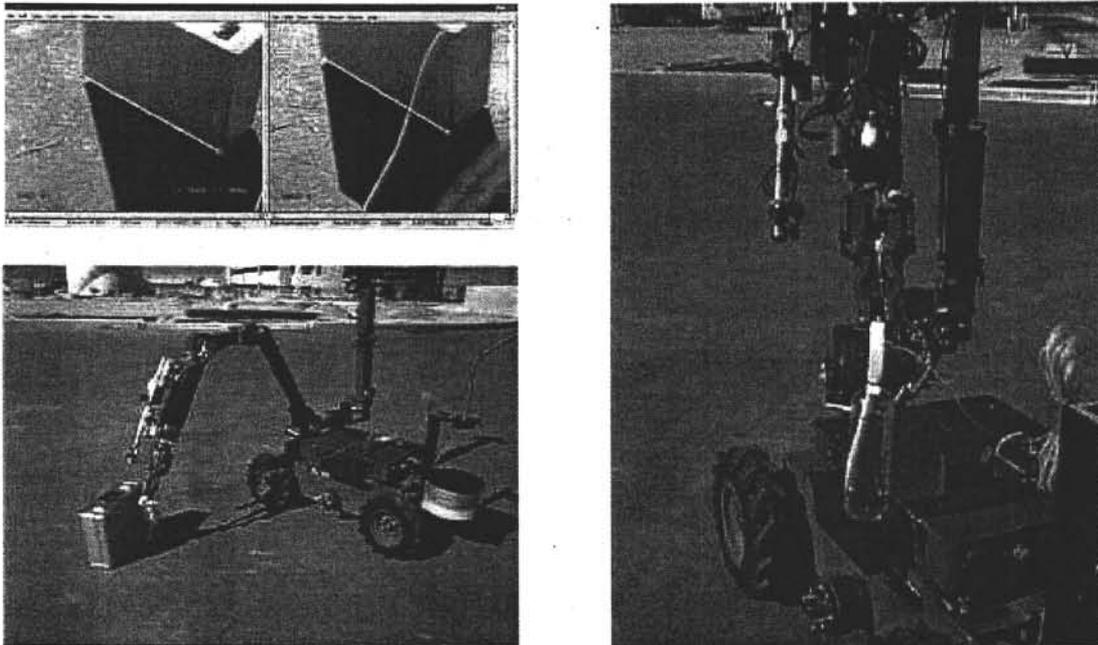


Figure 10: Target & Retrieve

Clockwise from top: Operator visually targets device by drawing a line at the base of the object on the video screen, thus telling the robot the position and orientation of the object of interest and the ground; Operator automatically retrieves disruption charge by pressing "Retrieve Waterbottle" button; Operator automatically emplaces the charge by pressing "Place Waterbottle" button.

Placement of Explosively Formed Projectile

An explosively formed projectile (EFP) was emplaced using the Wolverine robot. The EFP was pre-mounted on a tripod that was retrieved and placed using the robot.

Final aiming, using the manipulator, was difficult due to the two-handed design of the tripod adjustment mechanisms, which require simultaneous loosening/tightening of tripod knobs and the movement/holding of the EFP unit in position. The robot wrist camera was adequate for the aiming process. However, the aiming required significant iteration between moving the EFP, releasing it, moving the camera into position to see the aim, and repeating the adjustment until the aim was satisfactory.

Future demonstration: A new form of placement with a single-action adjustment is needed. Such a device would be beneficial for many military and civilian charge placement activities. Visual targeting could be used for target designation, and visual servoing technology utilizing external references could be used to align an arbitrarily gripped device to the target.

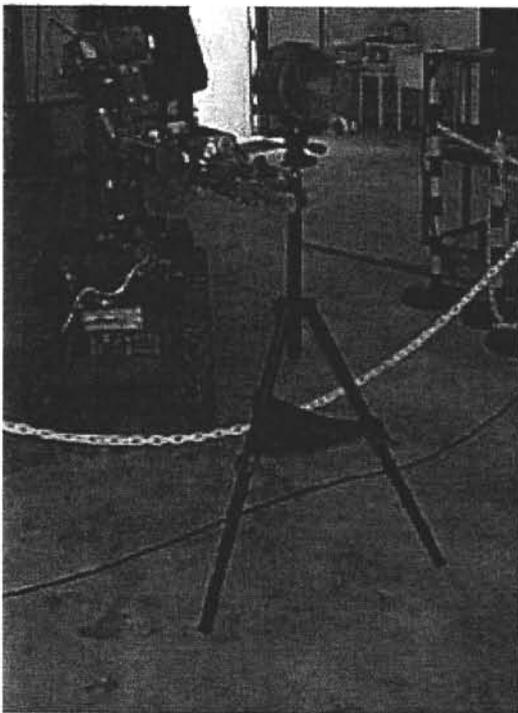


Figure 11: EFP retrieved

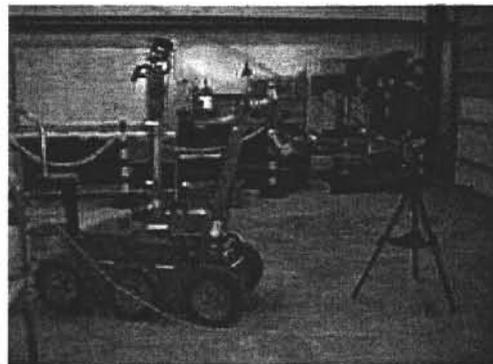


Figure 12: EFP emplaced



Figure 13: OCU during EFP placement

Breaching Frames

Engineers emplaced breaching frames for explosive breaching. Frames, normally lined with explosive and filled with water for tamping, were recovered from a staging area using the Wolverine robot, under telerobotic control, and emplaced against doors and walls. Initiation would be provided by shock tube, identical to that used in the charge placement demonstration. A stick to prop the frame against the wall was not used but provided for normal operations.

Future demonstration: Retrieving and emplacing the larger frame, when full of water and propped by the stick, would demonstrate the strength of the robot and any issues associated with propping the frame against the wall prior to backing away to a safe distance with the robot.

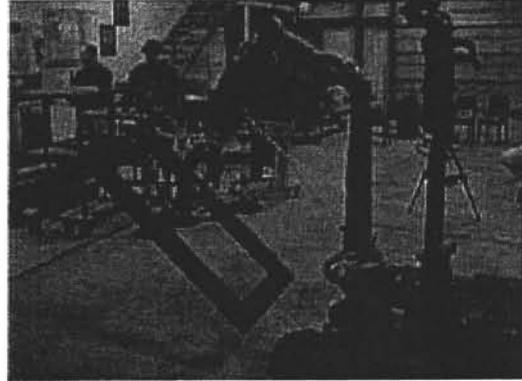
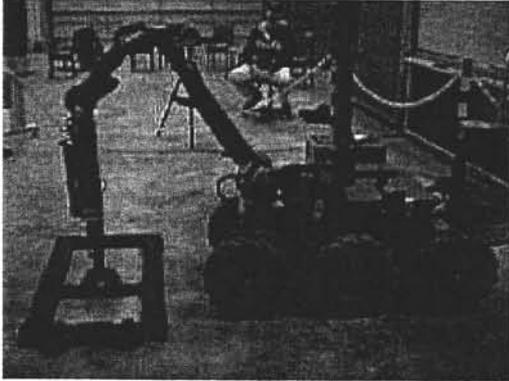


Figure 14: Breaching Process

Clockwise from left: SFC Rostad operates robotic breaching process; recovering frame from floor; movement toward target; emplacement at target.

Weapon Aiming.

The Wolverine robot is designed to aim and fire gun-type weapons. A percussion-actuated, non-electric (PAN) disrupter was mounted to the side of the manipulator and aimed automatically at a pipe bomb using visual targeting techniques. Bore-sighted laser crosshairs, developed at SNL and mounted on the PAN, enabled operator verification of proper trajectory and impact point prior to firing.

A shotgun for breaching was also held in the gripper to demonstrate sufficient dexterity for this type of task. Breaching operations may include engaging steel concrete-reinforcement bars with the barrel and firing a cutting projectile. Permanent shotgun mounts for the Wolverine are also sold commercially.

Future demonstration: Automatic aim verification using visual servoing technology. The system would then automatically check the bore alignment with the target point and trajectory, and automatically adjust the aim to simplify the operation.

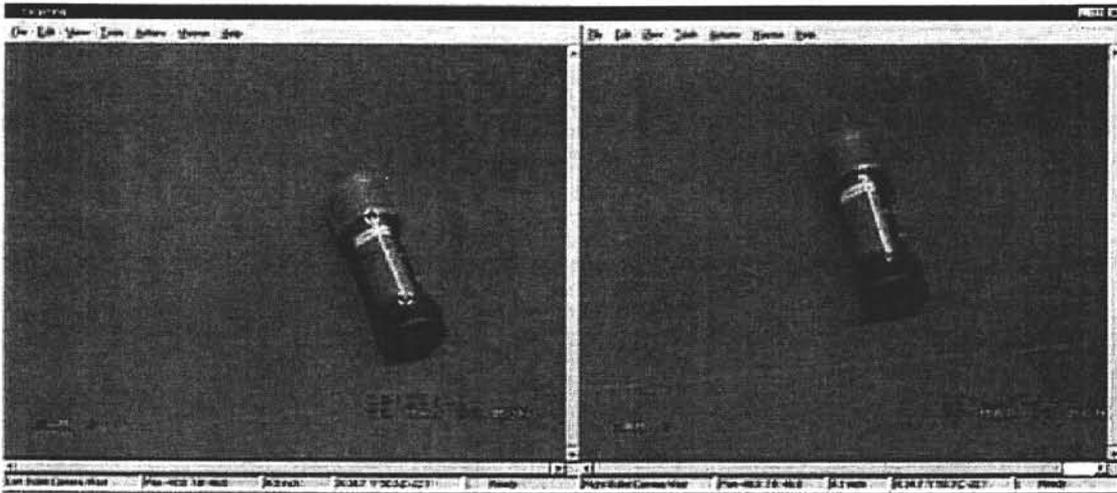


Figure 15: Visual Targeting

To shoot an object using visual targeting, the operator draws a line on video screen stereo images indicating target object, position, and orientation to the robotic system. It then commands the robot to take aim.

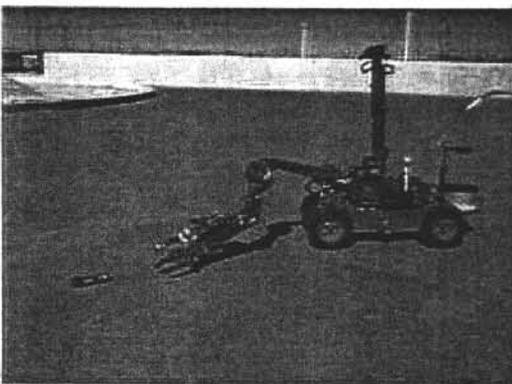


Figure 16: Wolverine

Wolverine targets a pipe bomb automatically after visual targeting.



Figure 17: Breaching Dexterity

Shotgun is held in the gripper for breaching dexterity demonstration.

Military Police

Perimeter Sensor Emplacement

Military Police (MP) are charged with the security of a maneuvering column in the field. Towards this end, securing a perimeter is mission-essential. The MPs had seen

the Perimeter Detection System demonstrated by SNL, using Miniature Intrusion Detection System (MIDS) sensors in conjunction with man-packable mobile sensor platforms that provide automatic alarm investigation with or without a soldier in the loop. Their challenge was to demonstrate that this could be set up using mobile manipulators to eliminate the need to expose a soldier to potential hostile fire or other hazards.

To demonstrate this, a MIDS magnetometer sensor was retrieved from a storage location on board the Wolverine robot and set near the emplacement site. The Wolverine manipulator then excavated a shallow hole, placed the sensor in the hole and covered the sensor.

Future demonstrations: Emplacement of a larger suite of sensors, including multiple magnetometers, seismometers, and passive and beam-break infrared sensors. Smaller marsupial mobile sensor platforms could also be deployed from the manipulator platform, and the entire system activated. Finally, the entire perimeter protection system could be serviced or retrieved by the manipulator platform and transported to its next location.

Charge Placement

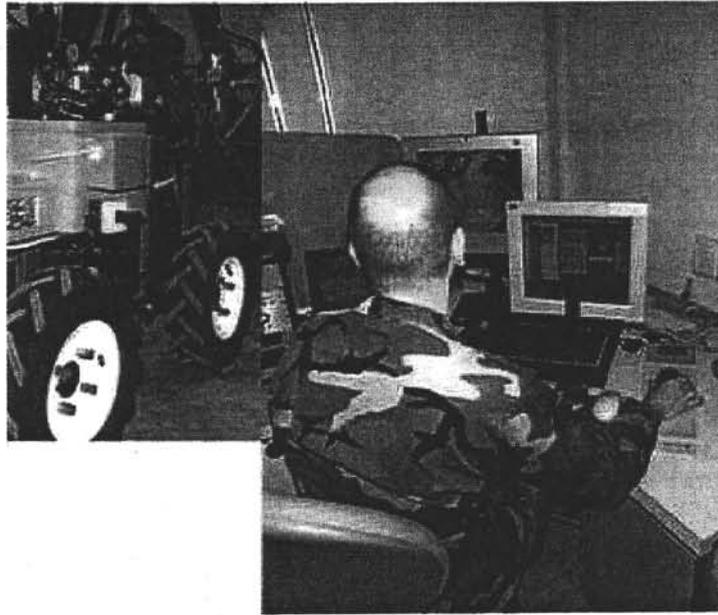
The disruption charge placement demonstration, described for the engineers above, was repeated by the MP contingent.

Weapon Aiming for IED Disposal

The weapon aiming demonstration described above for the Engineers was repeated by the MP contingent.

Covered Object Inspection

Using the Turing robot, MPs removed a tarp from a "suspicious package" in order to investigate and retrieve the package. Weighted objects on the edges of the tarp were removed remotely. MPs then grasped the tarp with the robot manipulator under manual control and dragged it from the pile of objects. The operator then remotely approached the package under manual control, and repeated the operation under automatic control, after visually targeting it as described above.



*Figure 18: Turing Robot
MP operator removes a tarp from a group of covered
objects using the Turing robot under manual control*

Figure 19: Turing Operation

*SSG Steltenpohl operates the Turing robot in an object
inspection and recovery task.*

Building Access: Door Opening

Accessing buildings for emergency response and inspection activities requires manipulation capability. MPs requested a demonstration on how to open building doors wherein the robot could pass into and out of a building without damage.

The Robotic Technology Integration Activity (RTIA) main building provided the door for the building access door demonstration. The door was approached from both sides to demonstrate both inward and outward swing. Using the Wolverine robot, the unlocked door was opened in under two minutes in each direction. Passing through the door from the direction toward which the door swung was not possible due to the

automatic closure device and a lack of auxiliary equipment to prop the door open (such as the articulating tracks on the EOD RONS robot).



Figure 20: Building access demonstration

Future demonstrations: Unlocking and relocking the doors with keys. The fundamental capability to insert keys in keyholes and turn the lock has been demonstrated at other venues with improvised tooling. Rapid insertion could be better accomplished using force-torque sensing at the wrist and visual servoing for initial alignment.

Vehicle Access: Truck Door Opening

Accessing vehicles for inspection and emergency response purposes also requires manipulation capability. The Wolverine robot was used to open a push-button latch on a pick-up truck door. The truck door, with a push-button type handle, was open within 30 seconds of the robot arriving within reach of the door handle. The primary difficulty was depth perception; the time required to determine when the robot was within reach of the handle was increased by several attempts to reach the door when the robot chassis was not parked within manipulator range.



Figure 21: Truck access demonstration

Future demonstrations: The use of reachability analysis software that indicates to the operator whether a particular object is physically within reach of the object of interest (e.g. a door handle). Such software exists at SNL, including the ability to indicate where the robot must go in order to reach an object. This software has not yet been implemented on the class of robots used in this demonstration. Visual servoing capabilities under development could then maneuver the platform for appropriate manipulator positioning, then properly align the manipulator and key.

Chemical Corps

The Chemical Corps was interested in the possibility of automating many of the difficult manual operations associated with the Fox vehicle, as well as chemical and radiological agent detection and sampling.

Fox Vehicle Activities

The Chemical Corps wished to explore the possibility of mounting a robot manipulator on the rear of a Fox vehicle to execute many of the operations currently done left-handed through a single glove port mounted too high in the vehicle to reach the ground.

Most of the operations in question could be demonstrated immediately. Some minor modifications to equipment and processes would be advised, in the event that robot manipulators are used, that would greatly streamline the processes and enable others.

Soil and Biological Sampling

Soil and biological samples are normally taken manually through a glove port in the back of the vehicle. In order to reach the ground, a tool drawer containing a set of tongs must be opened, the tongs retrieved, a plastic vial retrieved from a holder and opened, a sample scooped from the ground into the vial, and the vial closed and placed into another holder on the back of the vehicle, all with the left hand.

The Turing robot was used to scoop a sample and place the vial into the Fox sample holder as shown in Figures 18-20. Opening the drawer for the tongs was not necessary, as the robot itself could reach the ground. Opening and closing the vial was not possible using only the manipulator. However, clever engineering could provide a means of securing the vial and opening the lid.

Future demonstrations: Gripper modification to permit a firmer grip on the slippery sample vials, as well as a lid holder and modified lid attachment approach that would simplify the sampling and sealing process. A small "plug"-excavating tool may also improve the sampling process. Sensors for automatically locating the ground and for controlling force and torque during sampling, in conjunction with existing path planning software, would provide an automated means of sampling soils.



*Figure 22: robotic soil sampling
(executed by SSG Smith)*



*Figure 24: Turing robot retrieving soil from
stony terrain*



*Figure 23: Insertion of vial into sample holder
completed*



*Figure 25: Sample vial placement in Fox vehicle
sample holder*

Temperature Probe

A temperature probe is also located in the drawer described in the paragraph one of 'Soil and Biological Sampling' and depicted in Figure 22. The Turing robot opened the drawer (but not the latched door covering the drawer), removed the probe, and inserted the thermal sensor into the soil.

Future demonstrations: Automatic retrieval of tooling. Insertion of probes would benefit from force-torque sensing to prevent damage to the probe during an automatic insertion. Visual targeting could also be used to indicate multiple positions for automatic probe insertion, and result in automatic mapping of the thermal data to positions.



Figure 26: Turing robot opens the Fox vehicle tool drawer



Figure 27: Turing robot removes thermal probe and places it into the soil

Sample Wheel Replacement

Small sampling wheels are rolled along the ground behind the Fox vehicle to collect running chemical samples. Periodically, they must be removed and heated to desorb the sample for analysis in a gas chromatograph. Currently, the glove port described above is used to single-handedly remove the wheel and place it into the heating chamber. A new wheel is then installed on the axle and returned to the ground.

The Turing robot had sufficient dexterity to remove and replace this sample wheel, and the operation was demonstrated three times. Executing the replacement operation using manual control was both difficult and time consuming, even with the advanced control capabilities. Releasing the hub clip from one side of the wheel was not possible using the single manipulator. Several possibilities for improving the wheel clip design were discussed that would not only enable robotic manipulation, but would simplify the gloved manual operation as well.



Figure 28: Sample wheel with hub clip released



Figure 29: Turing robot removing sample wheel



Figure 30: Sample wheel removed



Figure 31: Turing robot replacing sample wheel

Future demonstrations: A manipulator fixed to the Fox vehicle, with pre-programmed positions and orientations for wheel removal and replacement. Tapering the hub of the wheel and altering the hub clip would enable easier robotic and gloved-hand replacement.

GB and Mustard Gas Surveys

This operation utilized the Wolverine robot with a Chemical Agent Monitor Simulator (CAMSIM) detector used to train Chemical Corps soldiers to detect simulated nerve and mustard agents. The demonstration required both area sampling as well as close-in scanning detection techniques.

The CAMSIM detector was retrieved from a tool holder on the robot, and then deployed near simulated agent on objects and on the floor. Samples could be detected only if the detector was within about $\frac{1}{2}$ inch of the sample. Therefore, scans were made maintaining the $\frac{1}{2}$ inch distance from the vertical and horizontal surfaces until detection was made. The operator could view the detection window of the sensor through the robot wrist or mast video cameras.

Future demonstrations: The scanning process could include visual targeting for the operator to designate an object, its volume and surfaces, to scan. Path planners are available to generate the scan pattern, which can be automatically executed. The infrastructure necessary to streamline and automate this process is in place, requiring relatively minor development to enable automatic scan generation and execution.

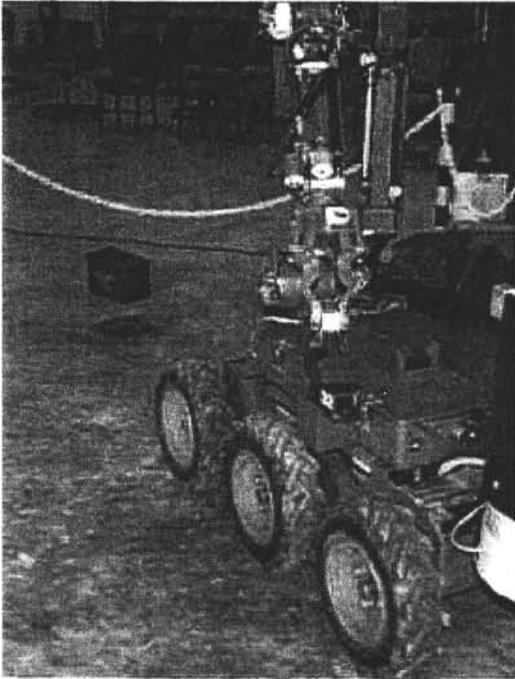


Figure 32: Wolverine automatically retrieves detector from storage location

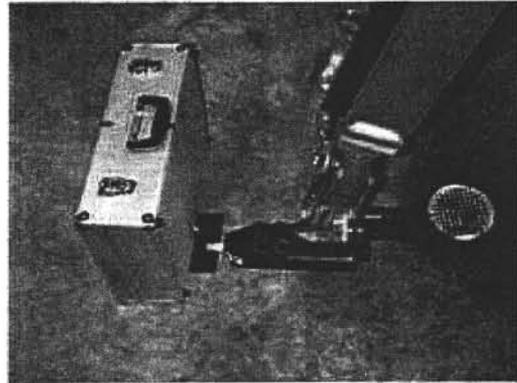


Figure 33: Wolverine scans across the container at 1/2" stand-off without collision until it detects the simulated agent near the floor

A contamination simulant representing off-gassing material was placed in the building and the robot operator was required to locate it. The sample was located in a bathroom, detected as the robot manipulator reached through the door. Again the operator was able to see the sensor read-out through the robot mast and wrist cameras.

It is important to note that to access buildings, rooms, and vehicles for scanning it is necessary to have manipulation capability. Vehicle sensor platforms cannot enter such areas otherwise, unless escorted by humans, which in turn puts them at unnecessary risk.



Figure 34: Wolverine robot executes area scan for mustard agent, detected from a distance of approx. 4'

Liquid Sample Testing

Liquid samples may be tested using a paper detector that changes color in the presence of certain agents. To demonstrate this, the robot retrieved a sample paper and placed it rapidly into a puddle on the floor near a "leaky" container. The color zoom camera on the Wolverine mast was able to see the paper and any color change clearly.

Future demonstrations: Liquid recovery and insertion into analytical equipment, utilizing both teleoperation and automatic capabilities.

Radiological Surveys

A contact radiological swipe was taken using the Wolverine robot. A sample paper was attached to a block of wood to provide stability, which in turn was attached to a spring-loaded cylinder via hook-and-loop material. Under manual control, the Wolverine retrieved the sample paper, placed it on a container, and swiped approximately 100 sq. cm. of the surface. At the push of a button, the robot automatically placed the paper into a container mounted at the side of the robot, where it was released under manual control.

Future demonstrations: Placement of the samples into a spectrometer for contamination identification. A version of this was done by SNL in the mid 1980s using robots to arbitrarily choose points on a spent nuclear fuel transport cask, swipe the surface and analyze for contaminants using a modified Canberra machine.

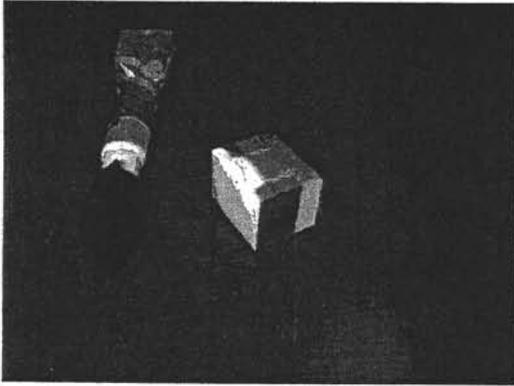


Figure 35: radiological contamination swipes to be taken from block mounted ample paper attached to a spring-loaded tube

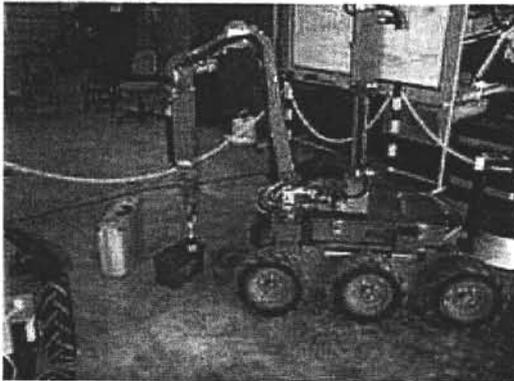


Figure 36: Wolverine executes surface contamination swipe

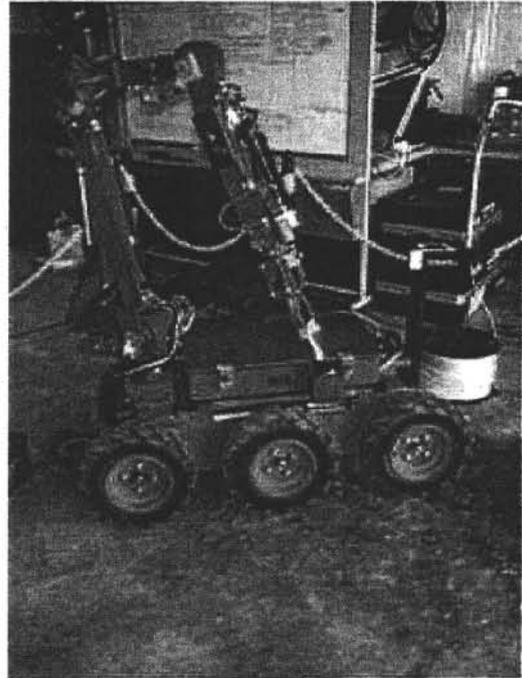


Figure 37: Swipe deposited in container on robot for later analysis

Explosive Ordnance Disposal

In addition to the planned School activities, EOD soldiers posted at Ft. Leonard Wood also participated in the demonstrations as a part of the MP group. The soldiers were trained in fundamental control of the robots in the manual and automated modes, and then executed access and disruption activities, as previously described.

Conclusion

Most challenges brought to the demonstration by MANSCEN were achievable with little training and some improvisation. All tasks were accomplished under non-line-of-sight (NLOS) conditions. With less than one hour of training, each soldier had a fundamental knowledge of the robot capabilities, and was capable of controlling the robots in both manual and automated modes. Within another hour, their comfort level with the robots had risen such that substantial increases in operational speed and creative use of the capabilities could be observed.

Standard hand tools and weapon configurations were utilized for the demonstrations. Modifications to the tooling for robot deployment consisted mainly of

adding tape and wooden blocks, or hook-and-loop material for gripping and mounting purposes. Robot-mounted cameras permitted visual reading of the detection devices, and the on-board microphones enabled audio feedback from the mine detector to the operator.

Written feedback from the soldiers was provided directly to RTIA personnel. Verbal feedback from the soldiers indicated a general belief that these and many other operations could be carried out using mobile manipulation systems with similar dexterity. Different reach and payload capacities may be necessary in future activities. All commented on the ease with which they could learn to use the robot. Most indicated that the space ball input device, after some practice, was the most efficient means of controlling the manipulator. This can be done with one hand, with input interpreted into straight-line motion of the tool tip in cardinal directions, which the soldiers confirmed is a very intuitive motion resulting in faster execution of operations.

EOD soldiers were the most vocal about the improvement of capability and robot control. Familiar with the currently fielded RONS vehicle, they were adamant that ease of control and improved dexterity, as demonstrated by these robots, is the direction the Army must take.

This demonstration was a preliminary step in experimental use of manipulation in the MANSCEN mission space. It is apparent that a limited set of small, medium and heavy manipulators would be useful in executing many of the difficult and hazardous tasks both current and future. SNL looks forward to the opportunity to work with the Army to develop efficient, easy to use mobile manipulation systems to meet the challenges of the interim and objective forces.

Appendix A Acronyms & Abbreviations

AP	Antipersonnel
CAMSIM	Chemical Agent Monitor Simulator
	Degrees of Freedom
EFP	Explosively Formed Projectile
	Explosive Ordnance Disposal
JAUGS	Joint Architecture for Unmanned Ground Systems
LAMA	Laser Mapper
MANSCEN	Maneuver Support Center
MIDS	Miniature Intrusion Detection System
	Military Police
NLOS	Non-Line-of-Sight
	Operational Control Unit
	Percussion Actuated, Non-Electric
	Robotic Technology Integration Activity
SMART	Sandia Modular Architecture for Robotics and Teleoperation
	Sandia National Laboratories
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