USING RANGE VISION FOR TELEROBOTIC CONTROL IN HAZARDOUS ENVIRONMENTS

M. G. LIPSETT*, M. GREENSPAN**, W.J. BALLANTYNE***

*AECL Chalk River Laboratories
**National Research Council of Canada
***Spar Aerospace Ltd.

ABSTRACT

This paper describes how range vision augments a telerobotic system. The robot has a manipulator arm mounted onto a mobile platform. The robot is driven by a human operator under remote control to a worksite, and then the operator uses video cameras and laser range images to perform manipulation tasks. A graphical workstation displays a three-dimensional image of the workspace to the operator, and a CAD model of the manipulator moves in this "virtual environment" while the actual manipulator moves in the real workspace. This paper gives results of field trials of a remote excavation system, and describes a remote inspection system being developed for reactor maintenance.

1. INTRODUCTION

Teleoperated manipulators are used for remote handling of hazardous materials and can also be used for remote inspections, decontamination, and site remediation. These operations require skilled operators who can visualize the remote work area and keep an awareness of the working situation. Existing mobile robot systems are joystick-driven with no automatic control; the only feedback to the operator is a video view. While reliable, such systems are slow and difficult to use, and there is little sensing capability [1]. Situational awareness can be aided by range imaging, which builds a three-dimensional view of the work space on a computer monitor. This view is called a virtual environment (VE).

The intent of a VE to present a view of the scene that is realistic enough for the operator to drive the robot as well as if the operator were actually looking at the machine. The advantage of laser ranging over video is that accurate, calibrated, high-resolution images of the robot workspace can be collected and used to direct robot motions with real-time collision avoidance. Laser range images also allow automatic recognition of objects in the scene for point-and-click automated operations.

In the present work, two broad application areas have been considered: outdoor site remediation and indoor inspection of hazardous environments.

The first area of interest for implementing a telerobotic system is site remediation in hazardous environments with no direct human contact. The U.S. Department of Energy has identified a number of contaminated landfill sites and land surrounding high-level waste tanks where remote operations are required for worker protection [3]. To address this need, a telerobotic excavator system has been designed, built, and tested; the robot operator control the excavator from a trailer 100 m from the work site, with input from a laser ranging camera. The laser camera is based on the NRC auto-synchronous scanning method [4].

The development system has a laser range camera mounted on the wrist of a PUMA 560 robotic manipulator arm. This laboratory system tests software and control techniques for field prototype systems [5]. After implementing the laboratory system, our attention turned to implementing the field version of the system and improving the user interface for specifying teleoperation tasks. Field tests of the outdoor laser camera and the telerobotic excavator were held in October 1995 at AECL Chalk River Laboratories. The system architecture is described. Results are presented of outdoor demonstration tasks performed to test the camera accuracy and to investigate the interaction of range data acquisition with manipulation.

The second application area is remote inspection of inaccessible industrial plant equipment, such as valves and pumps. This system is presently being developed, using a telerobot system to measure vibrations, temperature, and other diagnostic condition indicators [6].

2. TELE-EXCAVATION SYSTEM DESCRIPTION

The Laser Ranging Telerobot system (LRT) performs outdoor site remediation tasks remotely. The LRT combines a robotic excavator with a separate scout vehicle that carries a three-dimensional laser range imaging camera. The user, at a graphics workstation, controls the LRT at a distance over a wireless communication link or a tether.

The LRT is designed to allow an operator to excavate previously unmapped terrain remotely, or to supervise remote excavation. Workspace modeling allows complex tasks to be performed in cluttered environments; because obstacles are known, the environment becomes structured and the robot controller has no unexpected obstacles to avoid. The system uses range data gathered by the laser range camera to build a geometric model of the excavation work space displayed as a VE. Intensity images are also available for operator viewing on the workstation graphical user interface (GUI). The GUI design and real-time collision avoidance feature improve efficiency and reduce operator fatigue usually associated with direct-video, remote-control methods.

The system operates a manipulator (the excavator) in either direct teleoperation mode or supervisory control mode [7]. Manual override, automatic trajectory planning with real-time collision avoidance, and preprogrammed operations are standard features. It is possible for multiple machines to be supervised by a single operator, because many low-level tasks can be automated. This frees the operator to concentrate on tasks that require a human touch. Working at a distance ensures operator safety, supervisory control reduces fatigue, and real-time collision avoidance prevents accidents during complex tasks. The LRT can interface with other remote earthmoving equipment to perform site remediation without exposing workers to hazardous environments.

The system comprises: a commercial excavator modified for remote operation as the manipulator; a laser range camera for outdoor use; a remotely operated mobile vehicle that carries boom, pan, and tilt systems for the range camera and a video camera; a controlling computer with a graphical user interface; and support systems. The system is shown schematically in Figure 1; and a photograph of the field system is shown in Figure 2.

System software comprises image acquisition and analysis software, a world model and simulation system for task planning, and a graphical user interface for task execution with control of the excavator and the camera equipment.

2.1. Remote Excavator

The excavator is a Hitachi LC200 which was remotized before this project by Spar Aerospace, RSI Research, and the University of British Columbia.

The four hydraulic joints are electrically controlled by a joystick, which is connected to the VME-based embedded controller on the excavator by a serial communication link. The hand controller translates operator commands into serial command strings, which are sent to the excavator control computer and to the supervisory control computer. Control commands include both coordinated rate control (task space) and single axis control (joint space). The signals from the joystick are interpreted as rates in a cylindrical coordinate system.

There are a number of additional lines bundled with the joystick line in a tether approximately 75 meters in length. The tether also includes a dead-man safety switch cable that disables the excavator hydraulics when the operator releases the switch. An NTSC line connects a real-time video camera, which is mounted above the cab; and control lines are included to pan, tilt, and zoom the camera. A customized bucket includes a controllable thumb joint, which allows the grasping of barrels and other objects, and a dedicated line controls the position of the rate of the thumb joint.

The excavator tracks are also individually rate controlled, although these are not presently operated remotely. The excavator is drivable to an outdoor worksite and digs with resolved velocity control. The controller is of sufficiently open architecture to allow controller commands to be received from sources other than the joystick (e.g. a system control computer). The excavator is able to withstand normal outdoor weather conditions from -20 to +30 Celsius. The excavator electronics are not radiation hardened.

2.2. Scout Vehicle

A scout vehicle carries the sensor ensemble and transmitter to locations in the worksite. The video and laser range cameras are mounted on this vehicle rather than on the excavator, for two reasons. First, a scout vehicle allows a much richer number of views from which to survey the scene with the excavator in a given pose. Second, the cameras are physically separate from the excavator so that the cameras are decoupled from excavator structural dynamics.

The scout vehicle is a Robotech HazHandler, a remote Bobcat tele-driven by wireless link. The scout vehicle and its suite of sensors is completely untethered, the digital connection being an Arlan wireless Ethernet. This vehicle, however, has a separate radio controller from the rest of the system user interface.

2.3. Laser Range Scanner (LRS)

The Laser Range Scanner (LRS) is based upon the auto-synchronous scanning method developed at the NRC [4]. This camera rasters a laser beam and measures the distance of a set of points by triangulation. The particular camera used was built by Spar Aerospace and the NRC, and was reinforced for outdoor use. Its specifications are listed in Table 1. The LRS system comprises two items:

the Laser Range Scanner remote head; and
the Laser Range image processor.

The LRS remote head connects to an image processor on the VME cage via cable approximately 10 m long. There is also a fibre optic cable from the laser source to the scanner head. The remote head is 23 cm x 23 cm x 13 cm, with a mass of less than 5 kg. The mounting fixture is a standard 0.375 BSW tripod mount. The LRS is able to operate outdoors in clear weather, from 0 to 30 degrees C. Although weatherproofing is possible, it has not been done in this project.

The LRS commences scanning its current viewing area upon command from the operator workstation via the scout vehicle control computer. This image data (roughly 1 MB for 512 x 512 image) is stored in a shared memory interface in the LRS image processor; it is retrieved for transmission to the workstation.

2.4. Boom

The LRS is mounted on the scout vehicle on a 2 degree-of-freedom (DOF) pan-tilt unit (PTU) and an elevating boom, shock mounted to dampen vehicle vibrations. The position of the PTU and boom (PTU/B) is controlled at the operator workstation.

The retractable camera boom provides camera mount elevation on the scout vehicle. The kinematic design is a mast on a forward pivot with lateral supports, driven as an inverse slider-crank by a linear actuator mounted on the chassis. The actuator is an induction motor turning a ball screw and slide.

The boom supports the 13 kg mass of PTU and LRS at an elevation of 2.5 m above the ground, with the end of the boom level with respect to the base of the mount to within 2 degrees. The boom is stiff enough to support the mass of the cameras and the pan-tilt mechanism with minimal static deformation and vibration. The boom system uses corrosion resistant materials and boots to withstand adverse weather conditions.

This mechanism mounts to the HazHandler on a 1 m x 1.5 m aluminum plate. The boom is remotely adjustable via radio link. An inverter controls the boom elevation from the operator workstation via RS-232 link. A potentiometer is read by an analogue-to-digital converter that sends values to the operator workstation by RS-232.

2.5. Pan-Tilt Unit (PTU)

The pan-tilt unit (PTU) orients the video cameras and the laser range cameras with respect to the world coordinate frame, allowing the operator to aim the LRS by viewing the image in its field of view prior to acquiring a range image.

The mechanism is remotely controlled, able to support the 5-kg camera package and to withstand rugged environments; it allows continuous 360-degree pan at a slew rate of 30 degrees/s, and a tilt of +90 to - 40 degrees. The pan/tilt controller interfaces to the controller for scout vehicle functions on the VME-bus; an RS-232 link is also available. The pan/tilt mechanism has a mass of 8 kg, including the mounting base and motors. The pan-tilt system is resistant to normal weather conditions, including rain.

2.6. Operator Workstation (OW)

The operator workstation (OW) is the main user interface to the system. It supports a rich graphical user interface (GUI) to display the VE and provide a variety of image handling and simulation routines.

2.6.1. Graphics Workstation

All of these devices are monitored and operated from a graphics workstation. The richness of the range data is effectively displayed on a high-end graphics workstation; the graphics workstation for the demonstration system is a Silicon Graphics Impact with Elan Graphics running IRIX 5.3. This OW has full 3D hardware rendering support, allowing for real-time image manipulation and simulation capability. The code is portable so that several Silicon Graphics machines can be used for software development.

2.6.2. Embedded PC

The real-time requirements of the communication with the excavator controller require an embedded computer as an interface between the joystick, the excavator, and the OW. A 66 MHz 486 PC running the QNX real-time OS is used. This acts as a central data switch, accepting data from the various devices, and routing them to the proper destinations. The PC also processes and filters some of the signals, to improve the ease-of-use of the joystick, and to provide real-time collision avoidance functionality [8].

2.6.3. Connectivity

The OW interfaces with the real-time embedded control computer for the reception of sensory data (range images, video images, joint values, PTU/B values, etc.), and the transmission of motions (PTU/B motions, excavator motions).

The excavator and PC are connected by a full duplex RS-232 line. Data packets are transmitted to and received from the excavator every 50 msec. The message sent to the excavator is a cylindrical coordinate frame rate command, as read from the joystick. Joint rates can also optionally be sent. There are also a number of additional miscellaneous commands, such as emergency stop and standby. The message sent to the PC is an excavator joint encoder reading.

The joystick and PC are connected by an RS-232 line. The joystick is interpreted as Cartesian rate commands, and is polled every 25 msec, twice the frequency of the Excavator-PC communication cycle.

The PC is connected to the OW by an Arlan wireless Ethernet connection. The message sent to the OW contains present joint locations as received from the excavator. These are used to update the attitude of the excavator in the VE. The current joystick readings are also included in the message. The message sent to the PC includes operational state information, such as joystick filtering parameters. For example, certain degrees of freedom of the joystick can be toggled on/off, or made more sensitive. The world model containing the obstacle information is also transmitted to the PC for real-time collision avoidance.

The OW and PTU/B are also connected by wireless Ethernet. The message sent to the OW contains PTU/B position encoder readings. The message sent to the PTU/B contains motion commands to pan, tilt, and elevate the boom. The PTU and Boom have separate motor controllers.

The OW and LRS are connected by a wireless Ethernet. The message sent to the OW contains the acquired image data. The message sent to the LRS contains parameter settings, such as image size and field of view.

2.7. Video Cameras

Standard video cameras are mounted on the top of the excavator cab and on the PTU of the scout vehicle (for driving and for pointing the LRS). Output cables from the camera are coaxial with standard Phillips video connectors. Zoom, focus, and brightness are available on the excavator camera only.

The camera on the excavator is weatherproof, and has its own PTU. The excavator camera controller communicates by its own communication link through the tether. Its display is a stand-alone monitor. The Panasonic camera on the PTU has a mass of less than 200 g, with a barrel mount; it is not weatherproof. A wireless transmitter sends the video signal to a television monitor.

2.8. Power Supplies and Ancillary Systems

All scout vehicle systems are powered by three 12 V DC automotive batteries driving AC inverters; 120 V AC is available to run power supplies for subsystems, consuming 700 W. The HazHandler charging system is used to maintain the battery charge. All systems are fuse-protected.

2.9. Software Description

The OW software consists of a node library of C++ classes and C modules. The three main functions of the system software are :

- to register the acquired range images;
- to control devices (LRS, PTU/B and excavator); and
- to render and provide interaction with the VE to aid the operator's understanding of and interaction with the scene.

The GUI uses the Forms CASE tool. This package is public domain and specific to the SGI platform.

2.9.1. Range Image Registration

To construct a view of the worksite, the range images must be positioned with 6 degrees of freedom within the VE. The scout vehicle has no automatic telemetry (such as global positioning) to give an estimate of its location in the worksite. The contents of the range images themselves are therefore used to determine their relative locations.

When a range image is acquired, an effort is made to overlap some portion of the new image with a previously acquired image. If there is enough common information in two images, then the newly acquired image can be correctly positioned with respect to the reference image, in a process known as image registration.

The system supports three types of image registration : manual, semi-automatic, and fully automatic. In manual registration, the operator selects three corresponding data points in each image. The homogeneous transformation that maps the second set of three points onto the first is calculated and applied to the new image. As long as there are three points in each image that the operator visually recognizes as corresponding, this method succeeds in stitching the two images together.

In the partially automatic method, the operator provides an initial estimate of the location of the new image by visually *positioning* the image in the VE using the "fly-around" controls. Once the initial estimate has been established, a version of the Iterative Closest Point Algorithm (ICPA) [9] is invoked to calculate a more accurate correspondence. As long as the initial estimate is within the global minimum of the error metric used to calculate the residuals, this method succeeds.

In the fully automatic method, known as Signature Search [10], it is assumed that an initial relative position estimate exists. This initial estimate can be less accurate than in the partially automatic case, as it need not be close to the global minimum. A search is applied which refines the initial estimate, following which the ICPA is invoked. The criterion for success of this method is dependent upon the information content of the image and the accuracy of the initial estimate.

When a sequential chain of images are registered, there is an error that accumulates with respect to the initial reference image. This error can be reduced by scanning the initial location, closing the chain and distributing the refined error estimate over the images. The 6-DOF position of the Scout vehicle is determined from its relative position to the acquired range image. If the scout vehicle is not repositioned, and the PTU/B is repositioned to provide a new image view, then an initial estimate exists from the PTU/B encoder readings, and the Signature Search method can be invoked.

If a newly acquired range image does not overlap with any of the previously acquired images, then it can be manually positioned in the VE by the operator temporarily until further overlapping images are acquired.

2.9.2. Device Control

The OW is also used to control the LRS, the PTU/B, and the excavator.

The LRS is a highly flexible ranging mechanism, and there are a number of parameters that can be adjusted (field-of-view, scan pattern, and scan speed), depending upon the scene to be acquired. Typically, a low resolution 64x64 image is acquired first to get an estimate of the field-of-view and exposure settings, and then a higher resolution 256x256 image is acquired. Any rectangular region can be selected in an acquired range image to zoom the LRS and limit its field-of-view to a small region of interest.

When the scout vehicle is in motion, the boom is lowered to its home position to reduce the vibrations transmitted to the LRS. The boom is raised to an appropriate height when an image is to acquired. The PTU orientation is also commanded from the OW to capture a suitable scene.

Automatic paths can be generated within the OW GUI and are downloaded to the PC for the excavator to execute. If obstacles are identified in the environment, then a path planning search generates a collision-free trajectory. This feature was implemented on the laboratory prototype system, but it was not part of the field system until after an October 1995 workshop.

2.9.3. VE Rendering and Interaction

Range images are by far the most computationally expensive items to render in the VE. A single range image may consist of over 64,000 3-D points, with associated intensity values, and it is a system requirement to render and interact effectively with at least ten range images simultaneously.

A number of commercial systems exist to simulate and render 3-D CAD worlds (IGRIP, ROBCAD, ACT). Range images are relatively novel, however, and are not supported by these systems. It was therefore necessary to develop a VE rendering engine capable of dealing with both range images and articulated CAD models.

There are a number of rendering methods for the range images, depending upon the level of interaction required. The two representations used here are point sets and tile sets. In point mode, each individual point in a range image is rendered in 3-D space with its associated intensity value. In tile mode, a neighbourhood operation is applied to create small planar surfaces from adjacent points. Whereas the point mode is closer to the raw data, the tiles are more visually representative in many cases, as they give the impression of a connected solid surface. Both point and tile representations have a fine and a coarse rendering method, which trades off detail with rendering speed.

3. SYSTEM OPERATIONAL CONCEPT

The project goal is to enhance operation of a manipulator in an unstructured environment using range image data. Enhanced operation has been implemented with an incremental work plan, building additional functionality into the system in a modular way as it becomes available.

The first task is to acquire range image data and produce the VE, which is a 3-D picture of the workspace. Figure 3 shows an example of a workspace scene recorded by the laser camera. CAD models of the excavator and the vehicle carrying the camera are also shown. The OW GUI includes pose refinement and multi-view registration of scanned images. Real-time feedback from the controller to the workstation allows dynamic updates of the manipulator configuration, so the excavation is animated on the VE, following the actual excavation motions.

After the VE has been built up on the OW, the system plans and executes a collision-free manipulator path in two modes: autonomous mode, or teleoperated mode. In autonomous mode, the robot follows a preprogrammed trajectory; in teleoperated mode, the user drives the machine with a joystick while watching the VE. A model of the manipulator is updated as the machine moves, and the operator is able to view the scene from any direction---a conspicuous advantage over conventional (and even stereo) video.

The user is able to rehearse task execution by taking advantage of a real-time collision avoidance algorithm. This algorithm ensures that no part of the manipulator enters space occupied by objects detected by the range camera. This feature allows the operator to concentrate on the task rather than on avoiding objects cluttering the workspace. The user can construct virtual barriers in the environment to simplify task planning. These barriers are considered to be objects to avoid, and so the manipulator glances off a virtual wall if the user tries to drive the machine too close to a sensitive area of the work space.

3.1. Operational Modes

To demonstrate an enhanced mode of remote excavator operation using range imaging, two operational modes can be applied:

- direct teleoperation with collision avoidance supervision
- simulation and playback of task motions with manual override.

Attempts by the operator to teleoperate outside a permissible work area cause the manipulator to stop on-power.

3.2. Preliminary Image Acquisition and Reference Frame Identification

The scout vehicle is teleoperated to the worksite, using the real-time video link for navigation. At an appropriate vantage point where the area of interest is observable, a single wide angle image is acquired. If a single image is not sufficient to display the entire worksite, a number of images are collected by servoing the camera without repositioning the scout vehicle.

A global reference frame is determined. If a pose site (PS) exists, then the current location of the vehicle is acquired from the PS and is stored with the image. If no PS is available, the overview vantage point represents the local zero reference for the ensuing operations. All acquired images are stored in a database.

3.3. Laser Range Image (LRI) Survey

The location of the LRS within the vantage reference frame is determined manually using the ray of points from the first laser-range image (LRI). The LRS is pointed at successive regions, and images are acquired. Some features on a previously acquired LRI are used to direct the next scan. Once a series of scans have been acquired, existing scans are used to direct the next scan. The PTU/B are encoded to sufficient accuracy to update the VE.

3.4. Examine Laser Range Imagery

The acquired range imagery is examined by the operator, either as an intensity image or in the 3-D VE. To facilitate visualization in the VE, the LRIs can be displayed as point clouds or meshed. Using a variety of interactive graphics tools, the operator can reorient the LRIs (zoom in/out, fly around), measure properties of the data (e.g. point-to-point distances), and identify and label objects in the scene (using pose refinement or primitive extraction).

If a possible landmark is within the scanning range of the LRS, then the neighbourhood is scanned, and its location is accurately identified through manual operations on the acquired data. Landmarks (rocks, barrels, etc.) are located in the LRI using intensity images from different vantage points. At this time, objects are highlighted and any virtual barriers added.

The location of the excavator chassis is found by manually registering a model of the excavator chassis to the range data within the world model. The model reflects the current joint values of the excavator, as read from the joint encoders, and is automatically updated on the VE display.

3.5. Plan Excavator Work Activities

Using the VE, the operator plans activities through simulation in the world model, watching supervised teleoperation from different vantage points on the VE. Boundaries are projected onto the world model to restrict and guide excavator motions.

3.6. Execute Excavator Activities

After teleoperated sequences are practiced on the VE, the operator executes teleoperations using both the VE and real-time video. The VE excavator model is updated from changing joint angles on the excavator. Either direct teleoperation or playback mode is used.

4. RESULTS OF FIELD TESTS

Preliminary field integration tests were conducted at AECL Chalk River Laboratories in October, 1995. All of the described equipment was assembled and integrated. A test field was constructed which resembled a general dumpsite. The operator workstation was located in a trailer adjacent to the worksite. For safety reasons, a direct view of the excavator was available through a window of the trailer. During the formal tests and demonstration, however, the operator used only the video monitors and VE rendering to guide teleoperation.

The worksite was surveyed with seven images; the VE that was built is illustrated in Figure 3. This VE, displayed on the OW, was used for remote digging, dumping, and barrel retrieval tests.

The results of the tests were positive. The LRS exceeded nominal specifications, acquiring valid data as far away as sixteen meters in daylight conditions. The VE was visually descriptive. It was not difficult for the operator to understand the 3-D geometry of the workspace and discern even small, irregular objects. Complete rendering of the range images, plus CAD models of the excavator, scout vehicle, and other objects in an otherwise unmodeled environment, was executed at approximately 2 Hertz. This update rate was fast enough for teleoperation at normal operating speeds.

Video from the cab direction was useful for aligning the swing axis, but no depth cues were available. The VE provided depth cues in a side view that video could not supply. Audio cues from engine sounds and tilt of the cab during heavy lifting operations were absent; these were noted to be useful clues about the effort being exerted by the machine.

The major result was working confirmation of the operating principle of the system. The interaction with the VE allowed the operator to better understand the geometry of the worksite, and to plan and execute remote operations. As an example, working entirely from the visual queues contained in the VE, the operator was able to position the bucket, grasp a barrel, and place it into a dumpster.

In the laboratory prototype system, the LRS is mounted directly on the wrist of a Puma 560 robot. The straightforward extension of this onto the current hardware would have been to mount the LRS directly on the excavator stick near the bucket. This configuration was not used because of concerns that the excavator dynamics (i.e. vibrations), which were negligible in the laboratory system, might adversely effect the LRS operation. Also, it was conjectured that the use of a more manoeuverable scout vehicle affords greater flexibility to position the LRS and sense the scene. It was found during testing, however, that the LRS camera had greater range than anticipated, it was able to operate with the scout vehicle engine running, and the camera was not damaged driving over rough terrain. It was thus concluded that in future the LRS and supporting system could be mounted on the excavator chassis, eliminating the scout vehicle and reducing the complexity of the system.

5. FUTURE WORK

The results obtained to date demonstrate the benefits that range imagery can add to remote teleoperation. The eventual goal of this work is to increase the effectiveness and the safety of remote teleoperation, which will both reduce the level of skill required by the operator and increase throughput.

5.1 User Interface

Ultimately, the effectiveness of this system depends very much on the usability of the interface. One of the continuing areas of research is to improve the user interface to make teleoperations more complete and intuitive.

Another area of further research is representations for more effective rendering of range images. Hierarchical t-mesh structures are currently being developed for this purpose, with data from other sensors mapped onto the surfaces. This features shows results of radiation surveys and leak searches to locate trouble spots.

5.2 Operational Safety

Another focus of continued research is improved safety. In particular, real-time collision avoidance has been demonstrated on a laboratory prototype and has recently been implemented on the field system. Objects that are hazardous to contact are identified in the VE as obstacles. The low-level controller intervenes to disallow any motion commands which would result in an impending collision. (The field tests highly motivated the inclusion of real-time collision avoidance, as one of the excavator operators accidentally contacted and moved the dumpster.)

5.3. Remote Inspection and Maintenance of Process Equipment

The advantage of using a robot for inspection and maintenance is that a robot can gather information and do work in highly hazardous areas. In such areas, and to a lesser extent in inaccessible areas, conventional remote sensors and tooling can not be deployed.

Effective plant monitoring relies on timely and reliable information, not only about plant processes but also about the components and systems in the plant. Hazardous industrial processes are isolated from plant personnel, and often process control instrumentation is inadequate for diagnosing faults in equipment remotely. In some inspection tasks, such as radiation surveying and leak detection, the inspection covers the entire surface of an object. Information gathered by robots about the hazards can be used to rehearse procedures, which reduces human exposure to hazards during the task. In some cases, simple gripping and actuation tasks can be done by the robot instead of by a human, allowing tasks to be done in inaccessible areas quickly, cheaply, and safely.

Robots for CANDU remote inspection and maintenance fall into two categories: mobile vehicles and portable manipulators. The mobile robot is most useful for delivering sensors to a highly hazardous location to gather information. The portable manipulator is used for jobs with a limited work space where hazards are local (e.g. steam generators). As well, the fueling machine can be used as a robotic tooling delivery system at the reactor face.

Mobile robots with manipulators are sometimes used at CANDU stations. All share similar characteristics: they are wheeled or tracked machines with simple manipulator arms. The user drives to a location of interest to survey a scene remotely with video cameras, make a radiation survey, or perform rudimentary manipulation tasks. The robot is either tethered or self-powered and radio-controlled; the machine does not operate under automatic control.

Rather than redesign a new machine, commercial mobile robots should be modified to improve their performance and usefulness in CANDU stations. Such mobile robots require more versatile, modular tooling, improved communication links, supervisory control, and improved power supplies.

The manipulator must be able to release an end effector and pick up another when it needs a different tool. The robot therefore needs a tool changer for instruments and tools, with a standard mount with positive lock and a connector for power and signal conductors. Examples include tools to collect smears or collect grab samples, custom grippers, tools for fasteners, leak detectors, and gamma meters.

The user interface has to be able to read the modular sensors and actuate the modular tools, with a wireless communication link that accommodates the range of tasks the robot performs remotely. Using a containment penetration for radio transmission would improve reception, but the radio transmitter must not affect reactor operations. Mobile robots can operate over a tether or by radio link with batteries. A recharge adapter would allow an untethered robot to operate longer inside containment by plugging into a mains receptacle in the vault. Few mobile robot vendors offer a radiation-hardened controller, although spray-washable enclosures are common. The controller architecture should be open for expandability and reconfigurability. For remote inspection, collision-free automatic surface following should be available as an option. Primarily, however, the machine has to be reliable, and so the controller should fail safe so that manual control of motors remains possible, and actuators can be disengaged to retrieve the robot.

The laser ranging telerobot system is being adapted to this application, with a smaller vehicle and an articulated manipulator for the inspection of high radiation areas in nuclear facilities. Reactor maintainers are contributing to the system specifications.

6. CONCLUSIONS

A laser ranging telerobot system has been designed, developed, and tested in an outdoor environment. Laser ranging was not limited by outdoor conditions above zero Celsius. Range images were registered into a map that was used by a remote operator to grasp and move barrels of the type used in waste storage.

This telerobotic system has demonstrated itself to be a useful tool for hazardous waste site remediation. Future target applications include remote inspection and maintenance inside nuclear power plants.

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Range:	0.6 to 10 m
Field of View:	30 x 40 degrees
Image Capture Rate:	20,000 pixels /s
Image Size:	up to 4096 x 4096 (rectangular, preprogrammed).

Table 1: Laser Range Scanner Performance Specifications

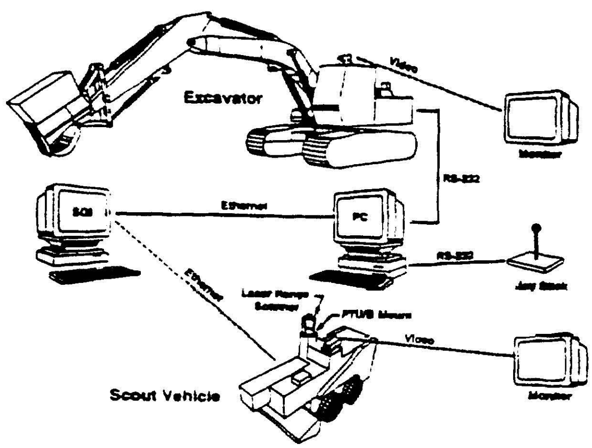

FIGURE 1: Telerobotic Excavator System Hardware and Connectivity

FIGURE 2: Telerobotic Excavator System Photograph

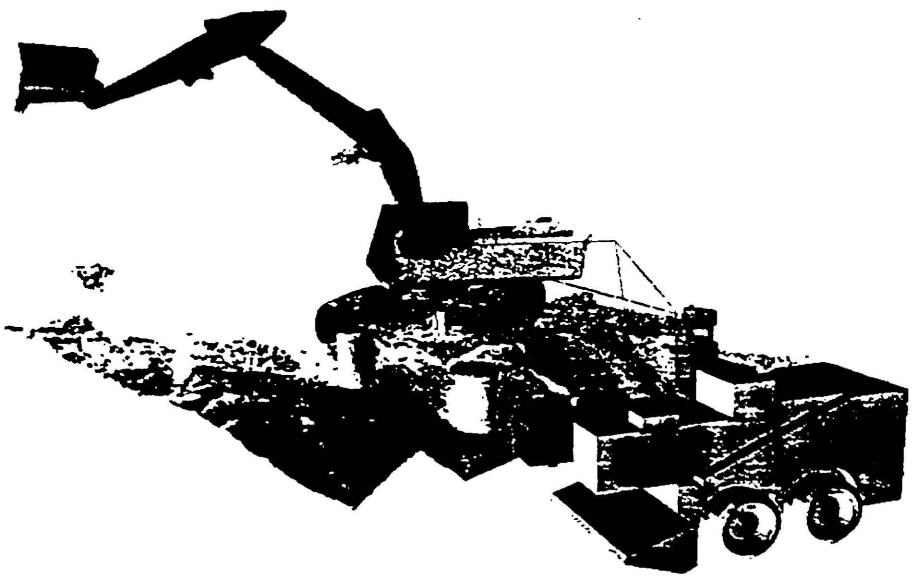

FIGURE 3: Virtual Environment Generated in Field Test