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DEVELOPMENT AND DEMONSTRATION OF A TELEROBOTIC EXCAVATION SYSTEM*

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ABSTRACT Oak Ridge National Laboratory is developing remote excavation technologies for the Department of Energy's Office (DOE) of Technology Development, Robotics Technology Development Program, and also for the Department of Defense (DOD) Project Manager for Ammunition Logisitcs. This work is being done to meet the need for remote excavation and removal of radioactive and contaminated buried waste at several DOE sites and unexploded ordnance at DOD sites. System requirements are based on the need to uncover and remove waste from burial sites in a way that does not cause unnecessary personnel exposure or additional environmental contamination. Goals for the current project are to demonstrate dexterous control of a backhoe with force feedback and to implement robotic operations that will improve productivity. The Telerobotic Small Emplacement Excavator is a prototype system that incorporates the needed robotic and telerobotic capabilities on a commercially available platform. The ability to add remote dexterous teleoperation and robotic operating modes is intended to be adaptable to other commercially available excavator systems.

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INTRODUCTION

For nearly five decades, the U.S. Department of Energy (DOE) and its predecessor agencies have performed broad-based research and development activities as well as nuclear weapons component production. As a by-product of these activities, large quantities of waste materials have been generated. One of the most common approaches formerly used for solid waste storage was to bury waste containers in pits and trenches. With the current emphasis on environmental restoration, DOE now plans either to retrieve much of the legacy of buried waste or to stabilize the waste in place by in situ vitrification or by other means. Because of the variety of materials that have been buried over the years, the hazards are significant if retrieval is performed by using conventional manned operations. The potential hazards, in addition to radiation exposure, include pyrophorics, toxic chemicals, and explosives. Although manifests exist for much of the buried waste, these records are often incomplete when compared to today's record-keeping requirements. Because of the potential hazards and uncertainty about waste contents and container integrity, excavating these wastes by using remotely operated equipment is highly desirable. In this paper, the authors describe the development of a teleoperated military tractor called the Small Emplacement Excavator (SEE).

The development of SEE is being funded jointly by DOE and the U.S. Army. The DOE sponsor is the Office of Technology Development (OTD), Robotics Technology Development Program (RTDP). The U.S. Army sponsor is the Project Manager for Ammunition Logistics, Picatinny Arsenal. The primary interest of DOE is whose application to remote excavation of buried waste, and while the primary emphasis for the U.S. Army is the remote retrieval of unexploded ordnance, technical requirements for these two tasks are similar and, therefore, justify a joint development project. Descriptions of this project at an earlier stage have been previously presented (B. L. Burks et al., February 1992, August 1992, and April 1993).

SYSTEM DESCRIPTION

The SEE was chosen as the development vehicle for this project because it is a commercially available system that is already supported by the U.S. Army. Hundreds of SEE units are already in service throughout the world. The goal of the project is to demonstrate the feasibility of retrofitting commercial equipment to achieve high-performance remote operations. SEE is not necessarily the excavator of choice for large-scale waste retrieval campaigns. However, the controls technology developed for SEE shall be readily adaptable to other mechanical systems.

The U.S. Army and DOE perspectives on SEE are different in that SEE modifications may eventually become a moderate-volume production item for the Army, whereas DOE's interest is in more general technology development that will be applied to remote excavation. Hence, within RTDP, development of SEE is part of a larger effort to develop and demonstrate a Remote Excavation System (RES). Because the excavator kinematics, hydraulic control technology, and electronic systems (computers, video, and communications) are similar to backhoes up to large-scale excavators, essentially all the developed technology will be transferable from the telerobotic SEE to the RES program. Although SEE is the specific vehicle that will be used for initial demonstrations of RES controls technology, additional demonstrations are planned to determine and illustrate the degree to which RES controls technology can be readily applied to other excavation platforms.

The SEE vehicle was developed by Freightliner for the U.S. Army for multipurpose use including unexploded ordnance retrieval. SEE has a backhoe on the back and a front-end loader on the front (Fig. 1). The backhoe is an adaptation of the Case 580E commercial backhoe, and the vehicle is a modified Mercedes Benz Unimog truck. Alterations to the vehicle made by Oak Ridge National Laboratory centered upon modifying the hydraulic systems for computer control. High-performance proportional valve components were used to greatly improve the dexterity over the existing manual valves. Proportional valves were chosen rather than servovalves because the former are less sensitive to contaminated hydraulic fluid; also, high-performance proportional valves are now available. Hydraulic pressure sensors provide limited indications of force exerted by the backhoe. Using the pressure data, torque at each joint was computed. The backhoe and front-end loader have also been outfitted with position encoders for use in robotic operations. Remote viewing is provided by two color television cameras with pan-and-tilt mechanisms mounted on the truck body and a third camera mounted on the backhoe boom.

Two productivity enhancement technologies have been deployed on the SEE. As mentioned previously, force feedback was used to give the operator quick feedback of the forces at the shovel. This quick feedback allows the operator to detect many buried objects with which the backhoe comes in contact before the object is uncovered, with the exception of very small or light objects. The second technology was resolved rate control, which allowed the operator to control the motion of the bucket rather than to constantly trade off boom-and-dipper motion to get the desired bucket motion. Industrial excavator vendors are proposing this control system, but none have been implemented on an excavator.

The control station diagrammed in Fig. 2, has been packaged as a portable field unit incorporating two flat-panel video displays and a UNIX-based graphical user interface in two suitcase-sited units. The vehicle's drive system has been modified for remote driving. Only manual transmissions are available for SEE, and because the development of a new transmission is not practical, pnuematic actuators have been installed on the clutch and shift levers to operate the vehicle. Remote steering has been implemented by attaching a hydraulic motor to the steering wheel.

The computer system is an adaptation of an industrial design that is being commonly used within DOE for the RTDP projects. The basic system is composed of a Sun workstation host networked to a VME-based Motorola 68040 target computer, which runs the VxWorks operating system. VME-based computer systems are powerful and flexible because of the wide variety of industrial input/output and powerful single-board computers available.

The communications system between the vehicle and the base station consists of two microwave video channels and an Ethernet data radio. The data radio is a sophisticated spread-spectrum Ethernet packet radio made by Telesystems. Transparent operation of the Ethernet radio enables flexible operation for the computer system. For U.S. Army applications, where a secure communication channel may be required, the option of a fiber-optic bundle has been developed. During the development phase, all computer programs can be downloaded by the radio, thus requiring no software storage on the vehicle. Software management can then be performed solely on the workstation embedded in the console. Near the end of the project, all

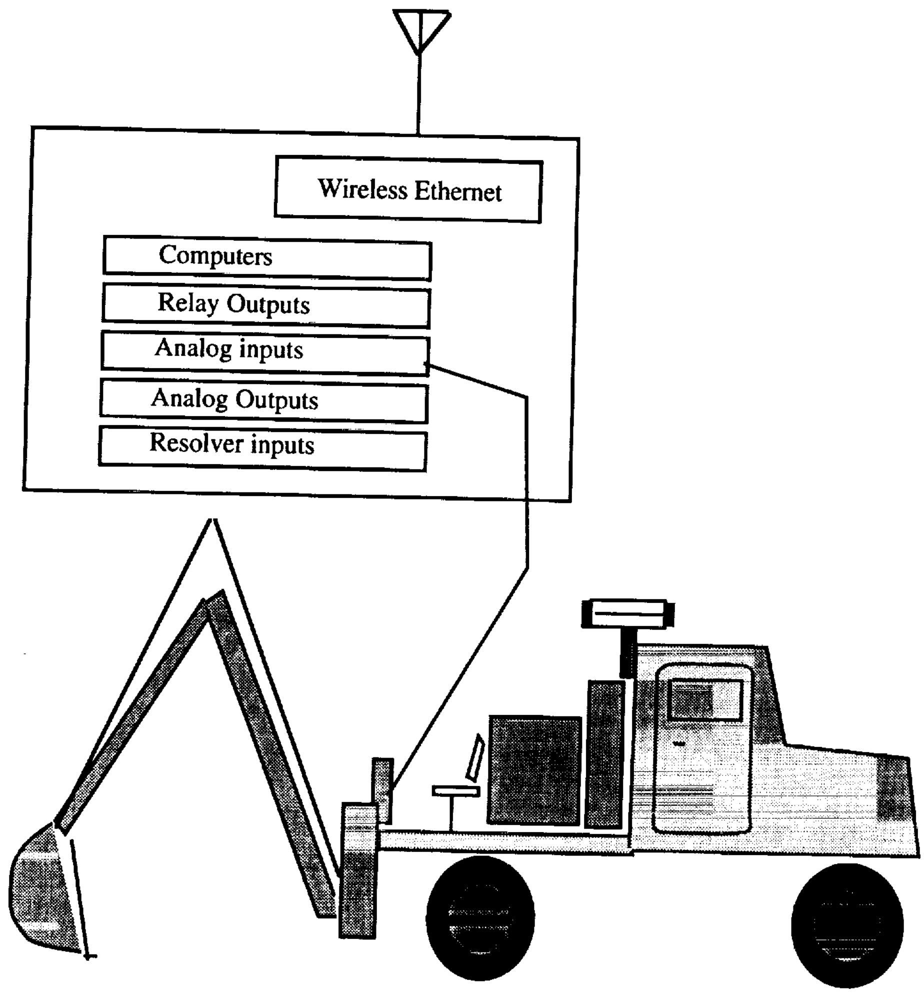

Fig. 1. SEE vehicle and computer interface.

of the software may be put in the computer's read-only memory. The high data rate (one megabaud) also permits teleoperation through the radio link.

Software development is being coordinated with other participants in the RTDP to enable synergistic operation of the various machines for restoration projects. Such coordination activities will involve sharing data between characterization and excavation operations, sharing computer and console resources to reduce expenses, and improving the transferability of collected data and control system code.

Significant improvements to the human-machine interface are featured in the base station to incorporate the data available from characterization activities and present available data from sensors on the vehicle. Computer graphic interfaces are be used to display collected data and aid in vehicle control by presenting vehicle status and position. This human-machine interface has been designed in collaboration with the other remotely driven vehicles in the RTDP to help produce a standardized interface that can be used for several vehicles.

RESULTS

The system was initially demonstrated in December 1992. This first phase involved only remote operation of the backhoe; the vehicle was still manually driven to the work site. The main demonstration focus was feasibility of remotely uncovering waste barrels and digging up contaminated soil or, alternatively, excavating unexploded ordnance.

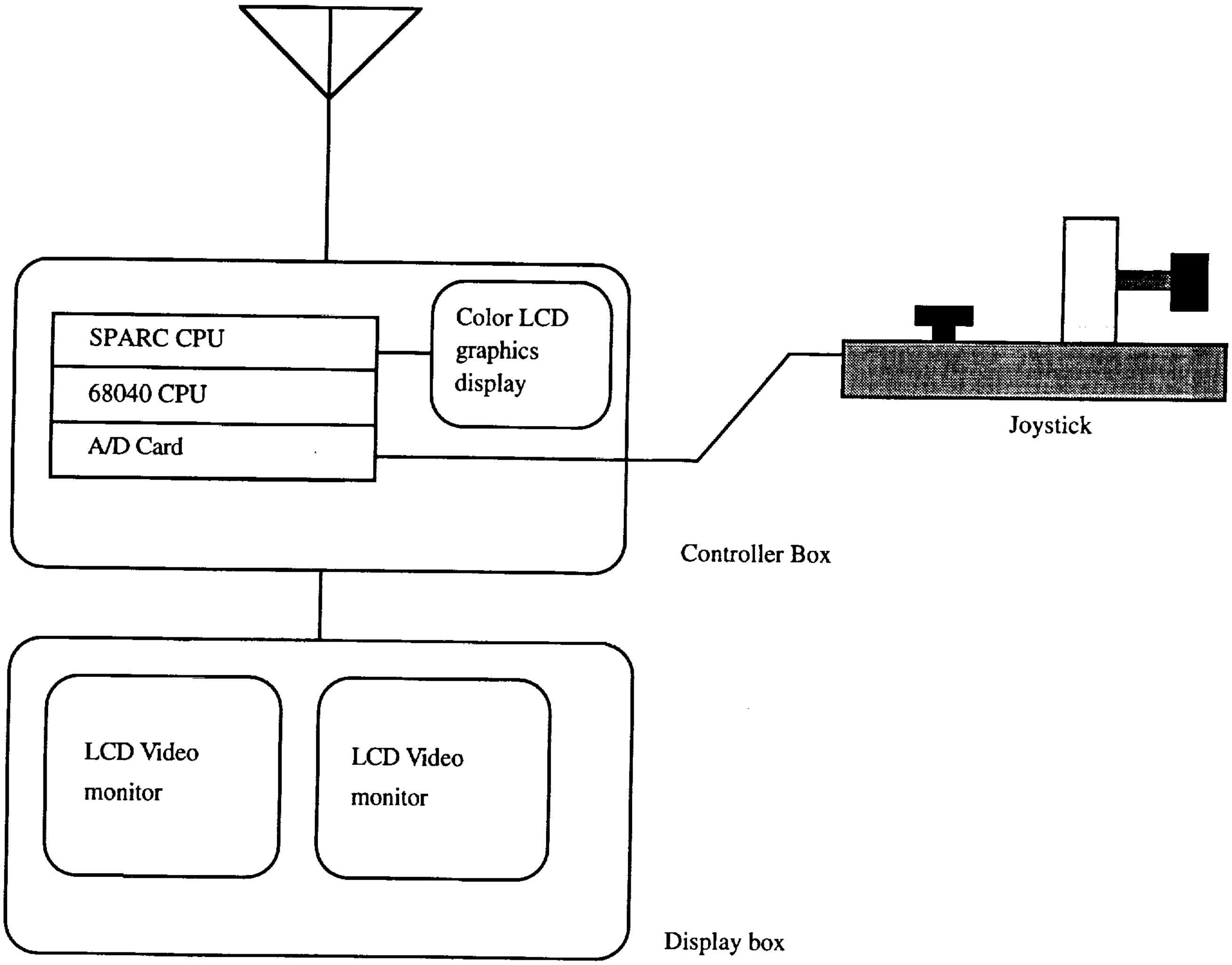

Fig. 2. Hardware architecture of the portable RES Controller.

The second phase of development was completed in the summer of 1993, and involved remote-driving and front-end-loader operations. Demonstrations were performed at the Idaho National Engineering Laboratory, Idaho Falls, Idaho, as part of the OTD Buried Waste Integrated Demostrations (BWID). Some of the results from these BWID demonstrations include comparisons between manual and remote operations for retrieval of a variety of waste container sizes and storage configurations. Demonstrations data are still under analysis, at this writing. However, initial results indicate the SEE, under telerobotic control, provides retrieval capabilities about 1.5 times faster than the same backhoe under manual control for similar excavation scenarios. This is remarkable since teleroperated systems typically require an order-of-magnitude longer for most manipulation tasks than manual operations.

The demonstrations performed from December to July have been extremely valuable in gaining experience in remote excavation, especially the BWID tests. During overburden removal tests a mean depth of within one in. of the desired depth was obtained for shallow digs. The dig depth standard deviation over the 10 ft wide test cell was ± 4 in. The graphical user interface was highly useful for maintaining the position of each backhoe link and location of objects such as the dig and dump areas. With typical teleoperation tasks, a time penalty of a factor of 10 is common. Using the SEE under teleoperation vs manual control a time increase of about 50% was observed for a variety of excavation and waste retrieval tasks. With training, this factor could be further reduced. The intuitive hand controller made operation of the SEE relatively simple, compared to manual operations. A group of novice operators were tested and were found to complete dexterity tasks with 65% accuracy during their first attempt using the SEE.

The third camera on the boom was found to be very useful for "in-hole" operations, in particular. The communications systems were successfully operated with up to one half mile separation between the vehicle and base station.

Additional human factors performance testing will be performed in the fall of 1993 at Redstone Arsenal, Huntsville, Alabama. These studies will allow the same soldiers who routinely operate SEE in manual operations to perform similar excavations by using the teleoperated and telerobotic modes. Field deployment of the telerobotic SEE for military applications will depend greatly on the results of these performance tests.

FUTURE PLANS

Several experimental features are planned for the SEE that will be of potential benefit on remote excavators. The four main experimental areas are robotic operation, new end effectors for the backhoe boom, improved graphics displays, and advanced radio communications.

Several opportunities exist to provide robotic operations that can significantly improve the overall performance of the excavation operation. One envisioned operator improvement is an automatic empty-bucket procedure that will empty the backhoes' load at a preset location. This feature will eliminate the need for the operator to reposition the television cameras for each dumping operation. This feature was implemented for the BWID tests but needs improvement. Another desired feature is robotic gradual excavation of a specified area. This feature would provide both excavation to a precise depth and higher throughput. An additional benefit of robotic excavation would be automatic digging in areas identified as contaminated by other robotic sensors. With such a direct method, the operator would not need to interpret the sensor-data map while operating the backhoe.

Adding to the backhoe the capability of lifting objects as well as uncovering them would be desirable. Ideally, the waste drums could then be lifted out without their contents leaking; thus, the drums could be sealed in a larger new container. Trying to push the drum out with the backhoe scoop would almost certainly damage the drums and spill their contents; therefore, a robotic grappling end effector will be required. Although a separate machine can be used for this task, the preferred option is to provide changeable end effectors for the backhoe. Several end effectors are being studied for this task, the main selection criteria being remote changing of the end effectors and dexterous handling of the drums.

Graphical aids can be used to describe to the operator the current circumstances with respect to vehicle position, area contamination, and excavated areas. Maps of contaminated areas can show the operator where digging operations need to take place. Three-dimensional plots can be used to describe the amount of soil that has been uncovered already and to show the current digging depth. Additionally, three-dimensional graphics can greatly benefit programming and controlling of robotic operations.

Alternate radio communication methods are being investigated because of problems associated with some previous communications schemes. Current microwave video systems perform well but are susceptible to multipath distortion and are poor in over-the-hill performance. They are also quite expensive. Because digital data radios perform much better at lower cost, we are investigating the possibility of digitizing and compressing video so that it may be delivered over a digital link. Technology is advancing rapidly in this area, and we anticipate that digital video transmission will soon become practical at a lower cost.

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