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HUMAN-FACTORS-BASED IMPLEMENTATION OF THE REMOTE CHARACTERIZATION SYSTEM HIGH-LEVEL CONTROL STATION*

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ABSTRACT The detection and characterization of buried objects and materials is an important first step in the restoration of the numerous U.S. Department of Energy (DOE) and U.S. Department of Defense waste disposal sites. DOE, through its Environmental Restoration and Waste Management Robotics and Technology Development Program, has developed the Remote Characterization System (RCS) to address the needs of remote subsurface characterization. The RCS consists of a low-metal-content (low-metallic-signature) remotely piloted vehicle, a high-level control station (HLCS) where operators can remotely control the vehicle and analyze real-time data from sensors, and an array of sensors that can be chosen to meet the survey task at hand. Communication between the vehicle and the base station is handled by a radio link. Site mapping is made possible through the use of geopositioning satellite data. The primary mode of vehicle operation is teleoperation, but provision has been made for semiautonomous or supervisory control that allows for automated site survey on simple sites. Data analysis and display is supported for both real-time observation and postprocessing of data. The particular emphasis of this paper documents the human- factors-based design influences on the HLCS and describes the design in detail.

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INTRODUCTION

Across the U.S. Department of Energy (DOE) complex are hundreds of acres of landfill waste storage areas, many of which will require remediation during the coming decades. These waste storage areas contain millions of cubic feet of radioactively contaminated materials and hazardous substances. Mixed in with the low-level radioactive waste from production and research facilities are hazardous chemicals, pyrophorics, explosives, and high-level radioactive waste. Because of the potential hazard levels due to the buried materials, remote performance of characterization and remediation operations is highly desirable. Also, because of the large volumes of waste that must be processed, introduction of automated remote operations wherever practical is desirable. The application of robotic systems to remediation of landfill buried waste offers opportunities for safer, faster, and cheaper solutions over the duration of these massive cleanup activities. The team of DOE laboratories that has participated in the development of technology to address the needs of buried waste remediation includes: Idaho National Engineering Laboratory (INEL), Pacific Northwest Laboratories (PNL), Oak Ridge National Laboratory (ORNL), Lawrence Livermore National Laboratory, and Sandia National Laboratories (SNL).

Initial demonstration of remote buried waste characterization was performed in 1990 at ORNL using the Soldier Robot Interface Project (SRIP) robotic testbed to examine concept feasibility (B. S. Richardson, et. al., 1990; B. S. Richardson, 1990). The SRIP vehicle, developed jointly by the U.S. Army's Human Engineering Laboratory, ORNL, and Tooele Army Depot, was configured as a research testbed used for studying mobile manipulation with respect to military applications. The SRIP robot platform consisted of an eight-wheeled, skid-steered vehicle powered by a 15-hp diesel engine with significant modifications and enhancements for remote computer control. Initial results of that demonstration showed that remote characterization was indeed feasible and that further development was merited. A series of tests and demonstrations were then performed during the summer of 1991 on actual buried waste pits at INEL and underground piping at the Idaho Chemical Processing Plant, again using the SRIP platform (B. S. Richardson, et al., 1991). The focus of these tests was the integration of multiple sensors on a single platform to provide input for program direction and further development. The objective of using multiple sensors in a remote operation was to obtain better data safer, faster, and, ultimately, cheaper. This testing represented the first known attempt to remotely deploy an array of various types of sensors for subsurface characterization. The vehicle was equipped with subsurface geophysical sensors plus sensors for detecting surface radiation and organic vapors. The sensor data and x-y position obtained from the mapping demonstration were displayed in real time on an operator's monitor and recorded for postprocessing and future reference. The display indicated areas of increased interest, allowing the operator to slow the platform or to return to the area of interest for more detailed surveying. The specific sensors used included ground-penetrating radar, a terrain conductivity meter (EM–31), a magnetometer, a sodium-iodide gamma nucleonics detector, and a photoionization organic vapor detector.

The results of the INEL testing and demonstration influenced the design of the remote characterization system (RCS). Specific recommendations based on experience gained at INEL included using a vehicle that is more appropriate for the specific site survey task. Vehicles used for this application should have a low metal content and a low magnetic signature and be easily transportable, highly reliable, and mobile. Additional work was also determined to be necessary to improve sensor response times and integration to allow for on-the-fly identification of regions of interest for further evaluation.

HUMAN-FACTORS-BASED DESIGN CONSIDERATIONS FOR THE GRAPHICAL USER INTERFACE

Human-Machine Interface

This section describes the RCS human-machine interface (HMI) proposed graphical user interface (GUI). The goal was to design an HMI that (1) makes acquiring information from the system easy and efficient for the operator, (2) makes all the necessary vehicle controls easy to use, (3) minimizes the steps necessary to reconfigure the displays and controls during the mission, and (4) meets the Motif™ graphical user interface guidelines where possible.

Task Analysis

Mission Phases. The mission of the vehicle is to survey outdoor areas and to map radiological contamination and other subsurface features using sensors aboard the vehicle and operating under a mixture of teleoperation, supervisory control, and robotic autonomy. A second vehicle may also be used that has a remotely controlled backhoe that will allow it to dig trenches (B. L. Burks, et al., 1992). Phases of a mission might include (1) approach, in which the vehicle is driven into the survey area; (2) survey, in which the vehicle conducts multiple passes over the survey area to collect sensor data; (3) resurvey, in which further readings are taken in areas of interest or where sensor coverage during the survey phase is deemed inadequate; and (4) departure, in which the vehicle departs the survey area.

User Functions. During a mission the operator will perform some mix of the following functions: (1) drive (differently configured vehicles); (2) supervise robot driving; (3) select sensors for survey; (4) monitor sensors during survey; and (5) plan survey route. Controls will be required for (1) driving the vehicles, (2) aiming and adjusting the viewing system; and (3) operating the sensor suite. Displays will be necessary for (1) vehicle status, (2) remote scene representation, and (3) sensor data. Remote scene representation will be by television.

User Functions within Mission Phase. The five mission phases, together with possible operator functions, are:

- The approach phase. The vehicle will be driven into the survey area by remote control. This may include any proportion of the following operator functions: (1) drive, (2) supervise robot driving, and (3) plan route.
- The survey phase. The vehicle will be driven through the survey area by remote control or robotically while sensor readings are taken. This may include any proportion of the following operator functions: (1) drive, (2) supervise robot driving, (3) select survey sensors, (4) monitor sensors, and (5) plan survey route.
- The resurvey phase. The survey vehicle will be driven through the survey area by remote control or robotically while sensor readings are taken. This may include any proportion of the following operator functions: (1) drive, (2) supervise robot driving, (3) select survey sensors, (4) monitor sensors, and (5) plan survey route.

- The departure phase. The vehicle will be driven out of the survey area by remote control or robotically. This may include any proportion of the following operator functions: (1) drive, (2) supervise robot driving, and (3) plan route.

Design Basis. An evaluation of the mission profile and the user functions during each part of the mission leads to the conclusion that the GUI will require two distinct configurations: (1) a drive/sensor configuration for driving, monitoring robotic driving, or monitoring sensors, and (2) a sensor select configuration for selecting and fine-tuning sensors. Both of these can be translated into a screen configuration for actual displays.

GUI Design Concept

Menu Structure. The flat, one-level menu structure for the RCS GUI has two interchangeable screen configurations.

Drive Screen Concept. The drive screen display (Fig. 1) includes (1) a position readout map located in the upper right quadrant of the display; (2) a speedometer panel located in the lower right of the display and including analog displays for vehicle speed and left and right track speed; (3) an orientation panel at the bottom right of the display; (4) a tachometer for engine speed; (5) a video control panel that allows the user to switch video signals from cameras aboard the RCS to either of his monitors; (6) a control system error/warning status display in the lower left; (7) a cruise control and engine control panel in the upper left part of the display; and (8) a vehicle status display located on the left side of the map for engine, hydraulics, and computer systems parameters.

The position map is an important display because it places the vehicle within the remote area, it establishes a context for sensor sweeps of the area, and can be used to evaluate coverage and plan future routes. Therefore, it is placed prominently in the display.

Operators will use speedometers to determine the rate with which the vehicle traverses the remote area and the speed of the independently controlled right and left drive trains. Therefore, the speedometers are important and are placed near the center of the screen; because they must be accessible when using the position map and when using the video monitors, they are placed near the bottom of the graphics screen, where they are between the map and the monitors. The speedometers provide the following information: (1) left-side speed and direction, (2) right-side speed and direction, and (3) vehicle speed.

Because the operator will receive no vestibular or tactual cues about the attitude of the vehicle, the orientation display is another important display. It also must be available when using both the map and the monitors; therefore, it is located at the bottom of the display on the right-hand side. The pitch/roll indicator will provide the following information: (1) vehicle roll, displayed using an aircraft-style artificial horizon accompanied by a digital readout, (2) vehicle pitch, displayed as a bar chart in the center of the artificial horizon, and (3) vehicle direction, displayed as a compass band at the bottom of the display.

The video control panel will be used to display information about camera-monitor assignments and to change assignments. It provides camera/monitor coupling by color-coding the camera representation and monitor icons.

The vehicle status panel provides readouts of the following information: (1) coolant temperature, (2) computer enclosure temperature, (3) supply voltage, (4) supply current, (5) vehicle voltage, (6) electronics voltage, (7) hydraulic fluid temperature, (8) hydraulic fluid level, (9) left-side hydraulic fluid pressure, (10) right-side hydraulic fluid pressure, (10) main hydraulic pressure and (11) fuel level.

Sensor Screen Concept. The Sensor Screen will most likely include (design not finalized at press time) three panels for monitoring and controlling sensors aboard the RCS: the magnetometer panel, the ground-penetrating radar panel, and the EM-31 panel. It also includes menu pads for changing to the drive display. The magnetometer panel provides the following information: (1) digital data readout, (2) data history strip chart, (3) status display, (4) magnetometer type in use, (5) sampling rate, and (6) range (analog input gain). The ground-penetrating radar panel provides the following information: (1) digital data readout, (2) data history strip chart, (3) status display, (4) gate start, (5) gate duration, (6) number of data samples, (7) TVG points, and (8) fixed gain. The EM-31 panel provides the following information: (1) digital data readout, (2) data history strip chart, (3) status, (4) sample rate, and (5) gain.

SYSTEM HARDWARE DESCRIPTION

The RCS low-signature vehicle (LSV) (Fig. 2) is a relatively small six-wheeled robotic platform roughly 4 by 7 ft weighing several hundred pounds and consisting mostly of plastics and fiberglass to minimize impact on geophysical sensors. (By comparison, SRIP weighed 5000 lb, was almost totally metal, and had a high ferrous content.) The LSV is designed with a flexible suspension system that permits smooth transitioning over rough terrain, which stabilizes height-dependent sensor performance. Low-power embedded control computers keep the required power consumption to a minimum and provide a thermal tolerance higher than that of normal computing components. These advantages facilitate environmentalsealing of the control packages and minimize the size of the power generation equipment on the vehicle. Individual sensor packages are designed to be modular, each

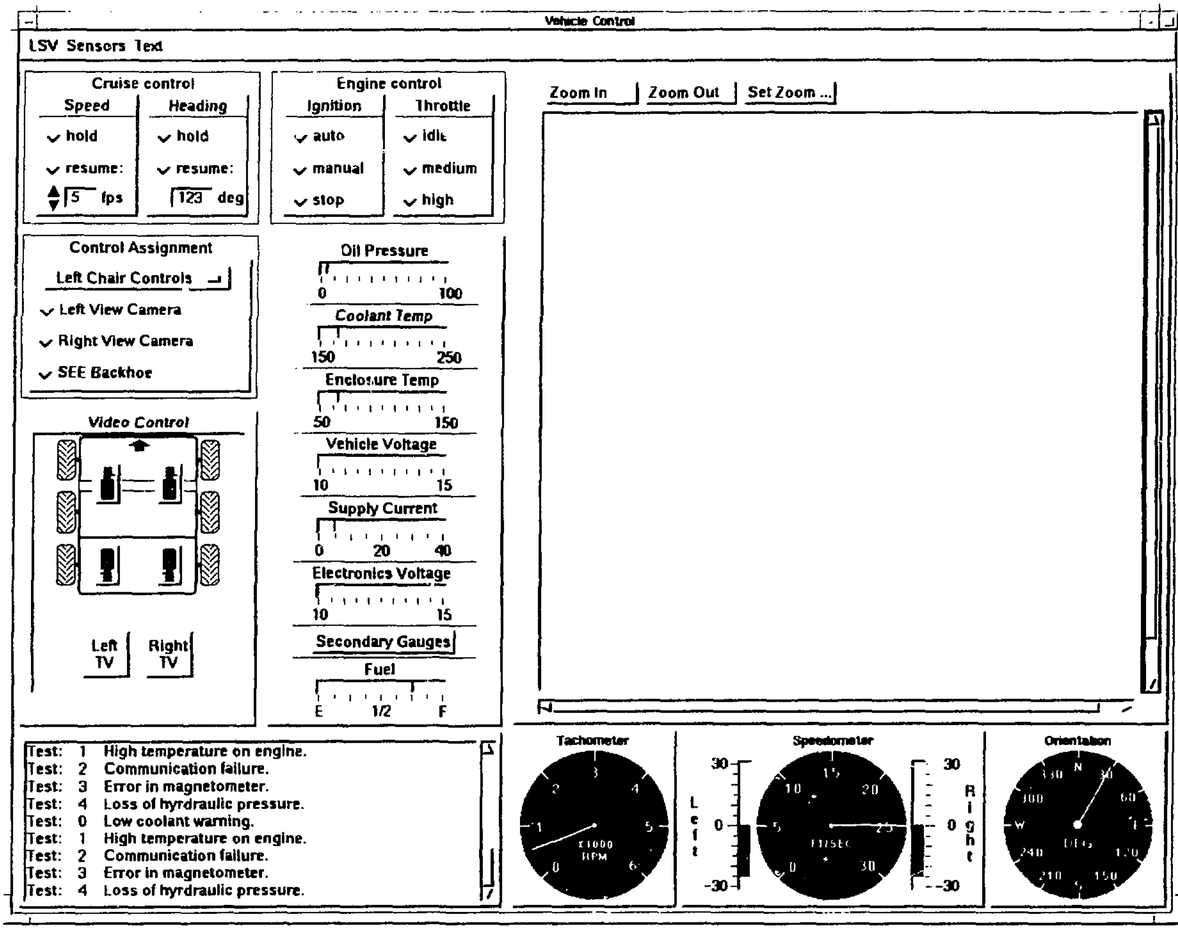

Fig. 1. Drive screen concept.

with its own control computer; installation requires only that the sensor package be plugged into vehicle power and the computer network. Control software will be designed to recognize which instruments are on-line, configure the data acquisition system, and initiate data collection from the operator's control station. Communication from vehicle to operator control station is completed via a radio frequency (rf) link for both data collection and vehicle control. On-board cameras provide viewing for remote driving. The x-y positioning on the displayed map is determined by geopositioning satellite (GPS) hardware.

The operator controls the vehicle and survey instruments through the high-level control station (HLCS) located in a base station vehicle safely out of the hazardous environment. The HLCS provides simple function control including camera positioning, remote driving (teleoperation), and real-time data display as well as higher level functions including supervisory and semiautonomous vehicle control and advanced data analysis (real-time and postprocessing). Simple teleoperation and real-time data display are meant to be an evolution of the previous work

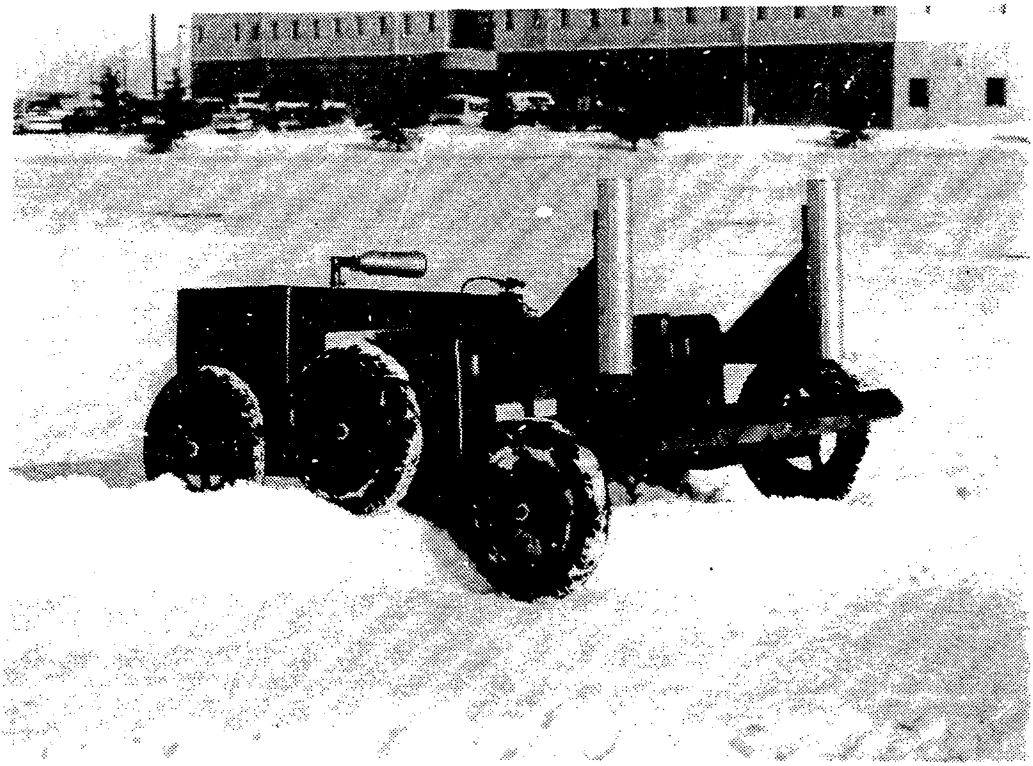

Fig. 2. Low-signature vehicle.

done at the ORNL and INEL test sites. The advanced control features will emphasize as much automated survey capabilities as possible to relieve the operator from information overload. Intelligent path planning of a mapped region and automated path following are the key elements of this feature. Multiple vehicle control by one station with occasional operator input during problem resolution is one ultimate extension.

The physical configuration of the HLCS (Fig. 3) revolves around a control chair that provides the operator with ergonomic vehicle joystick controls and a keyboard and cursor interface for command inputs to the graphics-based operator interface. This design concept enhances modularity and human factors issues simultaneously by moving much of the focus to the control chair. The viewing console is designed as a separate modular set of racks. Past remote driving station configurations have typically integrated hand controls directly into the remote viewing console. The operator chair was then added as a necessary but nonintegral afterthought. While this worked well in laboratory situations, it did not create a well-integrated field system. Modifications were tedious and costly. With the HLCS configuration, controls on the chair can be changed readily, and remote viewing hardware can be radically altered without affecting the other components in the system. The primary operator sits in the control chair, driving the remote vehicle and controlling cameras with joysticks and fingertip controls. Remote viewing and the GUI for the control computer are mounted in the displays in front of the operator. The operator also controls sensor selection, configuration, and data acquisition through the GUI. A secondary graphical data display station is provided to allow a geophysicist or observer to examine real-time data.

The viewing system consists of two racks, each of which contains a 19-in. video and/or graphics quality monitor. Since the racks are individual, anywhere from one to three may be assembled for a given application. This configuration is also highly conducive to modification and future expansion. The racks are positioned such that the view centerline for any one monitor is in the operator's 0° to –15° field of view for maximum comfort. Use of graphics quality monitors allows the possibility to implement multiple graphical menu overlays on multiple video views. The use of graphical overlay menuing and status with video is an entirely cost-driven function.However, the design of the system is such that enhancements may be made in future fiscal years without

Fig. 3. High-level control station.

major modifications or loss of existing hardware. Future needs for additional views may be further provided by stacking monitors on top of the original set of three. While these monitor racks would be considered reconfigurable, they would require bolting together since the application requires stability during frequent transport. This hardware will be mounted in the back of a control van, which will move frequently from site to site during survey operations.

The Sun/UNIX/VxWorks development environment is required based on general ER&WM Robotics and Technology Development Program (RTDP) guidelines to standardize development platforms and to facilitate software portability between the DOE laboratories. All actual control hardware resides in a dedicated 19-in. control rack that could be placed anywhere in the control van. The standard 6-ft-high commercial equipment rack houses Sun-compatible SPARC 1E/VME UNIX boards by Force Computer (for development and the GUI), VME-based VxWorks real-time target systems (Force 68040's), and all necessary analog and digital I/O boards. All miscellaneous control hardware, the radios, and the GPS hardware are also mounted in this rack.

The Force SPARC 1E VME board provides a Sun S-bus slot that allows video, graphics, and memory to be added directly to the SPARC VME board. This approach provides a complete working SPARC station with only the addition of a graphics monitor, keyboard, and a mouse or trackball. Two complete SPARC systems will be supported on the HLCS. The first provides the GUI and high-level control functions for the vehicle and sensors and also acts as the development system for all VxWorks software development. The second system shall provide graphical data display and analysis capabilities. Reasoning for the two separate SPARCs includes a need (1) to provide separate input and viewing stations for vehicle and data display tasks to accommodate two operators, (2) to minimize the clutter of mixing data display and vehicle function windows on the same 19-in. screen, and (3) to prevent loading down the vehicle command system while the secondary operator is performing extensive data postprocessing.

All HLCS high-level communication is transmitted via Ethernet or over the VME backplane in an Ethernet simulation mode. The graphical-based system controller and operator interface, data display, real-time vehicle control CPU, and the sensor data interface will be linked by a hard-wired Ethernet local area network or VME backplane network as appropriate. Data transfer will also be possible via normal VME backplane transfers since all of the previously mentioned CPUs are meant to plug into thesame backplane. Vehicle control is handled by a dedicated VME/VxWorks board and a point-to-point rf Ethernet link control loop operating at approximately 30 Hz to on-board vehicle-embedded controllers. GPS communication with the HLCS is through Ethernet.

The purpose of the real-time data display is to display data as it is acquired during a site survey or to play back stored data from previous surveys for mapping and analysis. The implementation provides sensor data transfer from the sensor controllers through the point-to-point Ethernet to the sensor data interface and from there through the VME backplane to the data display SPARC. Data will be automatically archived on the graphical system controller hard disk after it has been time-stamped and merged with GPS coordinates. The primary operator, acting under prior guidelines or directions from the secondary operator (geophysicist), will set up data files and sensor configuration parameters through the graphical system controller operator interface to the sensor data interface. The graphical system controller will then collect data as the survey progresses. The data display will be configured such that the secondary operator may view any real-time data generated by the survey or any archived data files at any time. Data will be archived to tape after each survey mission. The capability must exist for the postprocessing of data after surveys for cleanup and refinement or sensor fusion. Raw data files or processed files may be stored on the data display hard disk. Data must also be prepared for hard copy printing of useful survey maps. Therefore a color printer will eventually be provided.

DEVELOPMENT STATUS

HLCS hardware has been fabricated and assembled. The initial pass of the control software for the basic system has also been completed. The system integration and initial debugging phase occurred at the Hanford, Washington, PNL site in December 1992. Enhancements to the operating software will be added on an as-needed basis throughout the development and testing schedule during FY 1993. Significant planned enhancements include the supervisory control capabilities, path planning and path following, and semiautonomous modes of operation. First-stage refinements and enhancements will be made during the second quarter of FY 1993. Extensive testing on real hazardous waste burial sites will be conducted at INEL during the summer of FY 1993. Additional tests may be conducted at SNL and Fernald, time and funding permitting.

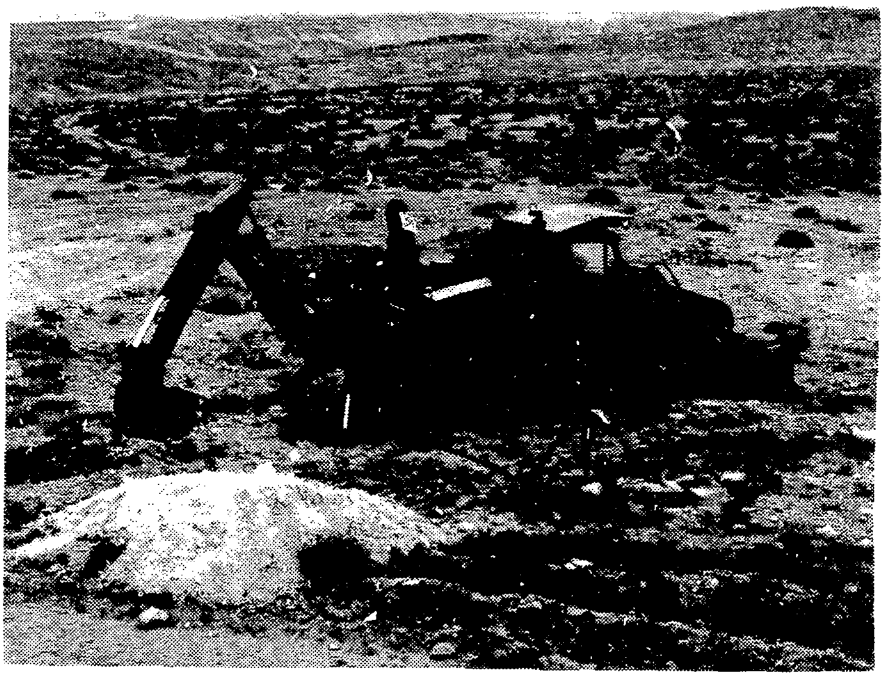

Fig. 4. Small emplacement excavator.

RELEVANCE TO OTHER MOBILE PLATFORMS

A significant key feature of the HLCS is that it has been designed in collaboration with another remotely driven vehicle project in the ER&WM Office of Technology Development's Buried Waste Robotics Program to help produce a standardized interface that can be used for many vehicles in the future. Provision has been made for generic vehicle control, remote viewing, and expansion to manipulation in order to accommodate any of the normal remote operations that may have to be supported for task completion. While the key "other" vehicle supported in the current development effort is the small emplacement excavator (SEE) (Fig. 4), any vehicle configured with a similar standard controls architecture could be operated from the HLCS.

The SEE, a U.S. Army truck with a front-end loader and a backhoe, was chosen as the development vehicle for remote excavation because it is a commercially available system already supported as an inventory vehicle by the U.S. Army with hundreds of manually operated units in service throughout the world (B. L. Burks, 1992). The goal of this particular project is to demonstrate the feasibility of retrofitting commercial equipment to achieve high-performance remote operations. The controls technology developed for the SEE will support both remote driving and excavation and are intended to be readily portable to other hydraulically actuated vehicles for conversion to remote operation. SEE testing will be coordinated with RCS testing in the third and fourth quarters of FY 1993.

SUMMARY

DOE, through its ER&WM RTDP, has developed the RCS to address the needs of remote subsurface characterization. The HLCS has been designed and built to allow operators to operate the RCS efficiently by remote control, to control any of an array of sensors that can be chosen to meet the survey task at hand, and to analyze real-time data from the sensors selected. Site mapping is made possible by combining sensor survey data with GPS data. While teleoperation is the primary control mode for the RCS, provision has been made for semiautonomous or supervised control that allows for automated site survey on simple sites. Data analysis and display is supported for both real-time observation and postprocessing of data. Design and implementation has also been coordinated with the SEE excavation vehicle to promote generic functionality of the HLCS. Testing of all functions is scheduled to run throughout FY 1993.

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