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A TELEOPERATED SYSTEM FOR REMOTE SITE CHARACTERIZATION

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ABSTRACT

The detection and characterization of buried objects and materials is an important first step in the restoration of burial sites containing chemical and radioactive waste materials at Department of Energy (DOE) and Department of Defense (DOD) facilities. To address the need to minimize the exposure of on-site personnel to the hazards associated with such sites, the DOE Office of Technology Development and the US Army Environmental Center have jointly supported the development of the Remote Characterization System (RCS). One of the main components of the RCS is a small remotely driven survey vehicle that can transport various combinations of geophysical and radiological sensors. Currently implemented sensors include ground-penetrating radar, magnetometers, an electromagnetic induction sensor, and a sodium iodide radiation detector. The survey vehicle was constructed predominantly of non-metallic materials to minimize its effect on the operation of its geophysical sensors. The system operator controls the vehicle from a remote, truck-mounted, base station. Video images are transmitted to the base station by an radio link to give the operator necessary visual information. Vehicle control commands, tracking information, and sensor data are transmitted between the survey vehicle and the base station by means of a radio ethernet link. Precise vehicle tracking coordinates are provided by a differential Global Positioning System (GPS). The sensors are environmentally protected, internally cooled, and interchangeable based on mission requirements. To date, the RCS has been successfully tested at the Oak Ridge National Laboratory and the Idaho National Engineering Laboratory.

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INTRODUCTION

Site surveys involving geophysical, radiological, and chemical sensors can often detect and map buried objects, materials, contaminants, and geological features to depths of several meters in the earth. Current applications include the cleanup of hazardous waste burial sites, the decommissioniong of bombing ranges, the evaluation of construction sites, the installation and maintenance of subsurface utility lines, and the investigation of archeological sites. A likely future application is the near-surface geological exploration of the Moon and Mars.

Vehicle-based surveys are more efficient than those which involve manual methods, but they have generally suffered from poor vehicle maneuverability and from degraded sensor performance due to interactions with the vehicle. Thus, the benefits of vehicle-based sensing can be more fully realized if the survey vehicle is specifically designed to be a sensor platform. A remote control capability in the survey vehicle is called for by the fact that many sites present hazards that make it undesirable to perform site characterization surveys with human operators either on foot or on board a survey vehicle. Examples of such sites are:

- Chemical and radioactive waste disposal sites where leakage of liquid wastes may have occurred or where the disintegration of solid waste materials or containers for liquid waste may have caused the formation of voids.

- Radioactive waste disposal sites where surface contamination is present.

- Areas where there is danger of a roof collapse in a near-surface cave, tunnel, or mine.

- Sites containing unexploded munitions.

To address the need for improved efficiency, data quality, and safety in site characterization operations, the U.S. Department of Energy's Office of Technology Development (OTD) initiated the development of the Remote Characterization System (RCS). The primary objective of this project is to develop a remotely controlled system that can perform site characterization surveys that will be safer and more cost effective than those that are being performed by other available methods. At the same time, it is expected that the data sets produced by the RCS should be at least as accurate and complete as those produced by other survey systems. The remote-control capabilities of the RCS will improve safety at hazardous sites by reducing on-site manpower requirements and by minimizing the exposure of personnel to unnecessary risks. The RCS will also provide:

- Reduced costs and improved timeliness of site characterization results.

- Accurate automated sensor tracking and data registration.

- A consistent digital base for all sensor data.

- Increased data density and more complete site coverage.

- Improved consistency and quality of data sets.

It is expected that RCS subsystems will be utilized in other DOE telerobotic applications to achieve time and cost savings in other phases of site cleanup efforts in addition to site characterization. The vehicle tracking capability of the RCS has already been transferred to a teleoperated excavation system that has been developed at the Oak Ridge National Laboratory.

The RCS Project was initiated in FY 1992. The major hardware and software components of the prototype system have now been developed and assembled. Initial system tests have been performed at test sites at the Oak Ridge National Laboratory and at the Idaho National Engineering Laboratory. Additional tests at waste burial sites and technology transfer of the RCS are planned for FY 1994.

Joint support for this work has been provided by the U.S. Army Environmental Center. The project is a collaborative effort involving the Pacific Northwest Laboratory, the Oak Ridge National Laboratory, the Sandia National Laboratory, the Livermore National Laboratory, and the Idaho National Engineering Laboratory.

SYSTEM OVERVIEW

The RCS design philosophy required that the remotely controlled survey vehicle and its instrumentation be small, light, and relatively inexpensive. This approach will: 1) ensure that the vehicle will have a minimal impact on the ground surface, 2) reduce the chance of causing a ground collapse, 3) allow a high degree of mobility and maneuverability, 4) make the system affordable so that multiple units can be deployed, and 5) minimize the financial risk associated with extremely hazardous applications. Another fundamental design requirement was that the vehicle must be constructed predominantly of non-metallic materials so that it will have a minimum effect on the operation of on-board geophysical sensors.

Figure 1 is a drawing of the system in a field application. Although some of the details are different in the actual system, this picture illustrates the basic system configuration. The vehicle is self-propelled and is guided by an operator located at a remote base station. Telemetered video signals give the operator the visual information needed to control the vehicle. Digital commands for vehicle and instrument control are transmitted to the vehicle. Data produced by the on-board sensors are transmitted from the vehicle to the base station where they are recorded, processed, and displayed.

The suite of sensors to be supported by the vehicle and its instrument package has not yet been fully defined, but it currently includes ground-penetrating radar (GPR), a metal detector, a magnetometer, a magnetic gradiometer, an induction-type ground conductivity sensor, and a radiological sensor.

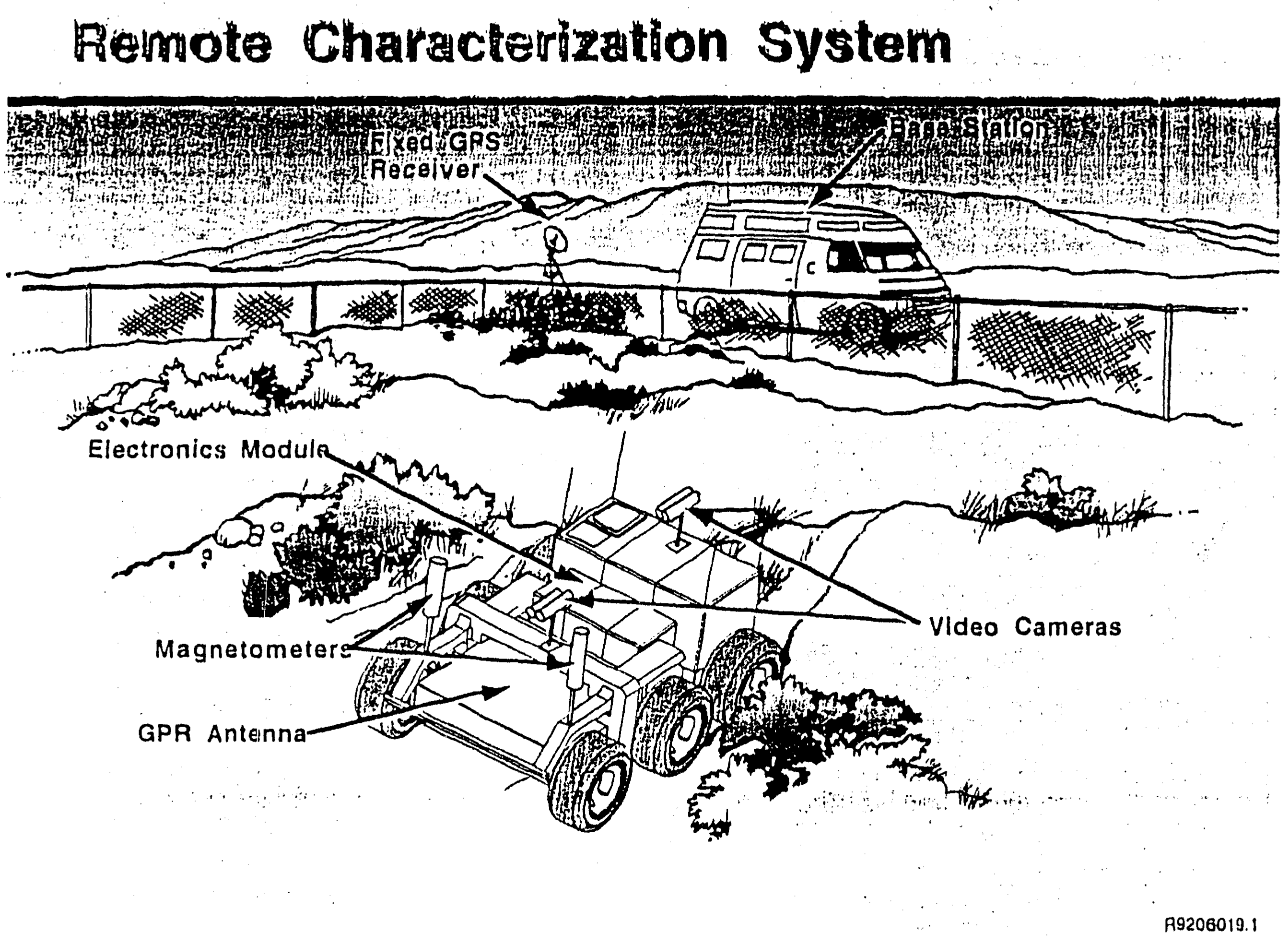

Figure 1. Drawing of the RCS.

THE SURVEY VEHICLE (LSV)

The survey vehicle is a key element of the RCS. Its compatibility with its on-board sensors, its stability, and its maneuverability will largely determine the quality of data received from the sensors during site characterization missions.

The construction of a low-signature vehicle (LSV) required the use of a minimum amount of metallic material. The current prototype vehicle contains approximately 130 lbs of metal, but this material is distributed so that it has only a small effect on the on-board geophysical sensors. The most critical part of this effort was to reduce the amount of magnetic material (steel) on the vehicle and to locate unavoidable steel components as far from the magnetometers as possible.

A typical site for a geophysical field survey exhibits surface features that make it difficult to operate a survey vehicle, even one with an on-board driver. Such features include bushes, trees, fences, buildings, parked vehicles or other machinery, open holes, depressions, ditches, hills, berms, rocks, and miscellaneous debris (wire, cable, 55-gal drums, concrete blocks, etc). These kinds of obstructions may require extraordinary maneuvers to avoid entanglement or immobilization of the vehicle.

To maximize the ability of the LSV to extricate itself from difficulties, we designed it to be able to back up and to turn in place. This has the significant consequence that the vehicle cannot pull a trailer or support a sensor on a boom. Thus, the payload must be carried on the vehicle and an instrument bay must be kept free of mechanical components, both above and below the vehicle, to accommodate the sensors and associated electronic components. In particular, the large size of a ground-penetrating radar antenna and the necessity of coupling it to the ground virtually dictated that the vehicle be designed around it. Thus, as illustrated in Figure 1, the front part of the chassis is an open structure that permits the GPR antenna to be suspended between the front wheels.

Figure 2 is photograph of the prototype LSV that has been constructed at the Pacific Northwest Laboratory. This vehicle is approximately 7 ft long and 5 ft wide. Its weight is approximately 800 lbs, including a payload of approximately 150 lbs. Its major components include the chassis, the engine, the drive train, and an electrical power generator. They also include an on-board digital controller and peripheral devices to monitor vehicle status and to provide low-level control inputs to the vehicle.

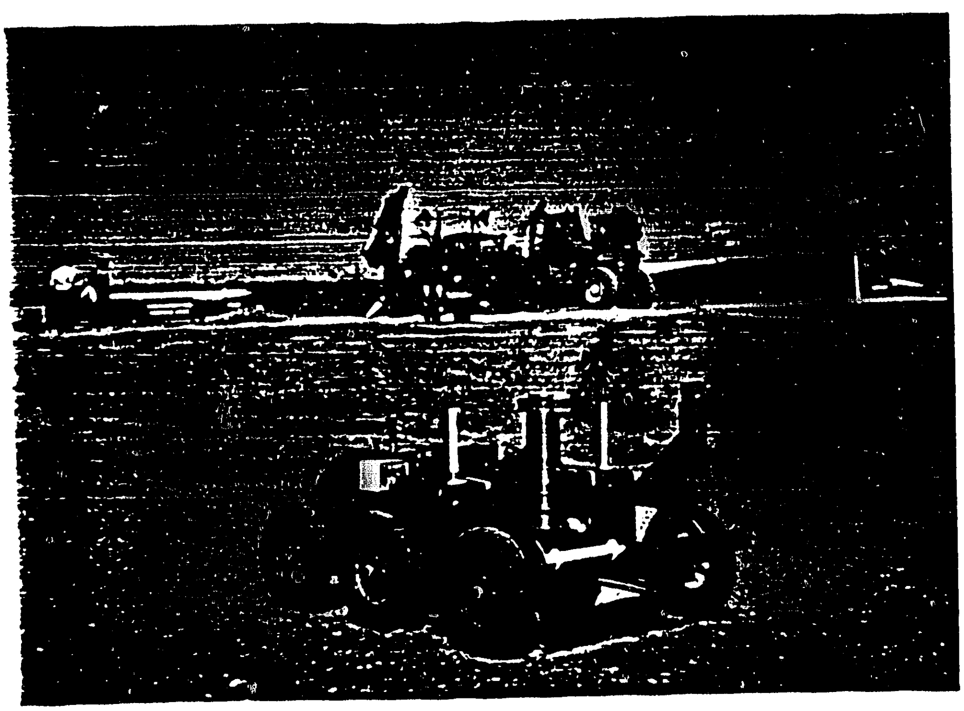

Figure 2. The RCS Low-Signature Vehicle.

The LSV is based on a six-wheeled design with modified skid steering. We considered a relatively small light vehicle with three driven wheels on each side to be an optimum mechanical configuration for our purpose. To equalize wheel loading and to minimize the vertical movement of the instrument platform in response to the roughness of the ground surface, we developed a unique articulated chassis that has proven to be very effective.

The chassis consists of two main sections that form the rear third and the forward two-thirds of the vehicle, respectively. A pivot located on the vehicle's longitudinal axis provides terrain damping by allowing the the front and rear sections of the chassis to rotate relative to each other. Additional articulation and damping are provided at the front end of the chassis. The two wheels on each side of the front section of the vehicle are mounted at the ends of a horizontal arm. Each of the two arms is connected by a bearing to the ends of a yoke, or inverted U-shaped member, that straddles the front part of the chassis. Each arm is free to pivot about a transverse axis located at the center of the arm.

A 20-hp, gasoline-powered, 2-cylinder engine is mounted on the rear section of the chassis. A 12-V, 50-amp alternator mounted on the engine provides electrical power for the sensors, control modules, and other electronic devices on the vehicle. A hydraulic pump, electronically controlled hydraulic valves, and four hydraulic motors provide power at the front and rear wheels.

The LSV has been designed to climb and traverse 35° slopes, to have a ground clearance of 8 in. (except for the GPR antenna), and to operate at speeds up to 5 ft/s. These features permit operations on most of the terrain present at DOE waste burial sites.

NAVIGATION SUBSYSTEM

A differential kinematic implementation of the satellite-based Global Positioning System (GPS) has been developed as the primary means of tracking the survey vehicle. The differential configuration involves the use of two receiver modules. The first is a remote, or mobile, module that is mounted on the LSV. This unit receives tracking data from a set of five satellites. An embedded computer and telemetry unit transmit these data to a dedicated computer in the RCS base station. The second GPS module is located at the base station. It is fixed in position for a given survey and provides error-correction information that is used by the GPS base-station computer to compute vehicle coordinates. Coordinates accurate to ±50 cm are calculated in real time at a rate of 5 measurements/s. Coordinates accurate to ±15 cm (typically) are obtained by post-processing the recorded GPS data.

COMMUNICATIONS SUBSYSTEM

A digital, radio-frequency (RF), command/data link provides Ethernet communications between the vehicle and the base station. Signals transmitted to the LSV include commands to control the direction and speed of the vehicle, the orientation of the video cameras, and the setup and operation of the on-board sensors. Vehicle status information and sensor output data are transmitted from the LSV to the base station. Setup commands are transmitted to each sensor prior to the initiation of a survey, and parameter update commands can be transmitted to the sensors at any time. After data collection has been initiated, the sensor data are transmitted at predetermined intervals without intervention or commands from the base station. This approach permits data to be transmitted at a rate of 25 kbytes/s. This data rate is needed primarily to handle the 17-kbyte/s output of the GPR sensor together with the output of all of the other sensors. Two separate RF channels are provided to handle video transmissions.

HIGH-LEVEL CONTROL STATION (HLCS)

The operator interface to the LSV and its survey instruments is called the High-Level Control Station (HLCS). It is contained in a base-station vehicle that will be located safely outside of the hazardous environment during a site survey and will communicate with the LSV via the RF telemetry link described above. The components of the HLCS are housed in a truck as shown in Figure 3. The cargo box was custom built to provide appropriate equipment mounting space, electrical power, lighting, heating, air conditioning, windows, counter space, and storage cabinets.

Figure 3. The truck housing the RCS base station.

The HLCS provides function control, including camera positioning, remote driving (teleoperation), and real-time data display. It also provides higher-level functions such as supervisory vehicle control, semi-autonomous vehicle control, and data displays in real-time and post-processing modes. Planned extensions of the control features emphasize automated survey capabilities that will relieve the operator from information overload. Intelligent path planning for 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 a further potential extension.

The physical configuration of the HLCS 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 (Figure 4). The system operator sits in the control chair, driving the remote vehicle and controlling the video cameras with joysticks and fingertip controls. The remote video images and a graphical interface to the control computer are presented on video displays located in front of the operator. The operator also controls sensor selection, configuration, and data acquisition through the graphical operator interface. A secondary graphical data display station is provided to allow a geophysicist or observer to examine real-time data.

Figure 4. The operator's control station.

VIDEO SUBSYSTEM

The system operator must receive visual information from the LSV so that he can recognize hazards and obstructions and can guide the vehicle around them. It is vital that the information available to the operator be sufficiently detailed that he can make on-the-fly decisions regarding the risks associated with anomalous features that the LSV will encounter in the field (e.g., rocks, concrete blocks, holes, barbed wire, steel cable, fences, posts, and vegetation). Although a stereo video subsystem is planned to provide the necessary detailed visual information, the current configuration provides two monoscopic channels that are set up for viewing in the forward and backward directions. The current system includes the cameras, camera control components (pan, tilt, and focus), and the associated telemetry links needed for stereo viewing, but does not include the necessary stereo display and head-tracking components. These, together with a data compression technique that will permit both video channels to be transmitted on a single RF link, represent goals for system improvement.

SENSORS

To date, five sensing instruments have been mounted on the LSV. These have been operated at test sites at ORNL and INEL:

- Fluxgate magnetic gradiometers (Applied Physics Systems)
- Cesium vapor magnetometers (EG&G)
- Sodium iodide gamma detector
- Ground-penetrating radar (Geophysical Survey Systems, Inc.)
- Electromagnetic induction ground conductivity sensor (Geonics Ltd.)

A chemical sensor under development at the Lawrence Livermore National Laboratory might also be incorporated into this package. Not all of the sensors will be mounted on the vehicle at any given time. This is largely due to inherent differences in operating requirements or operating modes. In particular, radiological and chemical sensors will probably be operated in a slow start-stop mode rather than the fast continuous-motion mode that is appropriate for the geophysical sensors. All of these sensors operate in a remote sensing mode, so will provide the desired information about subsurface features by non-intrusive means.

Figures 5 and 6 are contour maps that illustrate the data produced by the fluxgate gradiometers and the cesium vapor total-field magnetometer, respectively. These data sets were recorded at an uncontaminated (cold) test pit at the Idaho National Engineering Laboratory. In terms of sensitivity, these data sets compare favorably to equivalent data sets collected at the same site by manual data collection methods. Repeated measurements at the

Magnetometer Data - INEL Cold Test Pit (18-20)

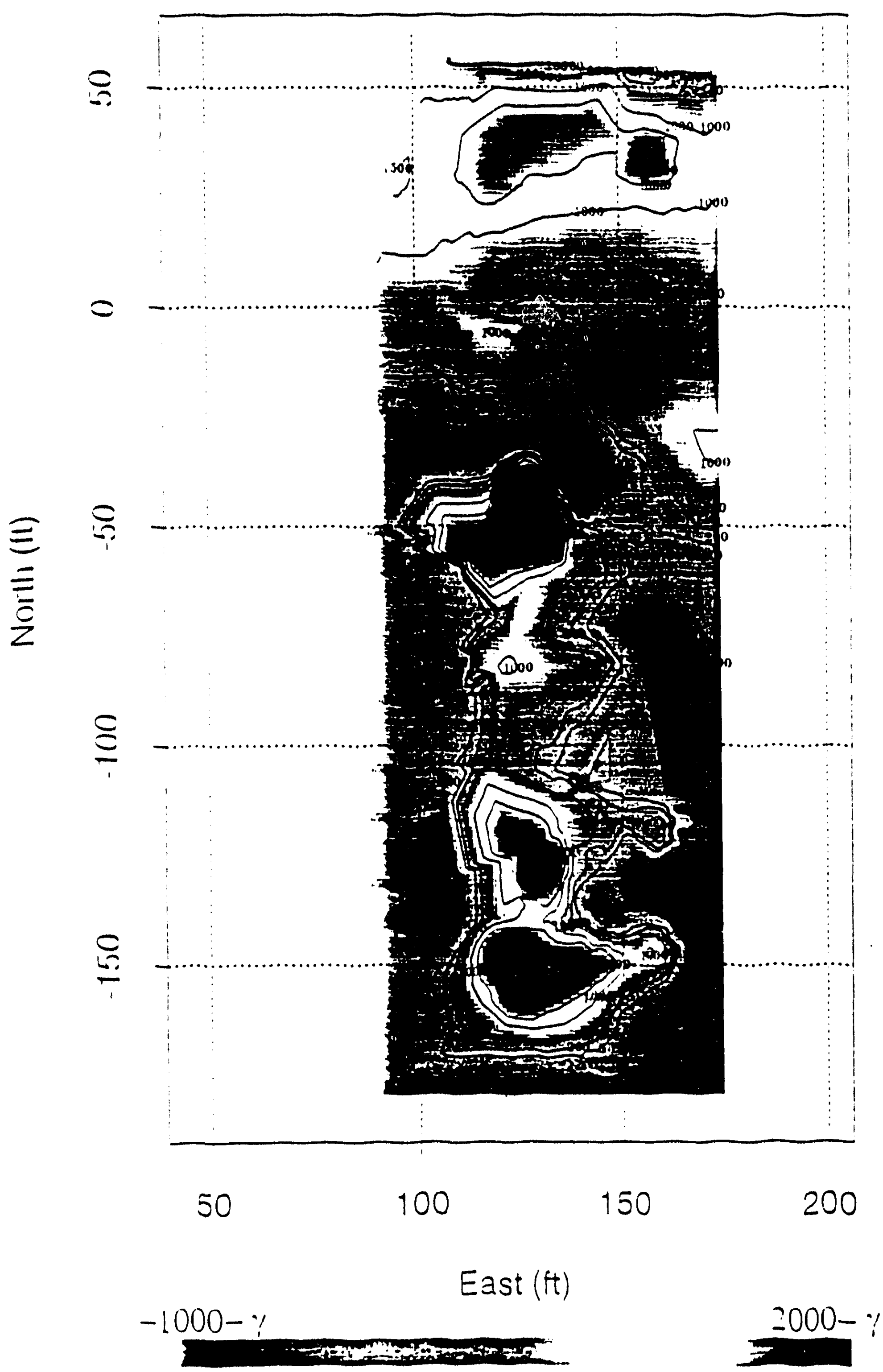

FIGURE 5. Contour Map of the Vertical Magnetic Gradient

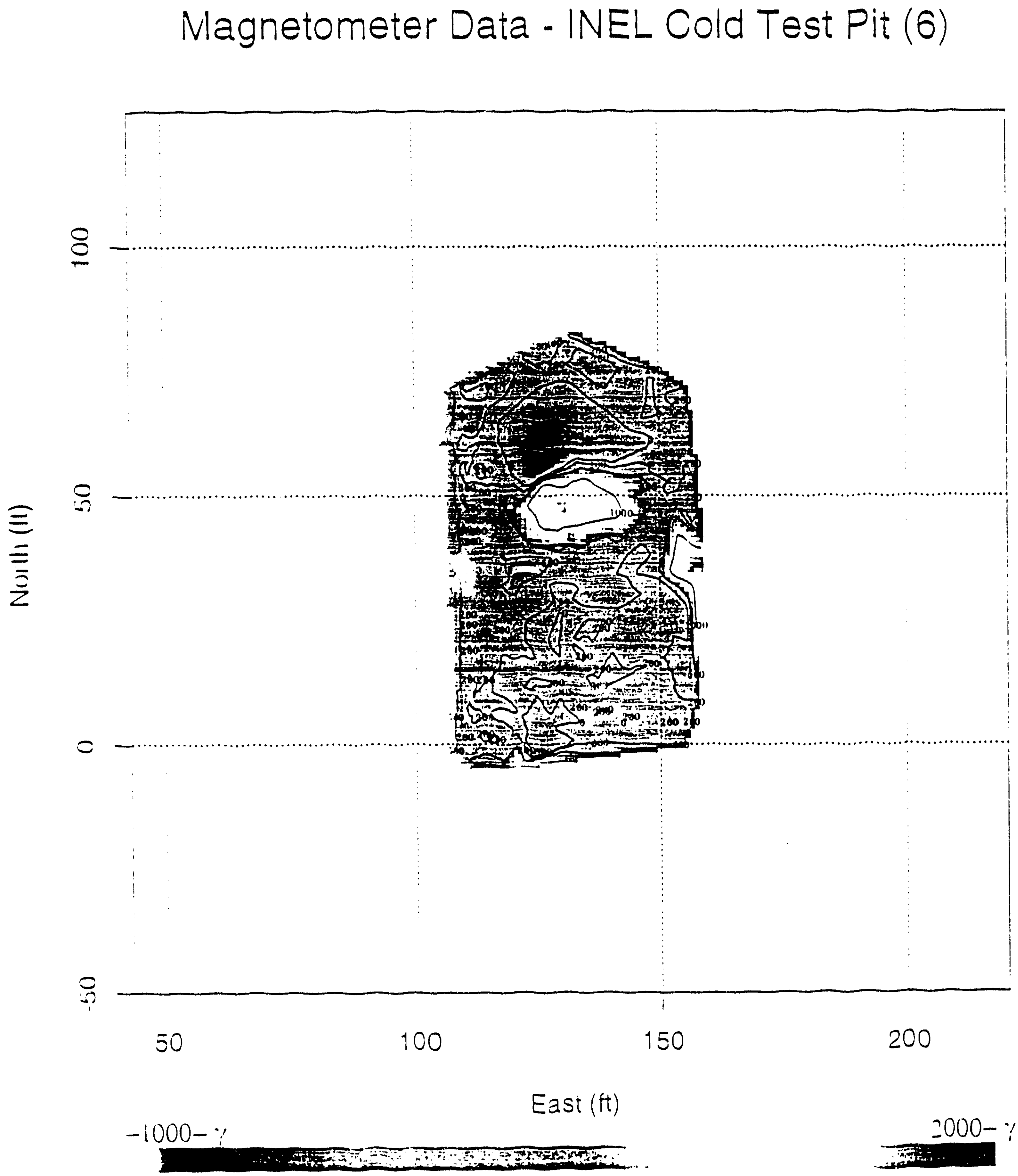

FIGURE 6. TOTAL-FIELD MAGNETIC CONTOUR MAP

site have shown that the data produced by the LSV-mounted magnetic sensors are both stable and repeatable. Figure 7 shows an orthographic projection of radiation intensity data produced by the sodium iodide gamma ray sensor. The radiation source for this test survey was a small packet of lantern mantles buried just below the ground surface. Data from the electromagnetic induction sensor and the ground-penetrating radar are not yet available.

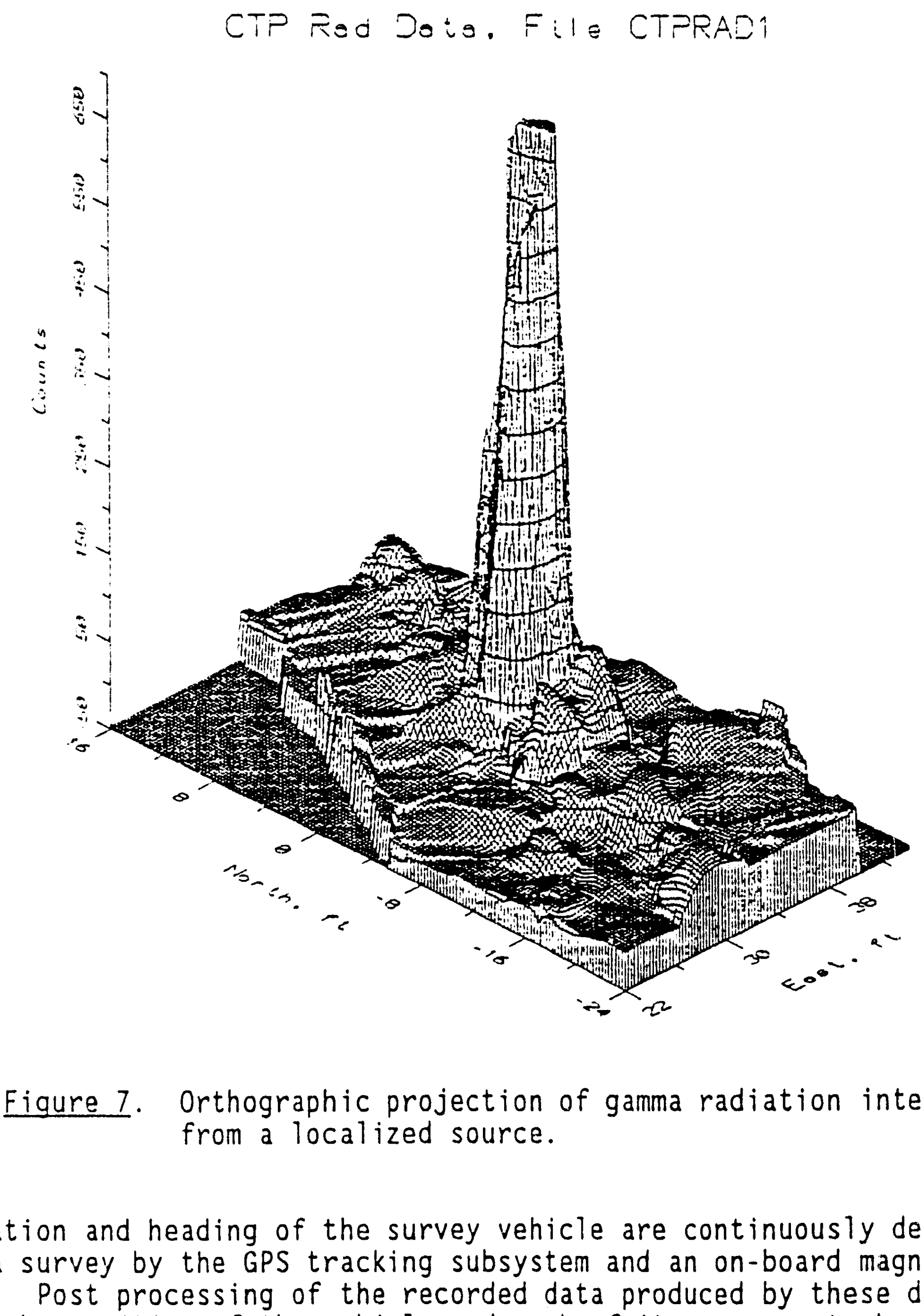

Figure 7. Orthographic projection of gamma radiation intensity from a localized source.

The location and heading of the survey vehicle are continuously determined during a survey by the GPS tracking subsystem and an on-board magnetic compass. Post processing of the recorded data produced by these devices permits the position of the vehicle and each of its sensors to be determined to an accuracy of approximately ±15 cm.

A project is currently underway at PNL to develop a compact, rugged, high-performance ground-penetrating radar system that can be operated in a remotely controlled mode. However, the sensors currently deployed on the LSV are commercially available instruments. Modifications are being made to minimize their size, weight, and electrical power requirements and to improve their ruggedness. The requirements include:

- waterproof and dustproof enclosures, connectors, and mechanical components,
- no pass-through air flow,
- 0-110° F minimum operational ambient temperature range, and
- decontaminatable with wash down.

Each sensor includes a small embedded computer that provides interfacing to the RCS communications network.

CONCLUDING REMARKS

The mission of the Robotics Integrated Program of DOE's Office of Technology Development is to produce needs-oriented, timely, and economical robotic technologies for use in DOE environmental operations. The goals of the RCS Project are consistent with that mission.

The RCS will provide unprecedented waste site characterization capability. Its design concept is based on earlier experience with a remotely operated sensor platform. A first demonstration and evaluation of the benefits of a remotely-operated integrated sensor platform was performed in 1991 at a DOE test site[1]. While the benefits of a multi-sensor survey were validated, several shortfalls in the initial system were identified. Corrections of these shortfalls have been factored into the design of the RCS as described in this paper.

Surveys of potential user groups indicate that the RCS LSV will be useful as a platform for many types of surveys at sites where contamination of the system is a major concern. The near-real-time data interpretation and presentation capability of the RCS will provide site remediators with data required to support decisions in a timely manner and will improve productivity over presently available means.

One of the operational modes intended for RCS is work in parallel with waste site excavation campaigns. Where soil properties limit the effective depth of measurement of geophysical instruments, work will be done in the "scratch and sniff" mode. In this mode, the RCS will perform repetitive site characterization surveys as layers of soil are removed. Data relating to the distribution of waste materials and contamination levels will be used to formulate excavation strategies.

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