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A REMOTE CHARACTERIZATION SYSTEM AND A FAULT-TOLERANT TRACKING SYSTEM FOR SUBSURFACE MAPPING OF BURIED WASTE SITES

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A REMOTE CHARACTERIZATION SYSTEM AND A FAULT-TOLERANT TRACKING SYSTEM FOR SUBSURFACE MAPPING OF BURIED WASTE SITES

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ABSTRACT

This paper describes two closely related projects that will provide new technology for characterizing hazardous waste burial sites. The first project, a collaborative effort by five of the national laboratories, involves the development and demonstration of a remotely controlled site characterization system. The Remote Characterization System (RCS) includes a unique low-signature survey vehicle, a base station, radio telemetry data links, satellite-based vehicle tracking, stereo vision, and sensors for noninvasive inspection of the surface and subsurface. The second project, conducted by the Idaho National Engineering Laboratory (INEL), involves the development of a position sensing system that can track a survey vehicle or instrument in the field. This system can produce coordinate updates at a rate of 200/s with an accuracy better than 0.1% of the distance separating the target and the sensor. It can employ acoustic or electromagnetic signals in a wide range of frequencies and can be operated as a passive or active device.

I. INTRODUCTION

The cleanup of hazardous waste burial sites requires site characterization surveys to detect and map buried waste deposits (e.g., trenches, pits, and cribs), to locate and identify waste-related features (e.g., tanks, pipes, and cables), and to define and assess geological and hydrological features (e.g., sedimentary layers, bedrock, and the water table). Geophysical, radiological, and chemical sensors are routinely used for these purposes. Site characterization surveys are performed with man-portable versions of these instruments or, particularly when the area to be surveyed is large, with vehicle-mounted instruments. The former approach tends to be time consuming and costly. The latter suffers from poor maneuverability and precision and from the loss of sensor performance due to interactions with the vehicle. Neither approach fully utilizes the capabilities of the sensing technology that is currently available.

Some 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 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.

To address these hazards and operational problems, the U.S. Department of Energy (DOE) is investigating the use of unmanned vehicles and remotely controlled instruments in site characterization surveys. Under its Robotics Integrated Program, DOE's Office of Technology Development has initiated the Remote Characterization System (RCS) Project to develop and demonstrate a remotely controlled, vehicle-based, sensing system. Joint support for this work is being provided by the U.S. Corps of Engineers Toxic and Hazardous Materials Agency.

The RCS Project was initiated in FY 1992. To date, functional design criteria have been formalized, the detailed system design has been completed, and assembly of the major system components is nearly complete. An initial field test of key system elements is planned in October 1992. A formal demonstration of the RCS is planned for the summer of 1993 as part of the Buried Waste Integrated Demonstration. Technology transfer and beneficial use of the RCS is planned for FY 1993 and FY 1994.

One of the necessary elements of a remotely controlled site characterization system is an automatic vehicle

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tracking subsystem. The primary approach adopted in the RCS project is to utilize the satellite-based Global Positioning System (GPS). However, a surface-based tracking system may be effective as a backup for, or a complement to, the GPS subsystem at some sites.

In the next major section of this paper, we present an overview of the RCS and briefly describe its major components or subsystems. Because we are at an early stage in this planned three-year project, this discussion is essentially a presentation of the project plan and a progress report. In the remainder of the paper, we describe the ground-based tracking system that has been developed at the Idaho National Engineering Laboratory (INEL), and present some concluding remarks.

II. THE RCS

The RCS Project has two primary objectives. The first is to develop a remotely controlled system that will perform site characterization surveys that will be safer, more cost effective, more accurate, and more complete than the surveys that are currently being performed. The second is to develop subsystems that will be applicable to other waste-related tasks that require remote visualization, control, and tracking capabilities.

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. At these sites, and at other sites that do not involve serious surface hazards, the RCS will also provide the following benefits:

- 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.

The utilization of RCS subsystems in other telerobotic applications offers potential time and cost savings in other phases of site cleanup efforts. In particular, RCS technology will be transferable to the design of vehicles and robotic systems that will be utilized in remediation activities such as the excavation and handling of waste materials.

A. System Overview

A basic element of the RCS design philosophy is that the remotely controlled survey vehicle and its instrumentation should 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 is that the vehicle must be constructed predominantly of nonmetallic materials so that it will have a minimum effect on the operation of on-board geophysical sensors.

Figure 1 is an artist's conception of the system in a field application. Although many 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 telemetered to the vehicle. Data produced by the on-board sensors are telemetered from the vehicle to the base station where they are recorded, processed, and displayed by a computer.

The full range of sensors to be supported by the vehicle and its instrument package has not yet been defined, but will include ground-penetrating radar (GPR), a metal detector, a magnetometer, an induction-type ground conductivity sensor, and a radiological sensor.

B. The Survey Vehicle (LSV)

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

To ensure optimum performance of the sensors, we designed and constructed a low-signature vehicle (LSV). It contains approximately 130 lbs of metal, but this material is distributed so that it will have 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 (collapse features), depressions, ditches, hills, berms, rocks, and miscellaneous debris (wire, cable, 55-gal drums, concrete blocks, etc.). As the operator maneuvers the vehicle around a site where these kinds of obstructions are present, it is inevitable that the vehicle will encounter difficulties that will require the operator to perform extraordinary maneuvers to extract it. In a situation of this kind, a lack of maneuverability is likely to end the survey and initiate a mission to salvage the vehicle. Therefore, the success of a remotely driven vehicle for this application will depend on its ability to maneuver.

To maximize its maneuverability and its ability to extricate itself from difficulties, we designed the LSV to be able to back up and to turn in place. Although this might

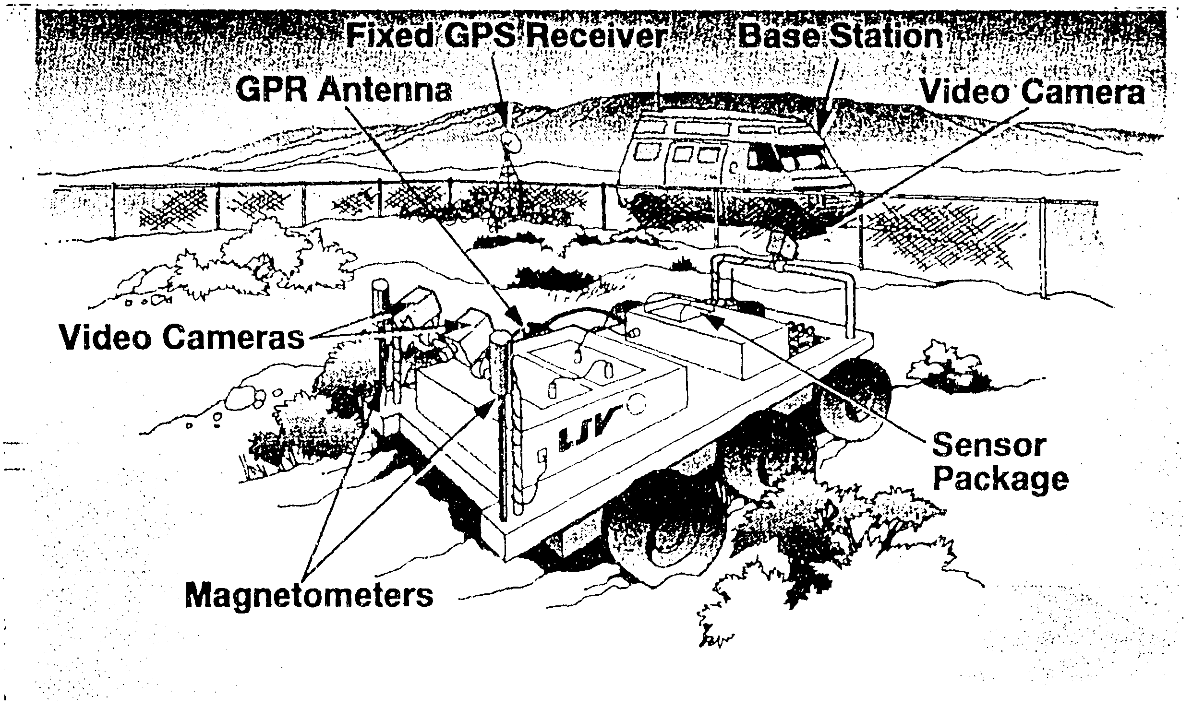

Figure 1 - Artist's conception of the RCS.

seem to be the obvious and normal thing to do, it 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 2, the front part of the chassis is an open structure that permits the GPR antenna to be suspended between the front wheels.

The prototype vehicle that has been constructed at the Pacific Northwest Laboratory is approximately 7 ft long and 5 ft wide. Its weight is approximately 500 lbs, including a payload of approximately 100 lbs. The LSV 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.

We adopted a six-wheeled design with modified skid steering for the vehicle. The choice of wheels rather than tracks was based in part on our view that small wheeled vehicles operating on loose surfaces are more reliable than tracked vehicles, require significantly less power and can be more easily decontaminated. We considered a relatively small light vehicle with three driven wheels on each side to be an optimum mechanical configuration. 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 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, 20-amp alternator mounted on the engine provides electrical power for the sensors, control modules, and other electronic devices on the vehicle. A belt-driven 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 10 ft/s.

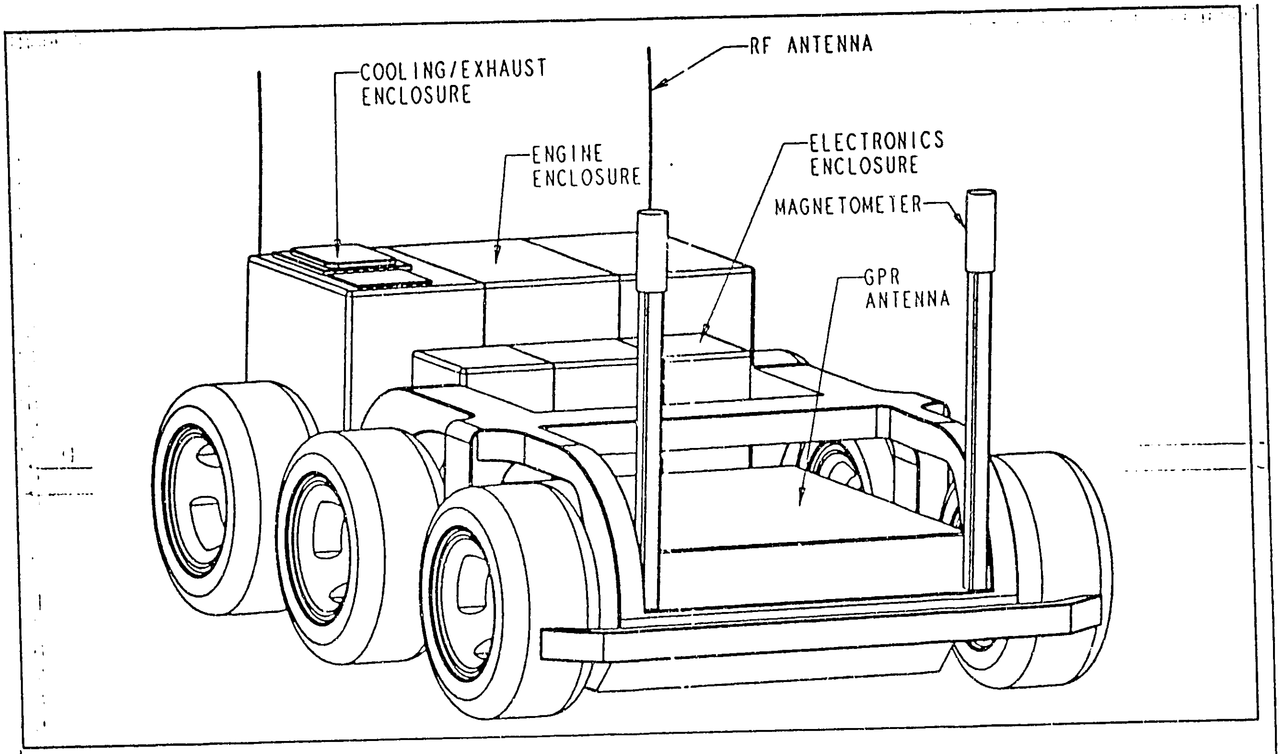

Figure 2 - A drawing of the low-signature survey vehicle.

These features permit operations on most of the terrain present at DOE waste burial sites.

C. Navigation Subsystem

A differential, kinematic, GPS-based subsystem 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 attached to the vehicle that houses 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 2 measurements/s. Coordinates accurate to ±10 cm can be calculated in a post-processing mode.

D. Communications Subsystem

Two radio-frequency (RF) data/command links provide Ethernet communications between the vehicle and the base station. One channel transmits vehicle-control commands, video-control commands, and vehicle status data from the base station to the LSV. The second channel

LSV and sensor output data 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. However, during the data collection phase of a survey, the sensor data are normally transmitted sequentially, without intervention or commands from the base station. This approach permits data to be transmitted at a rate of approximately 35 kB/s. This data rate is needed primarily to handle the 30-kB/s output of the GPR sensor as well as the output of all of the other sensors. Separate RF channels are provided to handle video transmissions.

E. High-Level Control Station (HLCS)

This subsystem is contained in the base-station vehicle. The central component of this subsystem is a console that includes an operator's chair as well as mechanical and electronic devices that permit the operator to control the LSV. A multi-processor computer performs high-level control functions for operating the LSV and its sensors. It also displays information and data and performs processing and display operations on collected sensor data. A secondary operator's station allows a geophysicist to view real-time data or to recall stored data files from previous surveys. The layout of the control station is illustrated in Figure 3.

The HLCS can accommodate and control a wide variety of vehicle configurations. This is facilitated by the use of a joystick on one of the chairside control modules. A

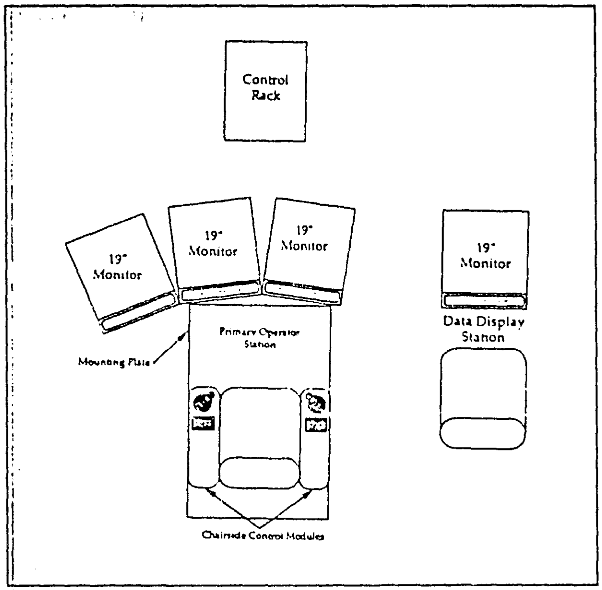

Figure 3 - Layout of the high-level control station.

large aircraft-style joystick controls all direction and motion functions for the LSV. Fore and aft motion of the joystick controls the forward and reverse movement of the vehicle. Side to side motion controls turning. Rotational motion commands the skid-steered vehicle to turn on its axis. Additional functions provided on the side consoles include camera pan and tilt, lens control, emergency stop, and a graphical menu interface.

During a site survey, the base station will be remotely located relative to the hazardous environment and will communicate with the vehicle and the on-board instrumentation via the RF telemetry links described above. The vehicle needed to house and transport the HLCS will be acquired and outfitted in FY 1993. Support components, including an enclosed trailer for transport and storage of the LSV, replacement components, and maintenance equipment, will also be added in FY 1993.

F. 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. Beyond this, 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, and vegetation).

A stereo video subsystem is being developed to provide the necessary detailed visual information. It includes cameras, camera control components (pan, tilt, and focus), d the associated telemetry links. Two video channels are included to provide for stereo vision or for alternative operational modes. A longer-term goal is to implement a data compression technique that will permit both video channels to be transmitted on a single RF link.

G. Sensors

The primary sensing instruments that will be transported by the LSV are: a GPR unit, two or three magnetometers, a metal detector, an electromagnetic induction (EMI) ground-conductivity sensor, and a gamma ray detector. 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 nonintrusive means.

Although most of the sensors included in the instrument package are off-the-shelf items, modifications are being made to meet stringent requirements on size, weight, electrical power, and ruggedness. Environmental requirements include:

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

In addition, each modified sensor includes a small embedded computer that provides interfacing to the RCS communications network.

H. Participating Laboratories and Their Responsibilities.

This development project involves the collaboration of five DOE national laboratories, each of which has responsibility for specific system components and project activities:

Pacific Northwest Laboratory - Task management, GPS navigation/tracking, vehicle development, system integration, GPR sensor.

Oak Ridge National Laboratory - Base station, including subsystem for operator interface and high-level control of the survey vehicle.

Sandia National Laboratory - Control system software, data display.

Lawrence Livermore National Laboratory - Telemetry, video, advanced sensors.

Idaho National Engineering Laboratory - Buried Waste Program coordination, magnetic sensor development.

III. THE INEL POSITION MEASUREMENT SYSTEM

Ground-based tracking techniques generally produce data which, after some trigonometric manipulation, yield the direction, or the direction and range, of the tracked object. One method is to mechanically or electronically point sensors or receiving arrays in the direction of greatest signal intensity. The direction to the signal source and the locations of the sensors are used to compute the source position. The classical radar method is to emit an energy pulse in a known direction, then determine the target range from the time at which the return echo is sensed. Another method, known as phase interferometry, compares the phases of the incoming signal at multiple sensors.

Though effective at relatively long distances, these widely known and used techniques do have some drawbacks. A mechanically directed system is subject to hardware failures and requires routine maintenance and calibration. An electronically directed system involves sensors that have a relatively high gain/sensitivity characteristic, so the interrogation zone is relatively small. Phase interferometry methods are complicated by the need to measure phase differences greater than 360°. Common to all of these methods is the inability to accurately measure direction or distance when the signal source is close to the sensing arrays.

If it were possible to maintain an accuracy of 0.1% of the range, where the distance varies from a few centimeters to many kilometers, we would have a multitude of new applications for these measurement techniques. The applications might include the supervision and control of remotely operated machines such as large unmanned excavators, master-slave devices, mapping equipment, and monitoring systems.

During the last two quarters of FY 1990, we (at the INEL) demonstrated the ability to passively track the position of a mobile platform as it communicates data to its control station. This capability allows us to easily fuse coordinate data, in real time, to the data being transmitted over a broadband communication link. The data stream may include video, magnetometer, ground-penetrating radar, temperature, pressure, spectroscopy, chromatography, or system status information. Some of the traditional methods of tracking were considered, but we found that the achievable accuracy was not satisfactory at short distances; i.e., distances less than 30 times the largest dimension of the sensing array. This meant that we had to have a very accurate phase measurement system and make our measurements at distances that give acceptable results or find another approach.

Our first choice was to acquire a better phase measurement capability, but we soon found this to be unrealistic. The pursuit of a new technology was begun with the following requirements: 1) use a commercial data link, 2) do not encode the data stream with positional information, 3) generate a coordinate update every 0.01 s, 4) perform the position sensing function passively, 5) maintain a positional accuracy of 0.1% or better over a square area of 1000 m on a side, 6) make the system portable and easily calibrated, and 7) make the system usable indoors and outdoors.

The original paradigms were reconsidered, and a different set of assumptions were adopted. The result is a system that looks very much like a classical phase interferometer, yet meets nearly all the requirements. We are still working the issues of portability and ease of calibration. A surprising aspect of the developed system is its ability to utilize either acoustic or electromagnetic sources; the only differences are sensors and computational constants.

The position sensor has been demonstrated several times at the INEL. The system was tested at several frequencies with different array dimensions. The block diagram in Figure 4 illustrates the major subsystems used for these tests. The energy emitted by a source is detected by an array of sensors. The output from each sensor is conditioned for amplitude uniformity, then processed to determine the phase difference between signals from the different sensor elements. The sensing, signal conditioning, and phase processing hardware are widely used in the tracking industry. The coordinate processor, however, is a proprietary piece of software that uses the phase difference data to generate emitter position data. The coordinate data can be fused with communication link data, displayed, and/or stored.

The system's capabilities were investigated at seven radio frequencies (49, 72, 900, 3000, 6000, 8000, and 21000 MHz) in an indoor environment. The data from these studies were used to verify our model which included phase measurement uncertainties. A similar system was configured

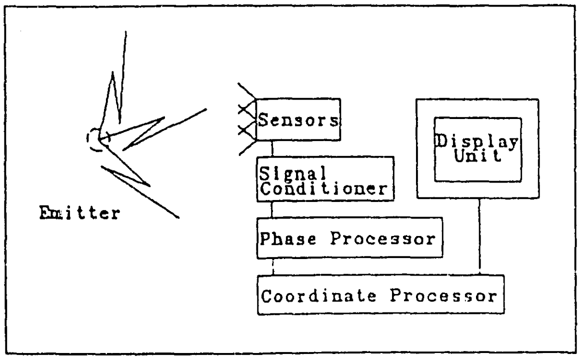

Figure 4 - Component block diagram of a passive short-range tracking system using a commercial communication link as the emitter.

to test our methodology using acoustic signals. We found that the same kind of hardware and software allowed us to track the position of an acoustic source. The acoustic system was tested at frequencies from 200 Hz to 10,000 Hz. Frequencies above the audible spectrum will be investigated at a later date.

For tests performed using electromagnetic hardware, we found that the experimental results compared exceptionally well with modeled data when the uncertainties were included in the model. The maximum array dimensions were from 2 to 20 wavelengths, with the distance between the emitter and sensor array varying between 0.02 and 20 m. System design parameters can be controlled so that the accuracies will always be 0.1% of range for a given maximum distance and phase uncertainties of ±2°. Accuracies in directions transverse to the radial direction are 3 to 50 times better than that of the range values.

A set of repeatability checks were conducted with our acoustic system. In the frequency range of 200 Hz to 10,000 Hz, we observed a transverse repeatability of ±0.02 to ±0.05 mm for an emitter/sensor separation of 1.7 m.

With the current system, it is possible to observe the position of an unmanned vehicle used in the mapping of buried waste. The position coordinates can be fused with other data at a rate currently in excess of 200 coordinates/s. If this measurement system were interfaced with an accurate global positioning system (GPS), it would be possible to establish a reference point from which the high-speed system could operate. This marriage of technologies would allow smaller tracking distances and greater accuracies. In addition, the tracking system could be reconfigured more rapidly for a multiple setup task.

IV. CONCLUDING REMARKS

The mission of the Robotics Integrated Program of DOE's Office of Technology Development is to produce needs-oriented, timely, and economical robotics technologies for potential 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 an INEL test site. While the benefits of a multi-sensor survey were validated, several shortfalls in the initial system were identified. Because the remotely operated vehicle that was used for this demonstration was not built specifically for geophysical mapping, it interferred strongly with the instruments. Also, the large size of the vehicle limited the areas in which it could be effectively deployed. 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, RCS will perform repetitive surveys of waste excavations as layers of soil are removed. Based on this repetitive information, the waste site remediator will make decisions regarding contamination levels and disposition of overburden and proximity to buried objects.

RCS development activities are planned to continue for the next two years. During that period, the RCS Project will lead to meaningful demonstrations at buried waste sites. An advisory group composed of site users and technologists has been identified to ensure that the RCS is responsive to site user requirements. Technology transfer to potential users and to industry is planned as part of the program.

The tracking system developed at the INEL provides opportunities to enhance position sensing capabilities in a wide variety of applications. The technology is scalable and can be implemented on robot manipulators and end effectors. In this mode, the system delivers the position of the end effector for any static or dynamic loading since it is not affected by the deformation of the structure under load. The position sensor might also be applied to a machining process for observing the dimensional characteristics of the workpiece during the machining process. Since the method is based on propagating wave phenomena, it also has subsurface marine uses and geological potential. The method possesses some very attractive possibilities for tracking the activities of multiple vehicles and allowing a supervisory control and collision avoidance capability.

We are not assuming or proposing that problems requiring further study and development do not exist. Some known challenges still loom before us. The issues of system characterization, calibration, and autocalibration remain. We are still looking for faster and more reliable ways of resolving cyclic ambiguities. Applications that involve multiple emissions at the same frequency and multi-path signals have a special set of problems. We are even considering a velocity enhancement to the system.

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