

Position and Orientation Tracking System (POTS)

Robotics Technology Development
Crosscutting Program



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Position and Orientation Tracking System (POTS)

OST Reference #1873

**Robotics Technology Development
Crosscutting Program**



Demonstrated at
Sandia National Laboratory
Albuquerque, New Mexico

INNOVATIVE TECHNOLOGY

Summary Report

Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine if a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available on the OST Web site at <http://OST.em.doe.gov> under "Publications."

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SECTION 1 SUMMARY

Technology Description

The Position and Orientation Tracking System (POTS) addresses the potential needs for enhanced safety, productivity, and operability for remote and robotic systems used for waste retrieval in Underground Storage Tanks (UST's) across the Department of Energy (DOE) complex.

POTS represents a substantial advancement in robotic systems component development, for navigation subsystems. It is intended to remotely track the location and motion of vehicle or arm-based manipulators. The active-triangulation based system can track a target's position to a resolution of .25 inch and orientation to .009 degrees (32.4 arc seconds) at a frequency to 25 Hz or higher. Current design operating range is up to 80 feet by 80 feet for indoor or outdoor applications.

A patent, number 5748321, has recently been issued for this novel approach (Reference 1). Design and demonstrations to date have been linked to requirements at Fernald, a DOE site near Cincinnati, Ohio, to address retrieval of waste stored in three silos there. This has included integration and coordination with the Houdini Remotely Operated Vehicle (ROV), also originally intended for use at Fernald.

As shown in Figure 1, the main system components are two pods mounted overhead in the tank, and a target box that is fixed to the object (robot, end effector, etcetera) being tracked. Electronics and a UNIX-

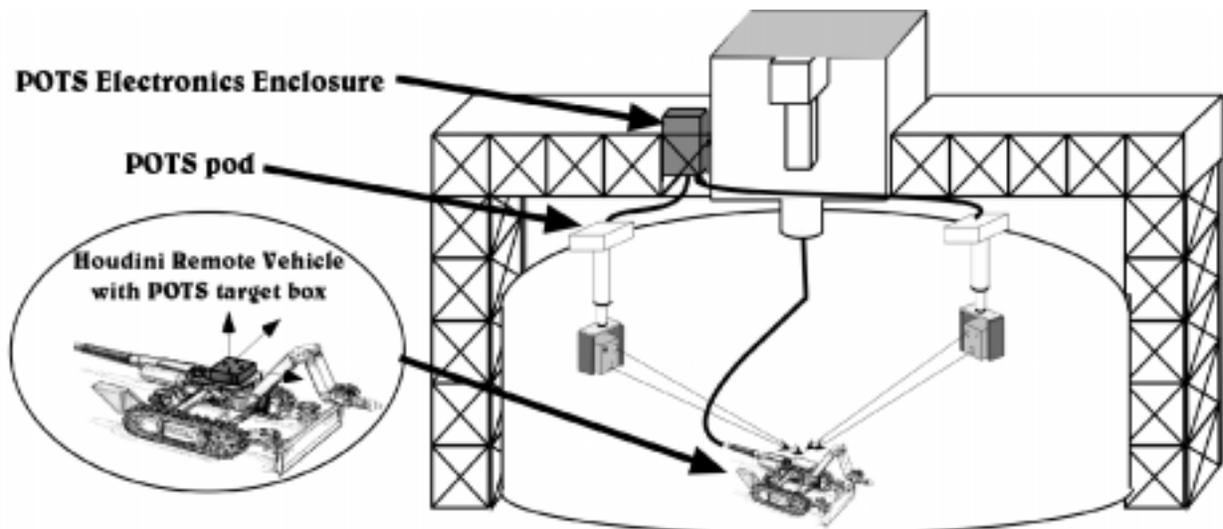


Figure 6- Position and Orientation Tracking System (POTS) components and application

based controller integrate and synchronize overall system operation, as well as computing the position of the tracked object and displaying the data generated.

The POTS components are shown within the context of deployment at the Fernald silos, and in conjunction with the OST-funded Houdini waste retrieval system. In this scenario, Houdini, with the POTS targets attached, is deployed from an equipment room suspended over the silos. The systems are controlled by operators in a remote trailer not illustrated.

The tracking is accomplished by sweeping a pair of orthogonal, laser generated light stripes from the pods to infrared (IR) sensors on the vehicle. The moment that sensors detect a light stripe, it is correlated with one of the four laser sources and the angle to its respective pod. Together, the four angles measured are sufficient to reconstruct the position and orientation of the target, after the system has been properly calibrated.



Data obtained through POTS are used to orient operators of remote systems within featureless tank interiors. POTS also enables the automated camera-tracking of the robot vehicle, giving well framed overhead views of the vehicle with no operator intervention. This reduces the operator's required hand motions, thus increasing productivity while lowering fatigue. In conjunction with geometric models of the tank and internal features, POTS can also be used to warn operators of impending collisions.

There is no applicable baseline technology comparable to the function provided by POTS. It provides a combination of precision, range, and response time that is unavailable in any other tracking sensor technology. Alternative laser-based navigation technologies are not sufficiently robust for high radiation environments, nor are they as accurate as POTS, which offers an order of magnitude more precision.

POTS most significant drawbacks at present include its complexity and expense, which could both be reduced somewhat through additional engineering effort and production experience. In addition, the system almost fully occupies two of the tank's risers (penetrations), which are typically limited, and are often needed for other retrieval equipment or ventilation systems.

Technology Status

POTS has been funded by the Office of Science and Technology (OST), through the Robotics Technology Development Program (RTDP). It was designed and built by an interdisciplinary technical team from the ORNL Robotics and Process Systems Division (RPSD), with site support from Fernald. RedZone Robotics, developers of the Houdini robot, has participated in the integration and test of POTS and its data display software. This report covers POTS activities from FY93 to FY96 and their relation to associated silo mapping (FY91) and waste retrieval (FY92-98) projects.

Application at Fernald

In 1991, a laser-based mapping system was rapidly designed and deployed in Fernald's Silos 1 and 2 by the same group of collaborators. POTS was originally conceived in Fiscal Year 1993 (FY93), and was to be used at Fernald as part of the proposed 'Waste Retrieval System' (WRS), an RTDP-funded effort. This retrieval campaign addressed waste stored in two of four 80 foot diameter, 36 foot high concrete silos on site, whose removal and treatment is a high priority at Fernald.

A remote vehicle with a dextrous arm would be deployed in the silos, with POTS providing high fidelity position feedback to determine its angle of pose on the waste surface, proximity to walls, and for potential closed-loop position control. It would also provide registry between graphical simulation environments (used to enhance safety), and the 'real world' environment. A minimum resolution of 1/2" over that large range was thus required at a 5 Hz update rate. However, a higher frequency of 100 Hz was specified so that POTS could also support position feedback control for another RTDP project active at that time, a long-reach manipulator for use at the DOE Hanford site.

Extensive energies were applied in order to have POTS completed in time to participate in this deployment. Late in FY93, however, procurement and management issues arose that forced the cancellation of the WRS project. ORNL continued to develop POTS with a reduced team, in support of long-reach arm application and also in anticipation of the still valid needs at Fernald.

By FY95, the Houdini remote system was proposed by RedZone Robotics (Reference 2) to address revised Fernald needs and schedules. RTDP then funded a modest additional effort in FY96 to complete POTS and integrate it with the simultaneous Houdini development. In addition, a few modifications were added based upon Fernald's revised waste retrieval plans and technical constraints.



Demonstration Status

POTS was first demonstrated at SNL with the ORNL-developed omni-directional vehicle in July 1996 as part of the annual RTDP Industry/University/Laboratory Forum, and was later tested along with Houdini at the RedZone facility prior to Houdini's delivery to ORNL in September 1996.

By early FY97, Fernald plans had been delayed, and Houdini-I had been redirected to ORNL, where the Gunite And Associated Tanks (GAAT) Operable Unit (OU) had a more urgent need for Houdini. At ORNL, waste retrieval schedule and cost pressures, along with different technical requirements, led them to deploy Houdini without the accompanying POTS.

However, Fernald's need had only been deferred, so RTDP funded a second generation Houdini for the Silos Project and also a Cooperative Research and Development Agreement (CRADA) with RedZone for a Graphical User Interface (GUI) to display the POTS data at Fernald. In March 1997, as Houdini-II redesign was getting started, Fernald announced that they would privatize the Silos Project and thus could no longer guarantee waste retrieval schedule nor deployment of Houdini. In response, Houdini-II was also directed to ORNL. Due to reductions in program funds and the immediacy of need, only a limited functionality POTS GUI was completed under the CRADA.

Thus, due to program and funding changes, POTS has not been deployed in a radioactive environment. Core POTS functionality is complete and tested, though additional effort would be required to finish system calibration. Performance goals have not been fully verified, though fundamental repeatability and accuracy of the equipment has been laboratory tested.

Cost-benefit studies have not been performed. POTS is fairly expensive and is intended to be used where precise positioning requirements, safety risk and/or importance are high enough to justify several hundred thousand dollars for the equipment, or in cases where additional software integrated with POTS and waste retrieval equipment improves productivity enough to save more operations expenses than the cost of the equipment.

Full advantage has not yet been made of the orientation, tracking, and collision detection applications that POTS enables. Related graphical simulation efforts that POTS would integrate with have been scaled back and the Houdini vehicle remains under simple teleoperated control, with no automated routines. The safety concerns that identified the need for such simulations, such as potential collisions with tank walls and internal features, have so far been addressed through other approaches, though the waste retrieval efforts to date have not attacked the most challenging tanks nor the longest duration campaigns in the complex, where these concerns would be significantly greater.

For those situations where the safety envelope must be expanded due to extreme challenges or risks, or for automated control, the functionality that POTS development has added to the suite of available technologies may become much more valuable to waste retrieval systems builders and operators.

Contacts

All published Innovative Technology Summary Reports are available on the OST Web site at <http://em-50.em.doe.gov> under "Publications" The Technology Management System, also available through the OST Web site provides information about OST programs, technologies, and problems.

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Licensing Information

Both the POTS equipment and patent rights remain at ORNL. Information on technology transfer is available from contacts listed above or through Joyce Shepherd of the ORNL Technology Transfer office at 423-576-2014. Graphical User Interface (GUI) software for POTS has been transferred to RedZone robotics (412) 765-3064.



SECTION 2

Technology Description

System Description

Components

As shown in Figure 2, POTS consists of two measurement pods, synchronization and data acquisition electronics, a UNIX-based computer system, and the target array, which is mounted to the system being tracked. Illustrated here is POTS application at Fernald, and in conjunction with Houdini, as was originally intended.

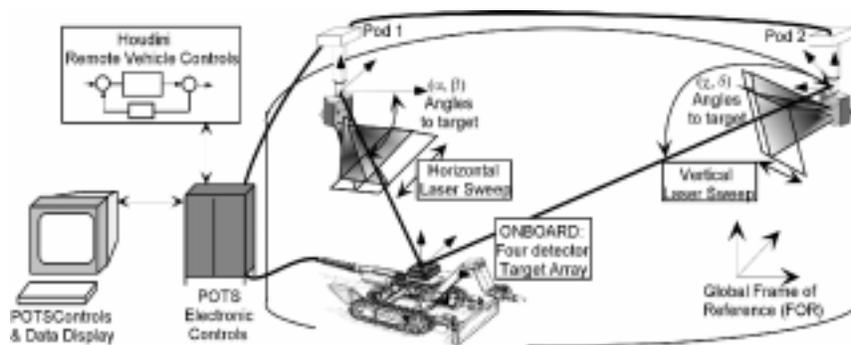


Figure 7- POTS system components

The pods are suspended overhead through two risers 14 inches or larger and are intended for operation in radioactive and condensing (foggy) environments. Two perpendicular planes of laser light fan out from each pod to the vicinity of the robot with target box attached.

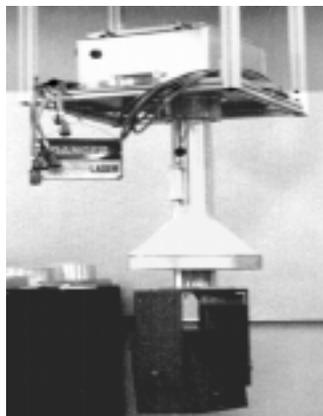


Figure 8-POTS Pod in laboratory at ORNL.

The target consists of four or more Infrared (IR) detectors in a fixed array. As the lasers scan across the target box, the angles of incidence with each detector are recorded. Redundant detectors placed on the target box can accommodate occlusions and improve measurement accuracy.

Applications

POTS was developed to enhance the safety of in-tank waste retrieval operations. It provides the data to monitor real-time activities with capabilities far beyond standard remote camera systems. It can also serve as the data link between graphical simulations of in-tank activities, and the real-world constraints and conditions at the time of task execution.

By capturing the exact position and orientation (pose) of the manipulator end-effector or ROV body, inaccuracies in tool positioning can be reduced, to the point that more precise operation is possible. It is intended to be used on either remote vehicles deployed onto the waste

surface or by long-reach arms that extend into the tanks through narrow risers. Figure 3 shows a complete pod in the laboratory and Figure 4 shows the Houdini-I, which was designed to be integrated with POTS.

A secondary benefit of the system's design is that overhead cameras mounted within the pods will automatically track the vehicle and thus keep it centered within the field of view without additional demands placed on operator attention.

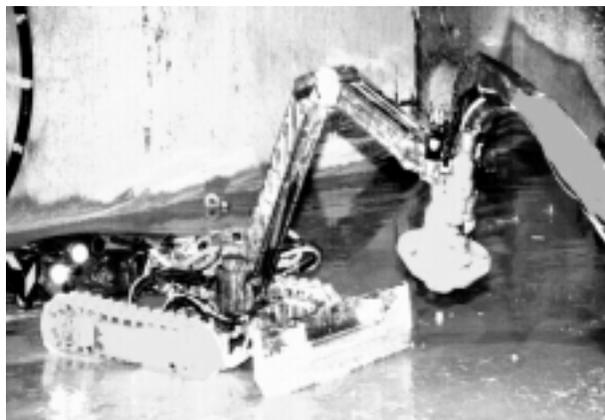


Figure 9- Houdini ROV at ORNL



POTS can also be used to calibrate large robotic arms for operations in cluttered areas or for wall-following tasks. Within a separately implemented graphical modeling environment, POTS can enable computer routines to simulate and then predict potential collisions with fragile in-tank equipment or walls, as well as allowing automation of routine operations, possible contour skimming operations on the waste surface, or wall following operations, such as decontamination and scabbling.

Geometric Basis Of Operation

Arrow triads in Figure 5 show a few of the key geometric Frames of Reference (FOR). The global reference frame describes the position of fixed and immobile objects such as the silo itself. Other FOR's illustrated describe Houdini's location and pose, and those attached to each measurement pod.

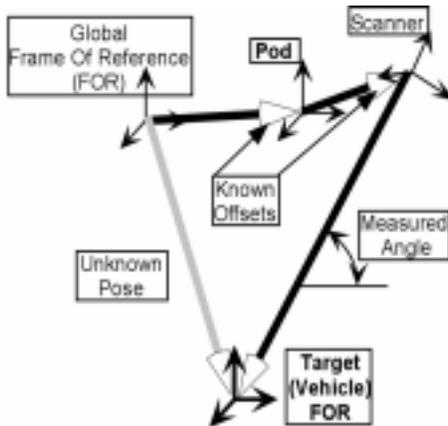


Figure 10- Geometry for vector calculations

Within each FOR, the position and orientation of object attached is described by six coordinates, three representing linear motion in each of three dimensions, and the other three representing rotations about each axis. Motion is tracked as the sequence of changes in position, which at any instant can be described with six measurements to represent the shift in position (3-D) and orientation (about 3 axes).

The shift between various FOR's is thus 6-D and requires special mathematical conventions to describe the 'transforms' between frames. Since the laser rays of light are symmetric about their center axis and are of theoretically infinite length, the problem is reduced and solved using quaternions, a 4-Dimensional vector space.

It is the relationship between the global and vehicle frame of reference that POTS deduces, through the measurement of the angular direction from each pod to the center of the target array on the robot. The four angles are sufficient to reconstruct the position and orientation of the target, assuming a precise model of several key known or pre-measured geometric relationships.

Figure 5 graphically summarizes the known and unknown vectors for a single laser source and detector, from the world (or global) FOR, to the pod, then through two axes of motion (tilt and pan), and lastly to the laser and mirror assembly that points at the target.

The algorithm used to solve this set of relations for the unknown heading and range to each target uses only the four angular measurements to completely determine the 6-D pose of the target box. Extensive mathematical models and complex algorithms were developed to produce the efficient and accurate subroutines embedded in the system controller, that can be calculated in real-time at the update rate of greater than 25 Hz on a modest computer with performance typical of Pentium-class PC systems.

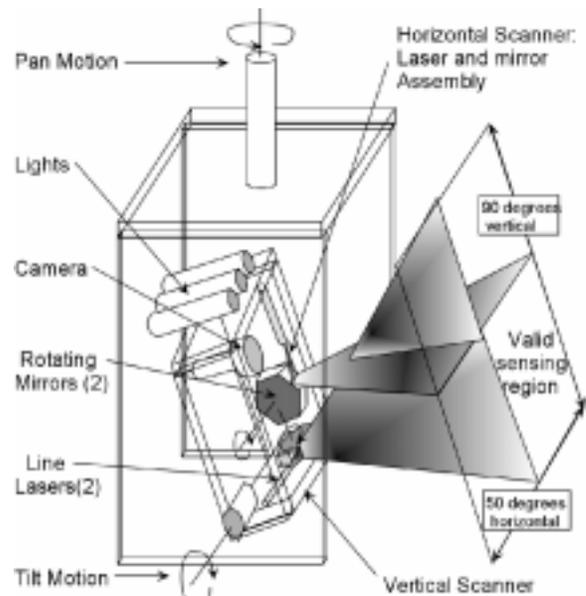


Figure 11- POTS pod details

System Details

Two scanners are mounted in each POTS pod, each consisting of a lasers pointed at a spinning mirrors to form sweeping stripes of laser light, cast in the vicinity of the vehicle. The instant a laser source is

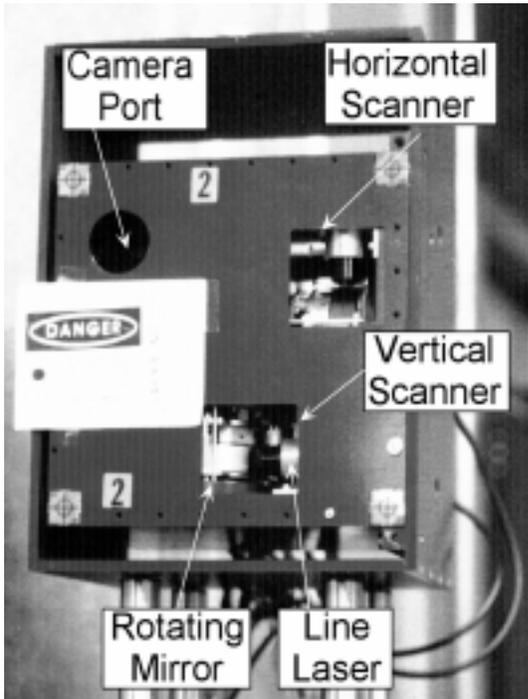


Figure 12- POTS scanner box

detected on the target box, the angle from that sensor to the pod can be inferred from the position of the mirror at that moment, and other known parameters. This smaller region swept by the scanning laser light stripes is used for the precise final real-time measurements. As shown in Figure 6, it fans the laser stripes 90 degrees in the vertical direction and 45 degrees horizontally.

The accuracy of this laser scanner subsystem has been measured to be better than one microsecond, which corresponds to an angular resolution of 32.4 arc-seconds at the mirror's speed of 3600 RPM. Tilt and pan motions on each pod keep the lasers pointed approximately towards the vehicle so that the target remains within the swept volume. Each pod extends about four feet into the silo to support its 13 inch wide by 12.5 inch high by 8 inch deep scanner box

The source of each laser is an infrared (IR) diode, operating at a power output of 35 milliwatts and a wavelength of 830 nanometers. Optics convert the spot laser to a line laser with a beam spread of 45 degrees. The optical scanners in each pod have been adjusted so that the generated laser lines are orthogonal. The low power lasers are not strong enough to harm other in-tank equipment, although goggles and safety warnings are required to protect eyesight during calibration procedures in the laboratory.

The laser scanners sweep a 3-dimensional wedge of laser light that is 45 degrees by 90 degrees, casting the two light stripes across planes extending from the mirror surface to the targets on the detector box. The scanner box from one pod is shown in Figure 7.

To determine both angles between the target and pod, the detectors must simultaneously be within the scanned area of both lasers. Thus the detectors must be within the intersection of both stripes of laser light, or a square shaped projected area of 45 degrees per side. At 50 feet between pod and target, the work area is at least 40 x 40 feet, giving the POTS controller sufficient reaction time to keep the vehicle within the active sensing area by repositioning the pod's tilt and pan axes.

An optical detector subsystem is included in the electronics support package, to register 'hits' from the laser scanner. When laser light of the proper frequency is detected on the target box, a pulse is sent to a customized digital controller.

By filtering the incoming light on the detector, the system can be used in natural or man-made ambient light conditions. Custom-built peak detectors are used to improve the accuracy of the time-stamp.

Only one detector has to register hits from both pods to continuously track position, and three are required to include full pose tracking. Four detectors are mounted on the target box. Thus, the redundant detectors in the array can permit continuous tracking even if some of the detectors become temporarily occluded due to mud, water, machine configuration, or position in the tank.

The digital controller fires each laser in turn and records the angular position of the scanner facet the instant the hit was registered. At the beginning of each laser scan the digital counter / timer is reset by a reference pulse from the scanner, insuring that proper synchronization is maintained over time. The controller also issues position commands for each pod's pan and tilt tracking motions.

System environmental hardening features include air- and water-tight sealed electronics enclosures for both the electronics enclosure and the overhead pods. The equipment rack is a watertight enclosure with 500W capacity air coolers. The scanner subsystem enclosure in each pod can be nitrogen-purged for use



Figure 13-POTS Calibration. Two pods are shown on extreme left and right and theodolite in foreground.

in explosive environments, though that has not been implemented in the prototype system. Motion controls for the pod's tilt and pan axes are housed in separate sealed compartments. The rotating mirrors and lasers can withstand radiation doses rates of up to 1 MR/hr and total absorbed dose of 100MR.

The pod has a conical shield above the scanner to keep condensing water from dripping into the sensitive equipment. Experience has shown that the tank interiors can often form their own atmospheric conditions, especially when sluicing and other water-based operations are in process. The pods are currently made out of anodized aluminum, to reduce the 'hung weight' of the pods on the somewhat fragile silo domes at Fernald. Other applications in corrosive environments could lead to the easy re-specification of stainless steel enclosures.

Calibration

The purpose of system calibration is to determine the precise geometric configuration and location of each system component's reference frame by means of instruments traceable to national standards. POTS calibration has two stages- first to measure each pod following assembly, and then to determine the pose and relationship of each pod to each other and to the global reference frame.

The first stage includes determining the relative positions of the lasers to their mirrors and the centers of rotation for tilt and pan, amongst others, to a high degree of precision. The performance of each pod can then be verified, and final corrections to the geometric mode can be made, by comparing pod measurements to a fixed target array (the target box).

The true positions are measured using a theodolite, similar to a surveyor's transit. Figure 8 shows the calibration setup used at ORNL. The target box, mounted on an optics table, was situated on the opposite wall (behind the viewer), to maximize the separation distance and thus increase accuracy.

A method developed during an earlier silo mapping campaign at Fernald (Reference 3) can be used once POTS is installed in a tank. It involves securing three small IR detectors (identical to those on the target box) at known locations within the tank and then sighting on each sensor with a pod and then applying an iterative algorithm to solve for the pod's location. The sensors are narrow enough to be deployed through smaller ports (6 in. diameter) on the dome that are plentiful at Fernald.

Operation

POTS display screens can be physically situated on the Houdini control console's shelving, providing graphical information directly to the operator. At present, POTS requires highly skilled operators for system calibration and data interpretation. However, automated calibration routines could be developed with IR targets on the pods as proposed above, and further GUI development could reduce the level of technical skill required for set-up and operation.

During system calibration, and any other time that people could be potentially exposed, care must be taken to limit exposure to the scanner's laser beams, as they pose a moderate hazard to the eye and skin. POTS requires two 20 amp power lines at 120 VAC for operation and tether lines for its target box on the robot vehicle. It is intended to operate completely automatically during waste retrieval operations, unless the single operator already dedicated to robot operation chooses to override POTS control.



Figure 9- POTS calibration

Maintenance of the pods would require glove bagging operations. However, each pod is completely integrated and ready to install, which shortens installation time and consequently radiation dose to operations personnel. Essentially no secondary waste is created through POTS operation, with the exception of glove bags needed to install or repair the pods.

Data Processing and Presentation

Software written for the project has been written in the 'C' programming language, and the user interfaces have been developed in the 'X' windows environment. The system is controlled by real-time

VME-bus based embedded computer. A Unix-based workstation is used as the development platform.

The workstation is needed only for system debugging and calibration and is not needed once installation is complete. The embedded controller uses a real-time UNIX-variant operating system called VxWorks, from Wind River Systems, Inc. All these tools were selected for their portability and ability to meet the demanding requirements for this application.

Two Graphical User Interfaces (GUI's) have been written to date. A system-level GUI displays raw data and can directly command low-level functions. Four windows display a time history of the angle between each scanner and the target array. Its use is shown in Figure 9. In Figure 10, the lines of dots in each of the four strip charts show the angle of a single laser source to each of the four detectors (four lines are present though two are superimposed in each window pane) and its change over time. Other status and control windows for pan and tilt motions on each pod are also provided. It is most useful for system development, test, and calibration.

System Description *Continued*

The second GUI is a customized 3-D representation of the POTS-collected data. It was developed in coordination with RedZone for integration with the Houdini robot. References 4 through 6 provide additional details on POTS.

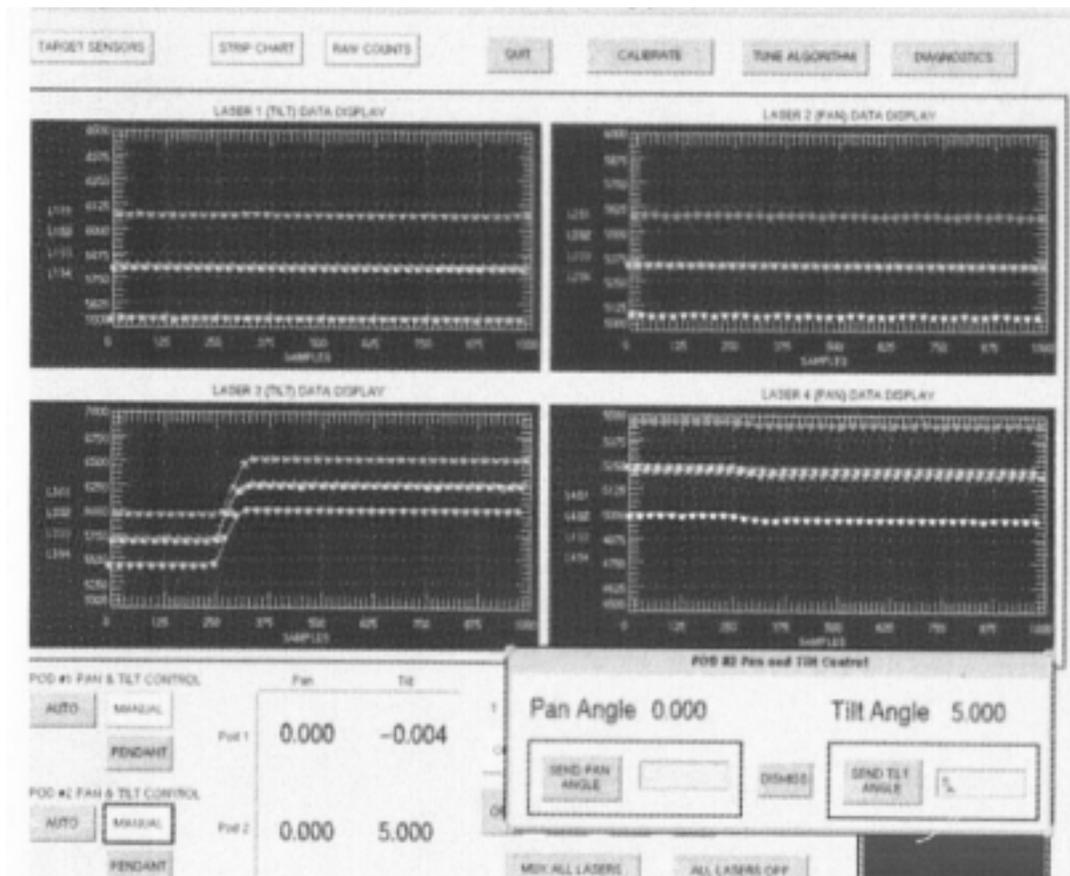


Figure 10- Display Screen



SECTION 3

Performance

Application Background

POTS was initially envisioned and designed to support waste retrieval operations at Fernald, and was to build upon a growing confidence in the development and deployment of laser-based systems to support silo remediation there. It would operate within a graphics-based controls environment developed by Sandia National Laboratory to provide enhanced safety and productivity for waste retrieval.

Fernald's silos have various non-pumpable objects that had accumulated from previous in-tank operations. The silos (see Figure 11) are each 80 foot diameter, above-ground concrete structures with a center opening and four additional 'risers' spaced evenly on a 50 foot diameter circle on its curved dome, each riser being only 22 inches in diameter.



Figure 16- Silo at Fernald during construction of superstructure for Waste retrieval testing

As joint participants in the RTDP, Fernald and ORNL had already collaborated in 1991 on a successful mapping mission of the waste surface of the two silos containing difficult to handle 'K-65' waste, a putty-like pitchblende residue from early uranium refining operations. A laser-based mapping system was developed by an ORNL team from the Robotics and Process Systems Division (RPSD), with site support at Fernald and some technical support from RTDP colleagues at Sandia National Laboratory.

The 'silo mapping system' as it was called, was successfully designed and deployed in less than a year. The mapping system demonstrated the potential for precise and advanced geometrical sensing systems to be successfully deployed in high priority EM-50

projects, and started to build up a body of experience and lessons learned at ORNL and Fernald in the design and deployment of these systems in radioactive tank interiors. It also served to build confidence in the use of advanced technology for in-tank applications, both in EM-50 program managers at the RTDP and EM-40 users at Fernald.

Demonstration Plan

Based upon the successful partnership, an integrated approach to K-65 waste retrieval was launched in FY93 by the OST's RTDP. Fernald would procure a tethered mobile robot to remove Fernald's waste from the tanks. The Waste Retrieval System, or WRS, consisted of a mobile vehicle with a manipulator that could scoop, plow, and sluice the waste on its surface, or, if necessary, submerged within it.

ORNL would design and implement the POTS equipment and software, to allow integration with a graphical control environment for simulating, monitoring, and automating the WRS operations. The planned system would run on high-end Silicon Graphics workstations within the IGRIP robot simulation environment from Deneb, Inc.



Development of POTS proceeded briskly and under considerable time pressure. The WRS was soon needed at Fernald in order to support several enforceable milestones, including the demonstration of a viable waste retrieval strategy, and extraction of enough material from the silos to support CERCLA Treatability Studies.

The nearly complete POTS prototype was demonstrated at SNL in July 1996 as part of the annual RTDP Industry/University/Laboratory Forum, and was later tested along with Houdini at the RedZone facility prior to its delivery in September 1996.

By early FY97, Fernald plans had been delayed, and Houdini-I had been redirected to ORNL, where the Gunitite And Associated Tanks (GAAT) Operable Unit (OU) had a more urgent need for Houdini. At ORNL, waste retrieval campaign schedule and cost pressures, along with a different set of technical requirements, led them to use Houdini without the accompanying POTS equipment.

However, Fernald's need had only been deferred, so RTDP funded a second generation Houdini for Fernald and a Cooperative Research and Development Agreement (CRADA) with RedZone for a Graphical User Interface (GUI) to display the POTS data.

In March 1997 Fernald announced that they would privatize the Silos Project and thus could no longer guarantee waste retrieval schedule nor deployment of Houdini. In response, Houdini-II was also directed to ORNL. Due to reductions in program funds and the immediacy of need, only a limited functionality POTS GUI was completed under the CRADA.



Figure 17-Waste Retrieval at the ORNL Gunitite Tanks

A second application for vibration analysis and control of long-reach robotic arms had also been planned and led to more demanding update and accuracy requirements for POTS. A testbed system was to be built to address Hanford waste retrieval scenario development starting in FY94. However, this project was canceled due to program changes before the system was ready for integrated testing.

POTS Performance

This section describes current technical status and performance of the system to date. As has been previously noted, however, both the funding profile and target applications for POTS have been inconsistent and prematurely terminated due to programmatic circumstances unrelated to the technology. Thus, POTS has not been deployed nor field-tested in any retrieval campaigns.

It is worth emphasizing that the most difficult waste retrieval applications in this country have still not been started, and may not be for a decade or more. The safety envelope required for these risk-filled projects will be much broader and will likely lead to the need for high-quality tracking systems such as is offered by POTS.



Current Technical Status

At present, the scanner boxes, pods, and electronics cabinet have all been assembled and packaged into sealed and field-ready systems designed for installation in any of Fernald's four silos. A stainless steel target box for the on-board detectors was fabricated and installed briefly on Houdini-I. POTS signal cables have been integrated into the tether design for both Houdini-I and -II. The full signal path from laser scanners, to the remote target box, and then through the tether and back to the POTS controller, was only briefly tested at RedZone.

The GUI for low-level control and calibration has been completed and used extensively during system testing and demonstrations. The high-level GUI for data display requires significant additional development. Integration with automation and simulation applications has not yet been implemented.

During system development, a scheme utilizing lasers with four distinct frequencies (colors) and filters on the detectors to uniquely identify each laser, was abandoned in favor of a simpler and less costly approach where each laser is fired sequentially, thus eliminating the need for correlation. A consequence of the trade-off to the selected approach, however, is that the update frequency is now at 25 Hz. This is more than sufficient for application at Fernald for real-time data display, where the natural frequency of the vehicle is around 1 Hz, but may need improvement for automation or vibration control applications.

System calibration to date has been performed in a 20x40 foot laboratory, with four detectors mounted on a plate in a cross pattern with 12 inch separation. POTS has been able to identify the angular direction to the target array to a precision of .009 degrees, or 32.4 arc-seconds, as specified.

Demonstrations to Date

POTS was first introduced to the public at the RTDP Industry/University/Laboratory Forum, hosted by SNL, on July 24-25 1996, at the SNL robotics laboratories in Albuquerque, NM. The system was installed by ORNL as part of an integrated demonstration of RTDP supported technologies and shown to the 200 attendees ranging from remediation contractors and DOE user-site representatives, to robotics systems developers from national laboratories and academia.

Following the Forum demonstration, the POTS equipment was brought to the RedZone facility in Pittsburgh, PA, for integrated testing with Houdini. POTS was set-up in the RedZone facility with a 40 foot separation between the pods, mounted upside-down from a second-floor interior balcony in their high-bay area. This positioned the pods approximately 26 feet above the floor. The target box was briefly mounted on the robot, and then was mounted on a manual push-cart for further testing.

The integration phase at RedZone concluded on September 9 1996 with an open-house for the Houdini project team and other interested observers. The system was demonstrated using the target calibration array and without full determination of pod locations within the facility. Though angular data was recorded and was qualitatively consistent with expected performance, no comprehensive studies were undertaken.

Further system improvements were planned for POTS, as part of integration with the second generation Houdini system, Houdini-II. Though some additional calibration work was done thereafter, the engineering effort was halted when application of Houdini-II at Fernald was again delayed, and no appreciable work has since been done, with the exception of prosecution of a patent application. Patent 5748321 was issued May 5 1998 to G.A. Armstrong, B.L. Burks, and others, and assigned to the DOE [Reference 1].



SECTION 4

TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Technology Applicability

The need for precise position tracking of robotic vehicles and end-effectors was first identified by the RTDP following an extensive survey of robotics needs in the DOE complex, as published in the RTDP Robotics 5-year Program Plan [Reference 8].

POTS was originally conceived as part of the waste retrieval strategy at Fernald and was to be integrated with a vehicle-based manipulator, originally the Waste Retrieval System (WRS) and ultimately Houdini from RedZone robotics.

Path and position data from POTS can be integrated with arm position data to yield a real-time graphical and geometric picture of the robot and its configuration, provided to the human system operator, working in a remote trailer.



Figure 18- The Modified Light Duty Utility Arm (MLDUA) and Houdini at work at ORNL



Technology Background

Arm based retrieval systems must be slender enough to enter the tanks through narrow risers and then reach the entire volume of the tank. Usually the arm must be relocated several times to access the entire tank interior. This leads to the potential for inaccuracy and vibration of tools deployed at the end of the arm, for sluicing, object manipulation, etcetera. With POTS target arrays mounted at the end of the arm, improved sensing and control of tool position or vibration is thus possible. The Modified Light Duty Utility Arm (MLDUA), shown in Figure 14, is an example of this type of system.

In the case of vehicle based systems, treads typically slip on the waste surface enough that navigation by 'dead reckoning' (computing position based upon heading and distance traveled) is impossible. Furthermore, the waste surface upon which the vehicle sits will be very uneven, and the end point of manipulators deployed from the vehicles will be affected by its instantaneous pose.

For instance, as the POTS system functional requirements were being developed, little was known at Fernald about the exact position and nature of the non-pumpable objects. Furthermore, there was significant uncertainty about the operational restrictions that would be assigned to in-tank remote systems, not to mention the intricacies of regulatory interpretation, final clean-up levels and the CERCLA process.

Figure 19- MLDUA



Safety concern was placed on maintaining containment integrity, and the potential for out-of-control automated systems to run amok and breach containment. There was also attention paid to the issue of operator fatigue and how disorientation could exacerbate it. Experience during the Fernald silo mapping campaign indicated that within the featureless interiors of the tanks, it was very easy to become disoriented during long duration operations.

Applications

POTS is first and foremost used to inform the human operator of the machine's location, pose, and configuration in the tank, from the vehicle, to the tools manipulated at the tip of the six-link arm. Overhead camera views are available that provide hands-free control of camera position. Interactions with the tank, its internal hardware, and waste surface, can be monitored, simulated, predicted, and, ultimately, automated. Tip and tilt on vehicle-based systems can be reported through POTS, thus allowing the vehicle to stay upright on uneven waste surfaces.

POTS is most useful when there is a dearth of data about the conditions of the waste and structural integrity of tanks or silos, and safety considerations lead to the need for predictive or automated control. It is also applicable to improvements in operator ergonomics productivity and control, and retrieval efficiency improvements for long-duration waste retrieval campaigns.

POTS measurements can be made with sufficient frequency (up to at least 100 Hz.) to determine the first modes of vibration for slender long-reach arms similar to the MLDUA shown in figure 14, as have at various times been proposed for use at Hanford. It can cover large overall volume to a high degree of accuracy, in a range consistent with the volumes of the largest radioactive storage tanks in the DOE complex. For long-reach applications, POTS is most applicable for long-reach (20-40 foot extension), heavy payload (200 pounds or more) applications where end-point position and vibration must be precisely controlled to less than one inch deviation.

POTS thus has broad applicability for below- and above-ground storage tanks containing radioactive, hazardous, or explosive materials, such as those at the Fernald, Oak Ridge, Savannah River and Hanford sites. By recording the actual operations and position of the robot in the tank, a high degree of precision is possible in the performance and documentation of waste retrieval, inspection and closure operations.

POTS enables automated graphics-based collision prediction algorithms to enhance the safety envelope by disallowing risky operations that could damage equipment or the tank walls. POTS can serve as the key link between graphical prediction and actual real-time in-tank events. Simulations can be used to evaluate operations plans for in-tank robotics applications, where the configuration of intermediate links and the shape of the retrieval end-effectors can then be checked for collisions with known objects and features of the tank.

POTS data can also be used as the springboard for implementation of automated routines for wall cleaning, waste retrieval and other contour following applications. With minor design enhancements, POTS could support additional tasks beyond the confines of tank interiors, such as outdoor automated vehicles and wireless (non-tethered) applications.

Integration with host system

POTS is not a stand-alone system but rather is intended to support the operation of other remote equipment. For a particular application, provision must be made to install and support the two pods, electronics enclosure, and controller. Detectors must be mounted on the vehicle such that they are in a fixed and precisely known configuration. The greater the fixed separation between detectors, the more successful POTS algorithms can be in pose determination.



Technology Applicability *Continued*

Electrical signals from the detectors must be conducted through the remote system's tether or harness, and the wires must be impedance-matched and shielded for noise immunity.

For instance, for integration with Houdini, a target box was developed and used as a convenient way to integrate or decouple the POTS detectors from its first intended 'host'. POTS cables are included in the tether and additional provision is made in the slip ring in the tether reel's hub to protect the detector's pulses from electrical interference. An area is provided in the operator control console for the POTS computer display.

With some further miniaturization, POTS detectors could be individually mounted at well separated locations. Each detector could be mounted in a small box no more than 2 inches per side, and could then also be mounted on reconfigurable components such as the links of the robot arm, with the integration of readily available real-time arm position data.

Competing Technology Alternatives

There is no applicable baseline technology comparable to the function provided by POTS. It was initiated to provide new and unique capabilities to enhance the operation and safety of remote systems for waste retrieval, both of long-reach arms and remote vehicles. From a technical perspective, POTS provides a combination of precision, range, and response time that is unavailable in any other tracking technology.

End-point tracking technology includes magnetic, optical, and laser based systems. Magnetic systems are robust and potentially inexpensive, but do not have a large enough operation range to cover an 80 foot diameter tank. The 'Polhemus' sensors used in head-mounted displays for virtual reality systems are an example of the typical range and accuracy obtainable.

Optical systems include position determination by the use of encoders, which can measure the angular travel of tracks or wheels in vehicle systems, or similarly, the motion of each link of a long-reach arm. The challenges associated with navigation by 'dead reckoning', or end-point control of slender arms, however, are significant, as previously described above. Another class of optical systems, visible light cameras, are available, though the software is complex, and systems are unreliable and less accurate.

Alternative laser-based navigation technologies are not sufficiently robust for high radiation environments, nor are they as accurate as POTS, which offers about an order of magnitude more precision. For instance, navigation systems for most mobile robot applications are landmark-based and optimized for 'on-board' intelligence and operation, whereas remote systems operate in featureless radioactive interiors, with the controls hardware removed from harsh environment. With only a few sensors required on-board, and most controls housed away from the tanks, POTS is optimized for this very specialized application area.

Patents, Commercialization and Sponsors

Patent 5748321 was awarded for POTS on May 5 1998 and was filed May 7 1996 [Reference 1]. Information concerning licensing of the POTS technology is available at ORNL. Please contact Joyce Shepherd at the ORNL technology transfer office at 423-576-2014.

POTS development has been funded by the cross-cut OST Robotics Technology Development Program (RTDP). POTS has been integrated with the Houdini™ Remotely Operating Vehicle, a commercially available product from RedZone Robotics in Pittsburgh, PA. RedZone also has a license for the existing GUI software to display POTS data, as developed during the CRADA.



The POTS equipment is presently at the ORNL and is potentially available for integration, and/or demonstration in support of upcoming EM-40 waste retrieval projects, though it is not completely field-ready at this time. To date, there have been no efforts made to develop business or commercialization plans. CRADA opportunities may exist for prospective commercialization partners willing to invest in the completion of the system and further engineering refinements.



SECTION 5

COST

POTS is a newly developed prototype system without any comparable cost or technical baseline. Being a prototype, the DOE's investment in the technology is not a good indicator of the replication costs for the system. A brief discussion of the replication costs and issues is presented below.

Its most important first application is to increase the safety envelope of remote in-tank operations. The replication costs of the current POTS design are about \$200K, which is a fairly sizable initial capital investment. However, since it is used in high-risk situations where the safety envelope must be increased, it is reasonable to compare that investment to the potential costs associated with a safety-related incident. We now discuss some scenarios relating to the cost-benefit of mitigating the risk of such incidents using POTS.

The financial consequences of a 'safety event', which POTS could mitigate, are clearly dependent on its severity, but they start high and increase proportionally thereafter. These could range from the minor to the highly significant- from breaking a tool, to in-tank equipment failures, contaminant release, to, worst of all, breaching containment integrity.

The first reaction to a safety event is an operational stand-down, which shuts down the process, resulting in significant downtime that can cost as much as on-going operations, as staff either wait at their stations to start work again or participate in safety reviews. Management and DOE oversight staff are also required, increasing costs. The stand-downs often last one to several weeks, and occasionally result in the project being terminated or completely redesigned. Operations costs at ORNL, for instance, are about \$25K/Day. Thus, avoiding a two-week stand-down will pay for the cost of a POTS installation, as ten days of operational downtime would cost \$250K.

The other major cost benefits of POTS are for automation applications and ergonomic improvements. Both ergonomic improvements to the operator interface and automation of routine tasks focus on the bottom line by improving productivity. For long-duration campaigns, which typically might take two years or more, small improvements in productivity can have a big impact on the overall duration of the campaign. For example, using the operational costs from ORNL, POTS pays for itself after two weeks of total schedule acceleration!

Since POTS has not yet been deployed, no data have been collected on the cost to operate it alongside the remote waste retrieval system it supports. The additional operational overhead is anticipated to be minimal, however, since the data collection and presentation are automated and a dedicated operator is not required. Some electrical power is required but the load demand is inconsequential, and thus the daily additional burden for POTS operation is essentially zero.

Other operational costs include installation, demobilization, and maintenance. Installation and calibration are required if it is deployed in multiple tanks for a waste retrieval campaign, or re-used at multiple projects. This requires skilled technical support at present, as well as Hazardous Waste Operators (HAZWOPERS) to install the pods, and rigging support to lower them into the tank or silo. Early installations might take a week or longer and involve several engineers, at a total cost of \$50K or more, though the specific requirements are not known at this time. This could subsequently be reduced with deployment experience, by streamlining the procedures and improving the technical process.

Life-cycle costs include the demobilization of the unit- extraction of the pods from the tank, decontamination and/or disposal of the pods, and beneficial re-use of the uncontaminated electronics enclosure. Most of the highest value equipment, such as the controls and display computers, can thus be re-used.



SECTION 6

REGULATORY / POLICY ISSUES

Regulatory Considerations

This technology is intended to support remediation activities as dictated by regulations such as CERCLA, RCRA or interagency or tri-partite agreements. Permitting processes are thus usually covered under the purview of the overall retrieval campaign. However, POTS does not add any new regulatory issues when used in such an application, as it does not contact the waste directly or add hazardous substances. As it replaces two hatches, it does serve as part of the containment for the tank or silo. A minor amount of secondary waste would be generated during pod installation, repair, and retrieval.

Safety and Risks

POTS improves the safety of potentially risky operations in the most difficult waste retrieval jobs. Its main purpose is to act as a risk mitigator by allowing the accurate operation of slender or vehicle-based manipulators, and the preview-simulation of tasks based upon measured real-time coordinates. Community perception up to this point has been minimal. However, this technology offers a convincing secondary control on the high-powered equipment introduced into the tanks and remotely manipulated by robots and their human operators during the execution of waste retrieval tasks.

The lasers used in POTS are class IIIb and thus require eye protection and administrative controls such as signs and barriers during system test and/or calibration in a laboratory. During system operation, eye safety is not an issue since there are no workers in the tank. Some radiation dose may be received by workers during system maintenance, though the pods are designed so they can be quickly retrieved for repair as required.



SECTION 7

LESSONS LEARNED

Implementation Considerations

POTS is most readily integrated with the Houdini waste retrieval robot, available from RedZone Robotics, as the Houdini tether and slip ring have been specifically designed to support POTS electrical signal requirements. Use of POTS with other remote systems beyond Houdini would require determination of locations and mounting details for the IR detectors and a method to pass well-shielded power and signal electrical conductors to them.

The current POTS prototype has been mechanically and electrically assembled and could be deployed with relatively minor additional work as described below.

Scanner calibration has been completed but requires further adjustment of parameters due to instabilities in the mathematical algorithm that computes calibration coefficients. These parameters are used to determine offsets from the real-world position to the system's frame of reference when measuring the four unit vectors. The routine performs well at one position, but is inconsistent in performance at various locations in the work space.

Algorithm convergence has been found to be dependent on the separation distance between the detectors. At short separation distances, POTS reports position accurately but fails to properly compute the vehicle's pose (or orientation). Both the calibration and orientation determination difficulties could be addressed by increasing the separation distance between the detectors in the target array, or splitting the target array detectors into individual housings mounted at long distances across the vehicle body. Smaller detectors are now commercially available, complete with signal conditioning electronics that are now mounted in the target array box.

In-tank calibration schemes would be required for a deployment of the current POTS hardware. Existing techniques that were previously used for the silo mapping project could be employed to provide basic functionality, though these require significant on-site engineering support.

To improve beyond basic operability of POTS, or to support collision detection and telerobotic automation applications, further improvements would be required and are now described.

Automated calibration methods have been conceptualized but have not been implemented. Integrating inclinometers on the target to assist in determination of the system calibration coefficients would be one approach to simplify this task. Off-the-shelf integrated IR sensor packages can be used to increase the separation distance of the target during system calibration. Integrating inclinometers in the pods could simplify the process of in-tank calibration.

Basic POTS data display is currently available, but further work is needed to complete an integrated 3-D modeler that can simulate, play back, or display in real time, the full pose of the Houdini vehicle along with the configuration of the dextrous manipulator and end-effectors in use. Commercial robot simulation software, such as the IGRIP package from Deneb, Inc, is available that can incorporate many of those features with some software integration effort. While IGRIP programming routines have already been developed to incorporate static data from POTS, a major effort would be required to integrate real-time POTS data for collision detection applications.

Long-reach arm applications and others needing a faster update rate than 20 Hz require improvements in both the scanners and detector circuitry. The simplest approach to improving the update frequency is to increase the rotation speed of the mirrors, which is possible with the currently available hardware, though it would also require further modifications to the electronic circuits to improve response time.



Implementation Considerations *Continued*

Commercially available products have been identified that support the faster update rates, though most of the electronic components and interconnections for the detector circuitry would have to be re-specified and re-manufactured to complete implementation.



Appendix A

References

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Appendix B

List of Abbreviations and Acronyms

ALARA	As Low As Reasonably Achievable
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
Ci	Curie
DOE	Department of Energy
EM-40	Environmental Management, Office of Environmental Restoration
EM-50	Office of Science and Technology
EPA	Environmental Protection Agency
FOR	Frame Of Reference
FY	Fiscal Year
GAAT	Gunite and Associated Tanks
GUI	Graphical User Interface
Hz	Hertz (Frequency)
IR	Infra-Red (light)
MLDUA	Modified Light Duty Utility Arm
NTF	North Tank Farm,
ORNL	Oak Ridge National Laboratory
OST	Office of Science and Technology
OU	Operable Unit
POTS	Position and Orientation Tracking System
RCRA	Resource Conservation and Recovery Act
ROA	Research Opportunity Announcement
ROV	Remotely Operated Vehicle
RPM	Revolutions Per Minute
RTDP	Robotics Technology Development Program
SNL	Sandia National Laboratory
UST	Underground Storage Tank
VAC	Volts Alternating Current

