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LONG RANGE POSITION AND ORIENTATION TRACKING SYSTEM*

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ABSTRACT

The long range Position and Orientation Tracking System is an active triangulation-based system that is being developed to track a target to a resolution of 6.35 mm (0.25 in.) and 0.009° (32.4 arcseconds) over a range of 13.72 m (45 ft.). The system update rate is currently set at 20 Hz but can be increased to 100 Hz or more. The tracking is accomplished by sweeping two pairs of orthogonal line lasers over infrared (IR) sensors spaced with known geometry with respect to one another on the target (the target being a rigid body attached to either a remote vehicle or a remote manipulator arm). The synchronization and data acquisition electronics correlates the time that an IR sensor has been hit by one of the four lasers and the angle of the respective mirror at the time of the hit. This information is combined with the known geometry of the IR sensors on the target to determine position and orientation of the target. This method has the advantage of allowing the target to be momentarily lost due to occlusions and then reacquired without having to return the target to a known reference point. The system also contains a camera with operator controlled lighting in each pod that allows the target to be continuously viewed from either pod, assuming their are no occlusions.

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I. INTRODUCTION

The long range Position and Orientation Tracking System (POTS) is being developed to support the remediation efforts of the Fernald K-65 Waste Silos at Fernald, Ohio and the underground storage tanks (USTs) on the Hanford site in Richland, Washington. Radiation levels in the tanks at both sites prevent remediation by manual techniques and therefore require the use of remote technology. The Hanford site is studying on the use of long-reach robotic arms for remediation while the Fernald site is planning to use a teleoperated tethered vehicle for remediation.

The long reach manipulator (LRM) concept includes a vertical mast with an approximately 10 m of horizontal reach and a total of up to 11 degrees of freedom with a lift capability of several hundred kg. The weight of the arm, the varying positions and configurations of the arm and the weights of the objects that the arm will be handling present an infinite number of end-point locations for the end-effector due to the arm dynamics. As a result of manipulator compliance, the anticipated error in the computed end-point position and the actual end-point is estimated to be up to 0.5 m. In addition to preventing the use of robotics, this presents a collision hazard that could cause damage to the tank walls, as well as the manipulator arm and retrieval tools. The POTS system could be used to provide real-time updates to the arm controller of the end-effector position and orientation in space.

The Fernald tethered vehicle will be designed for deployment through a 0.61 m (24 in.) manway in the dome of the storage tank. The vehicle will then fold out to an approximately 1.2 m by 1.5 m footprint and be deployed on top of the waste surface in the tank. As the sludge in the tanks exist in varying degrees of consistency there will be some slippage of the vehicle and the possibility that it can become partially submerged. Dead reckoning sensors on the vehicle will not be able to properly update the vehicle controller as to the vehicle position or orientation. The POTS system will be used to provide real-time updates to the vehicle operator on the vehicle's current position and orientation relative to the tank structure. Figure 1 below illustrates one POTS tracking system that will be deployed into a waste storage tank.

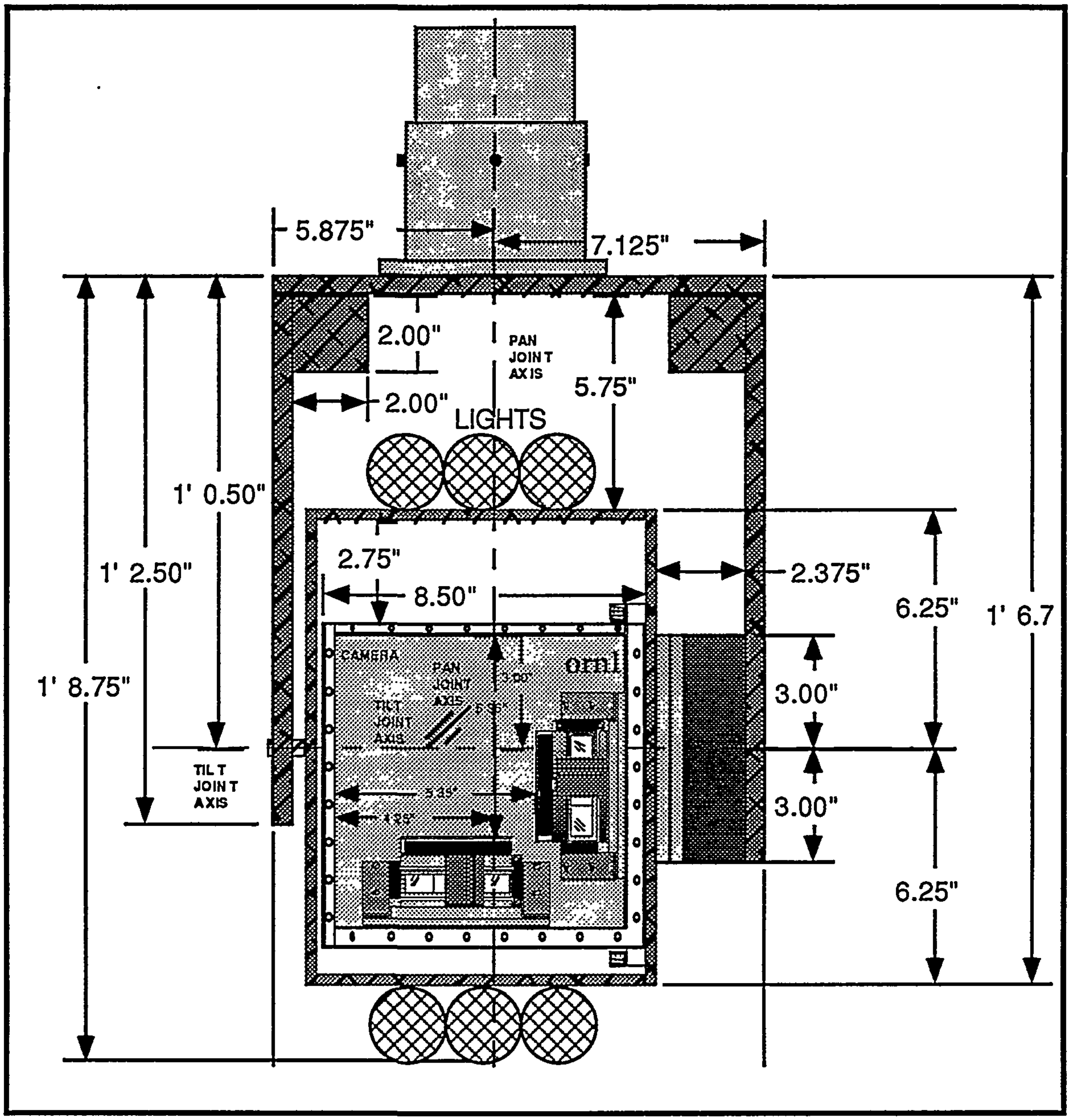

Fig. 1. Assembly drawing of one POTS tracking station.

II. SYSTEM DESCRIPTION

The POTS consists of two measurement pods, a VME-based computer system, synchronization and data acquisition electronics, an IR detector array, and a human machine interface (HMI). The pods have been designed to be mounted in the 0.356 m (14 in.) man-ways of the domes of a storage tank. Each pod has two laser scanner subsystems. One of the laser scanners will be oriented to scan in the pan direction, the other in the tilt direction. As the lasers scan across the IR detector array, the angles of incidence with each detector are recorded. Combining measurements from each of the four lasers yields sufficient data for a closed-form solution of the transform describing the location and orientation of the target. Redundant detectors will be placed on the target to accommodate occlusions, to provide improved measurement accuracy, and to determine the target orientation.

The performance requirements for the tethered vehicle used at Fernald are relatively low. However, in an effort to address the needs of other position and orientation tracking projects, the actual performance objectives of the system are being set much higher. Tracking performance goals are being set which will satisfy needs for dynamic control of an LRM. Accuracies of ±12.7 mm (±0.5 in.) and ±0.09° (±324 arcseconds) at a distance of 18.29 m (60 ft) are targeted, with an update rate of 100 Hz. These are ambitious objectives, but success for this system should result in a significant impact on the control of compliant LRM systems. The minimum performance needed for Fernald is ±50.8 mm (±2.0 in.) and an update rate of 15 Hz.

The laser scanner subsystem is used in conjunction with the optical detector subsystem to determine the direction of the target from each of the two pods mounted in the dome of the storage tank. Each scanner subsystem is used to determine either the pan or the tilt from the laser platform on the pod (or tracking station) to a optical sensor on the target. Each set of pan-and-tilt angles are combined to make a unit vector from the coordinate frame of reference of the pod that measured the two angles. By combining the unit vectors from two pods whose coordinate frames are known with respect to each other, POTS is able to determine range to the target by triangulation. By combining the measurements to three or more points on the target with the known geometry relative to one another, POTS can also determine the orientation of the target. The current laser scanners have an accuracy that has been consistently measured to less than 1 microsecond (which corresponds to an angular resolution of 32.4 arcseconds).

The source of the each laser beam will be an IR laser diode. The IR laser diode operates with an approximate power output of 35 milliwatts and a wavelength of approximately 830 nanometers, which is in the near IR region of the spectrum. The laser diode contains line generating optics that converts the spot laser into a line laser with a full angle of 45°. Mechanical alignment actuators have been custom designed by Oak Ridge National Laboratory (ORNL) to align the line laser with the scanning mirror.

The laser scanner sweeps a three-dimensional wedge that is 45° by 90°. The combined pan-and-tilt laser scanner wedges are shown in Fig. 2 below. To determine a detector's pan-and-tilt angle from the laser scanners, the detector must be simultaneously hit by the laser scanners. This requires the detector to be within the 45° by 45° work area depicted in Fig.1. At 15.24 m (50 ft) the work area will have a planer size of 12.62 m by 12.62 m (41.4 ft by 41.4 ft). The pan-and-tilt motion controllers on the pod will be used in conjunction with the data from the scanning system to keep the target centered in user definable region of interest with the 45° by 45° work area.

The optical detector subsystem is used to register hits from the laser scanner subsystems. Each time a laser is swept over an infrared detector a pulse is sent to the ORNL custom designed Field Programmable Gate Array (FPGA) based digital controller and data acquisition system. The infrared sensors have optical filters that only accept infrared light which allows the system to work in ambient light from the sun or from incandescent or fluorescent light sources. The pulse from the laser sweep is gaussian in nature. The transimpedance amplifier stage following the infrared sensor passes the gaussian pulse to a second amplification stage. The pulse is then fed to a peak detector to help in normalizing the registration of the gaussian pulse from the many possible angles of incidence.

The timestamps are correlated to the angle of the target relative to the laser scanner reference coordinate frame in each pod. At the beginning of each 90° laser scan, a digital counter is reset in the FPGA based digital controller by a reference pulse from the scanning mirror. This is used to insure that the mirror rotation and the counter are properly synchronized with respect to a mechanical reference mark on the front of the scanning mirror. The counter is used to correlate the time that the infrared detector is hit with the angle of the scanning mirror.

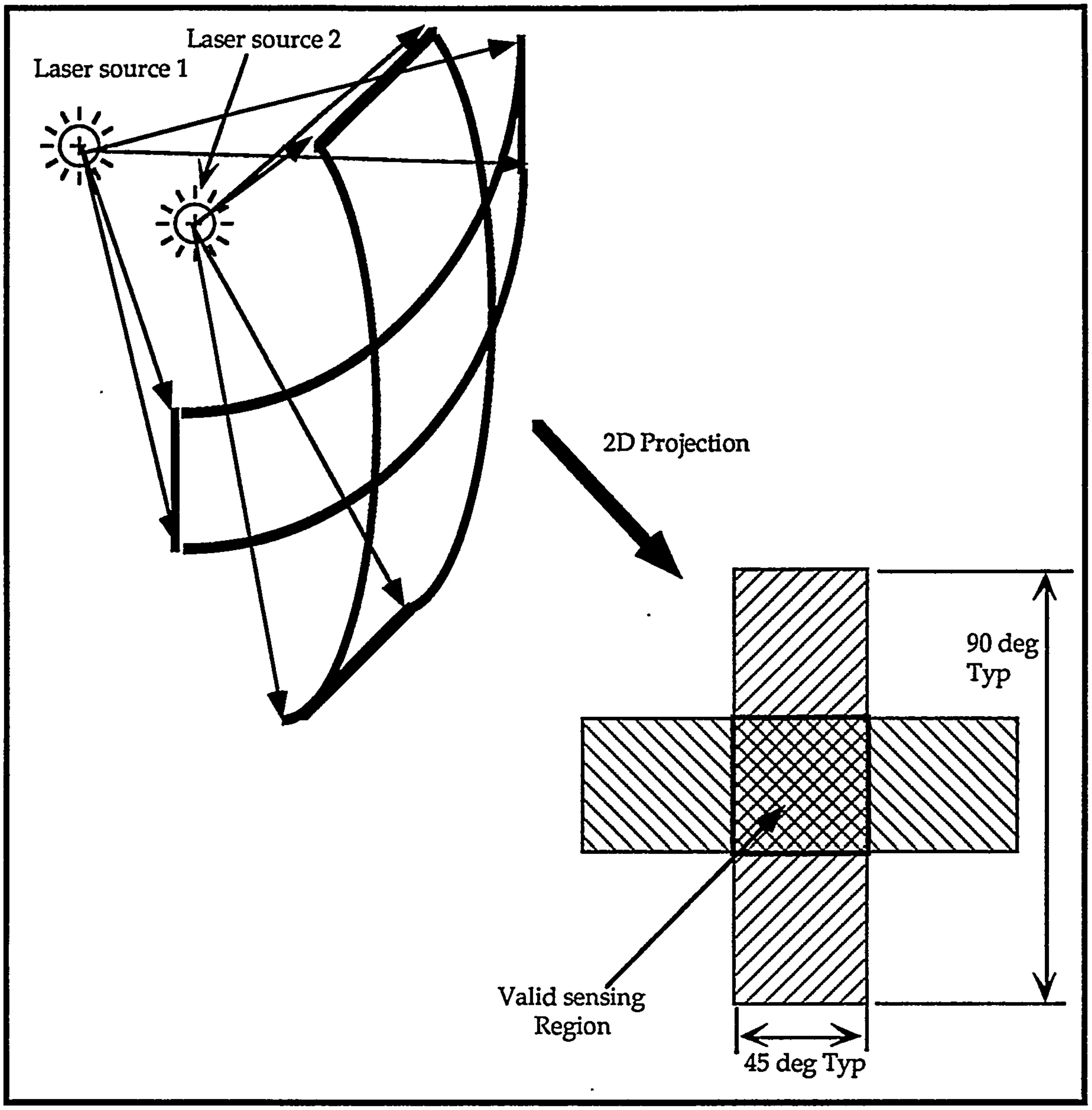

Fig. 2. Pan-and-tilt laser scanners work area.

III. ORIENTATION ALGORITHM

On the basis of quaternion algebra, the orientation of the target frame of reference with respect to the world frame can be determined by solving a low-order eigenvalue problem. The data requirements to this algorithm are simply the sensor locations with respect to the target frame and the measured sensor location with respect to the world frame. Occlusion of the sensors can be readily handled by this algorithm. The advantage of this type of formulation over other methods is that this scheme is numerically robust to sensor noise and at the same time has low computational requirements. The orientation algorithm determines the positions of the detectors on the vehicle by analyzing the vector addition problem geometrically depicted in Figs. 3 and 4.

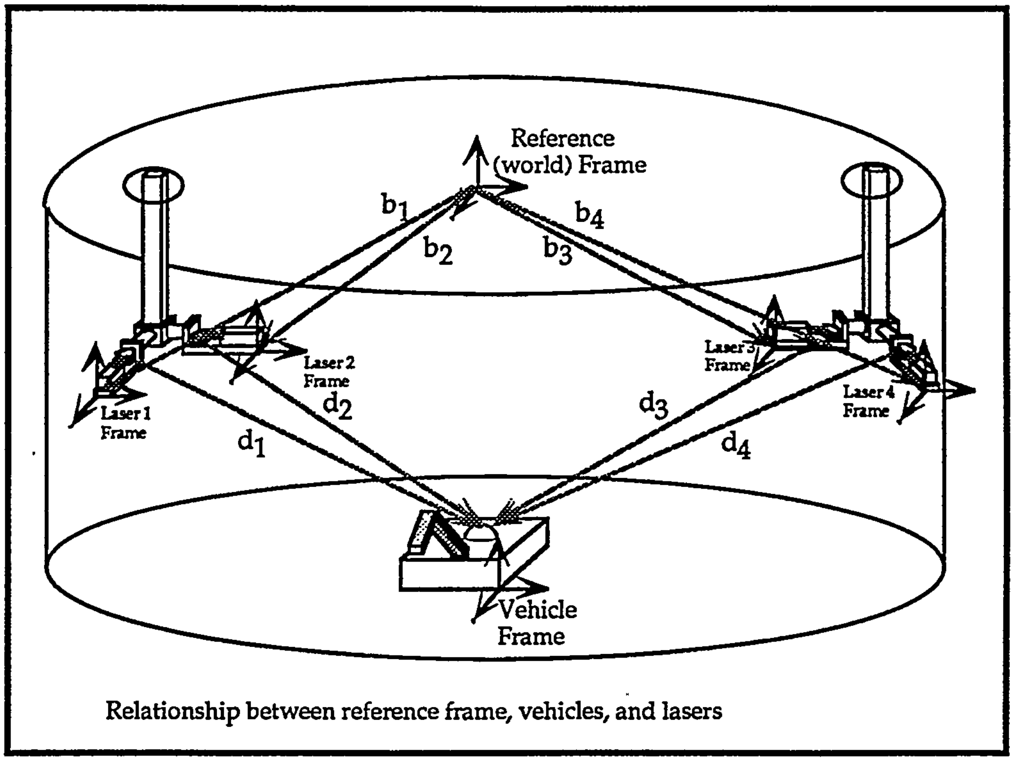

Fig. 3. Vector analysis of detector location.

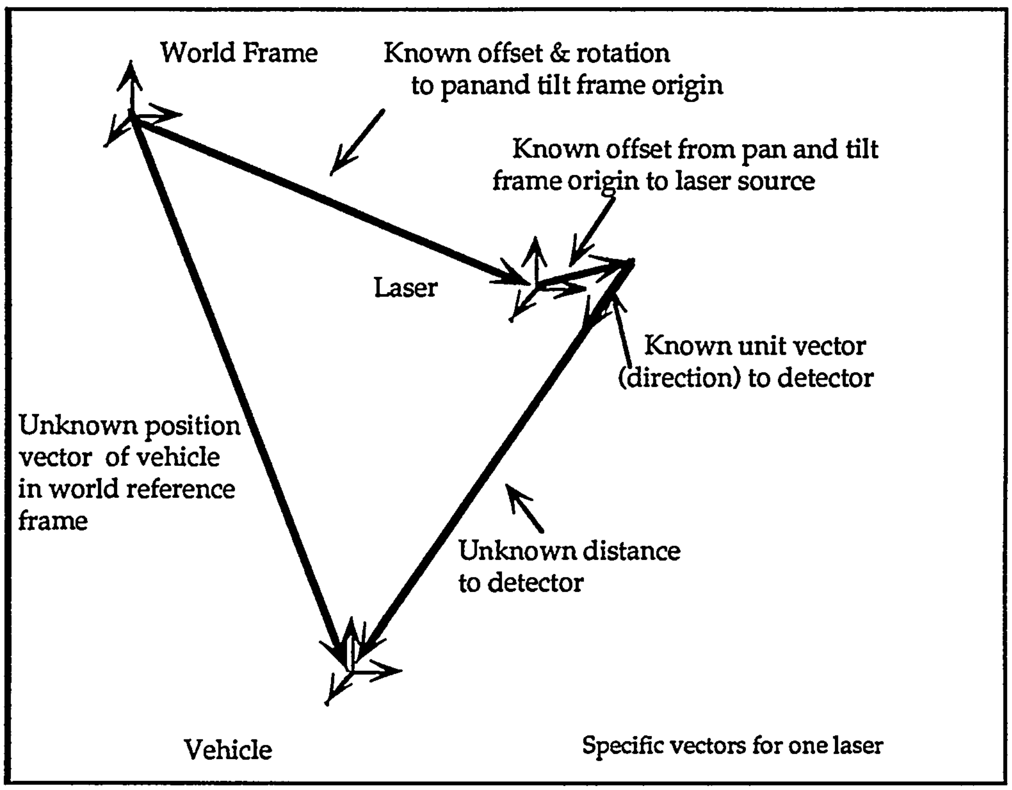

Fig. 4. Detector location determination by vector algebra.

IV. SYSTEM CALIBRATION

The purpose of system calibration is to correctly model geometric relationships that exist between various system components such that the results of the model match what is know to be true by means of measurements with NIST traceable calibrated instruments. These relationships are required in order to allow the tracking system to make accurate measurements. Some of these relationships describe the internal geometry of each pod, for example, and can be determined during the development phase of the project. The alignment of pods in the silo or tank is another aspect of the system calibration, however this geometry varies with installation. Hence the in-tank alignment must be determined after the pods have been placed in the silo. A method for determining the in-tank alignment has been previously developed by ORNL.[1] The technique involves placing small bulbs around the perimeter of the silo. The bulbs are then used to form a frame of reference for measurements. The geometric relationship between the bulb reference frame and the pods is determined by sighting on each bulb with a pod and then applying an iterative algorithm to solve for the pod's location. ORNL is also studying a second approach to in-tank alignment which involves placing IR sensors on each measurement pod.

The POTS system is currently being calibrated. A Pentax PTS-V5 theodolite which offers a resolution of 5 mm at a range from 1.3 m to 2900 m is being used to determine a stationary target's true position and orientation.[2] Internal offsets in the laser scanner model are currently being determined by comparing the <XYZ> from the system model with the <XYZ> positions from the theodolite and using the "Downhill Simplex Method in Multidimensions" routine to minimize the system error.

Once the linear parameters are determined to an error less than 6.35 mm (±0.25 in.) the four angles from each of the laser scanners can be used in real-time to find the <XYZ> point for each of the IR sensors. The position of the IR sensor is determined in space with respect to the world coordinate frame (WCF) by finding the intersection point of each plane of laser light at the IR sensor. The angle for the plane is determined from the time of the IR sensor hit and this provides the normal vector to the plane.

$$\text{normal vector to the plane} = \langle a, b, c \rangle \qquad (1)$$

The plane is defined in space by a normal vector and one point on the plane. The point on each plane is taken to be the intersection of the laser plane with the rotating mirror.

$$\text{intersection of the laser plane and the rotating mirror} = \langle x0, y0, z0 \rangle \qquad (2)$$

The inner product of the normal to the plane and any vector formed by the known point and any other point in the plane defines the equation of the plane.

$$\langle a, b, c \rangle^T \langle x-x0, y-y0, z-z0 \rangle = 0 \qquad (3)$$

By solving all four plane equations simultaneously you get the location of the IR sensor.

$$a1(x-x1) + b1(y-y1) + c1(z-z1) = 0 \qquad (4)$$
$$a2(x-x2) + b2(y-y2) + c2(z-z2) = 0 \qquad (5)$$
$$a3(x-x3) + b3(y-y3) + c3(z-z3) = 0 \qquad (6)$$
$$a4(x-x4) + b4(y-y4) + c1(z-z4) = 0 \qquad (7)$$

$$\begin{vmatrix} a1 & b1 & c1 \\ a2 & b2 & c2 \\ a3 & b3 & c3 \\ a4 & b4 & c4 \end{vmatrix} \begin{vmatrix} x \\ y \\ z \end{vmatrix} = \begin{vmatrix} k1 \\ k2 \\ k3 \end{vmatrix} \qquad (8)$$

The solution of the matrix equation 8 requires the inversion of a nonsquare matrix which is solved by the use of the Moore Penrose Pseudoinverse and QR decomposition.[3]

$$Ax=b \qquad (9)$$
$$x=(A^TA)^{-1} A^T b \qquad (10)$$
$$A=QR \qquad (11)$$

The R matrix is upper triangular and the Q matrix is orthogonal, such that

$$Q^TQ = I \qquad (12)$$

Substituting Eq. 11 into Eq. 10 produces the following,

$$x=(R^TQ^TQR)^{-1}R^TQ^Tb \qquad (13)$$
$$Rx=Q^Tb \qquad (14)$$

The result is then found by solving Q^Tb and then back solving for x.

V. SOFTWARE DESCRIPTION

The software has been written in the ANSI C programming language and developed on the Wind River Systems, Inc. VxWorks operating system and development environment. VxWorks is a UNIX-like, multitasking, single-user operating system that has been stream-lined by Wind River System, Inc. to operate real-time applications demanding high speed performance. The development environment consist of Sun Microsystems, Inc. SPARC II UNIX-based scientific and engineering workstation and a high performance VME-based computer system. The VxWorks package serves as a compliment to the development tools on the SPARC II during development and shall be the stand-alone target operating system for the final application. The target system is the VME-based computer, the VxWorks operating system, and the ORNL designed POTS controller. All graphical displays and user interfaces have been constructed with X11R4 window system graphics. The X11R4 window system is a public domain industry standard for UNIX-based scientific and engineering workstations graphics applications. The use of the industry standard ANSI C programming language, the VxWorks development environment, and the industry standard X11R4 windows system shall make the system portable to all Robotics Technology Development Programs (RTDP) projects and programs.

VI. HUMAN MACHINE INTERFACE

Local HMI graphically based interfaces have been supplied for the calibration routines initialization, diagnostic, debugging and the position and orientation routines. The POTS HMI shall be used to operate the POTS system in stand-alone mode for calibration, tuning, and testing purposes. The calibration HMI shall provide the operator with local control of the laser scanner and sensor subsystems for manual operation. The position and orientation HMI shall allow the operator to tune the algorithms. The graphics-based HMI has been built with the X11R4 library and the Open Windows toolkit library. The use of the X11R4 based graphical user interfaces shall insure that the graphics software can be ported to any UNIX-based scientific and engineering workstation. The POTS HMI is shown in Fig. 5.

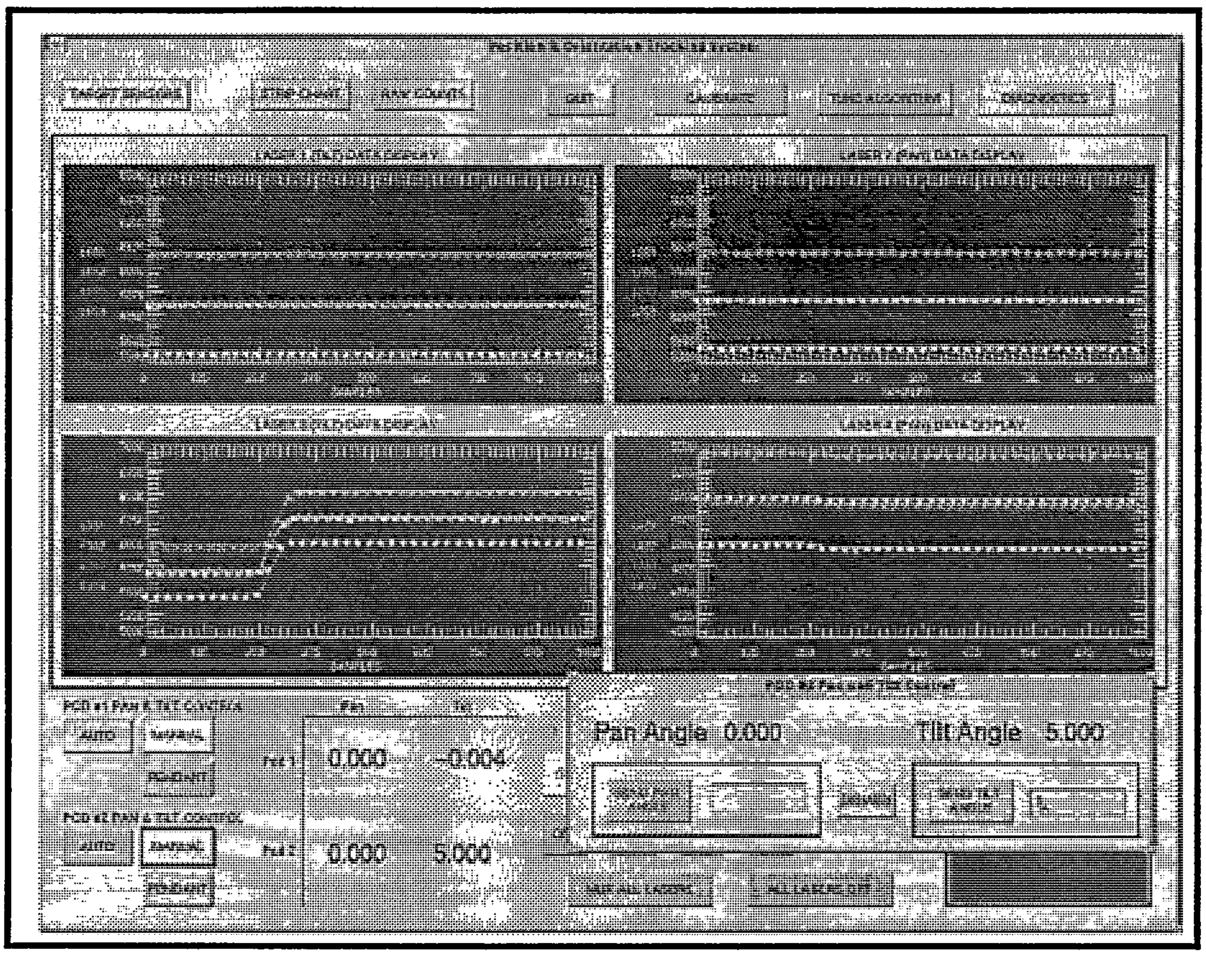

Fig. 5. POTS HMI Display

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