Neptune: *Above-Ground Storage Tank Inspection Robot System*

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I. Abstract

The *Neptune* system is a mobile robot system used to remotely inspect above-ground storage tanks (ASTs) while immersed in the petroleum product, in order to ascertain from the inside-out the state of corrosion of the floor and side-walls using video and ultrasonics, according to the guidelines laid out by the American Petroleum Institute (API). The robot system allows unmanned entry and sensor data collection in ASTs without the need to empty or clean the tanks nor the required human walk-through inspection which results in a very sparse data set from which the tank's state is statistically extrapolated. The complete system is comprised of (i) a specially designed robot crawler vehicle suitable for classified locations which carries visual and ultrasonic sensors, (ii) a deployment pod atop the tank to lower and retrieve the crawler, (iii) an in-tank acoustic positioning system to chart and control the location of the robot, and (iv) an external remote control console utilizing commercial and custom software for display, planning and control tasks. The crawler, pod and navigation systems are all designed for certification in hazardous environments, classified as Class I, Division 1, Group D by such agencies as the National Electric Code (NEC) [2] and the National Fire Protection Agency (NFPA) [1]. The system will be completed by the fall of 1994, demonstrated in a water tank, and then submitted to a certification agency such as Underwriters Laboratories (UL) or Factory Mutual Research Corporation (FM) for testing and certification. Initial tank inspections are anticipated to begin in the summer of 1995.

This article describes the design aspects of the system which is currently undergoing testing and evaluation. Emphasis is placed on the overall system configuration and the approach used to obtain certification for classified environments, and other newly developed and engineered mechanical and electrical solutions to meet the stringent environmental requirements of such an inspection task.

II. Introduction

The *Neptune* system was conceived in order to provide a more cost-effective and timely solution to the continuously required inspection of hard-to-reach areas of above-ground storage tanks - namely the floor plates and the first eight feet up the inside walls. Other robot systems [5],[6] are available to inspect the outside and inside of emptied tanks, while *Neptune* targets filled tanks. The required inspections are spelled out by the API inspection guideline standard 620 [3], which dictates the frequency, type and location of tank-inside inspections to determine the integrity of the tank in the face of corrosive processes.

- **Inspection Task Requirements**

The requirement for inspection stems from the need to monitor the corrosive processes present in single-shell steel above-ground storage tanks. These tanks are typically located inside of a lowered, membraned and diked area in order to retain all the tank contents in case of a tank rupture. The most common failure mode of an AST is that of stress corrosion along the weld seams of the steel plates, or the corrosive processes leading to pitting and even complete section loss. Most of the tank welds and surfaces that are subject to the elements are reachable from the outside, such as the walls and the dome. However, only external corrosion and weld areas can be inspected from the outside, while internal corrosion and the entire tank bottom can only be inspected from the inside. Current methods require that the tank be emptied, cleaned and vented before a human inspector can gain access into the tank and perform the inspection, yielding a sparse data set. This approach takes a tank out of commission for at least 2 weeks, which can be easily translated into a substantial monetary operational expenditure for the owner/operator of a tank farm. The *Neptune* system obviates the need for temporary emptying/cleanup of the tank since it can operate immersed in the product, while providing the

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inspection quality and improved data-density required by the API.

The *Neptune* system will be able to provide a visual record of each weld seam in the tank using an on-board color camera, as well as a thickness-contour map of the tank bottom plates using an ultrasonic thickness measurement sensor array. We are currently only targeting open-roof, floating roof and closed-roof tanks filled with such petroleum products as kerosene, gasoline, jet-fuel and other light-crude derivatives. However, the system will eventually also be able to service internal floating-roof tanks containing such products, as they represent 40% of all ASTs in the US petrochemical market.

- **Design for classified environments**

The biggest challenge to the system design was to conceive of a system able to remotely fit through the 20” to 36” diameter manway openings atop the tank, and to design such a system rated for these environments. The requirements spelled out by the NFPA, NEC, FM [4] and UL clearly state that the certification needed would be for Class I, Division 1, Group D, which implies (i) deployment in explosive petroleum gas or fume environments - Class I, (ii) operation in areas where the explosive product is present during normal operating conditions - Division 1, and (iii) the type of product that will be encountered typically rated by its ‘ease of explosion’ and expressed in terms of the compounds' auto-ignition temperature (AIT) - Group D.

There are four approaches to insure that a system can operate in such environments without causing an explosion. These are (i) intrinsically safe, (ii) purging, (iii) pressurization, and (iv) explosion-proofing. If one has a low-power system which would under no circumstances be able to ignite any gaseous mixture, the system can be termed ‘intrinsically safe’. A system requiring more energy and capable of igniting a gaseous mixture, can be housed in an enclosure and be continuously purged with fresh/inert air/gas at a specified pressure and flow rate - such a system (with the proper safeguards) can be termed a ‘purged system’. Should purging not be an option, an alternate approach would be to simply pressurize the enclosures to a pressure above that of ambient and monitor it - such a system can be termed a ‘pressurized system’. The most common approach in fixed installations and large moving equipment is to design enclosures which could withstand an internal explosion without igniting the surrounding gaseous mixture - such an approach is termed ‘explosion-proofing’.

In the case of the *Neptune* system, the explosion-proofing approach was not selected, as it would have resulted in an overly bulky and heavy system which could not have been made to fit through the manway nor crawl up the tank walls. The intrinsic-safety approach based on a purely electrical approach was not feasible as the necessary power required for sensors and locomotors (~500W) far exceeded established safety limits. Use of pneumatics and hydraulics as a power source for locomotion was also ruled out as the

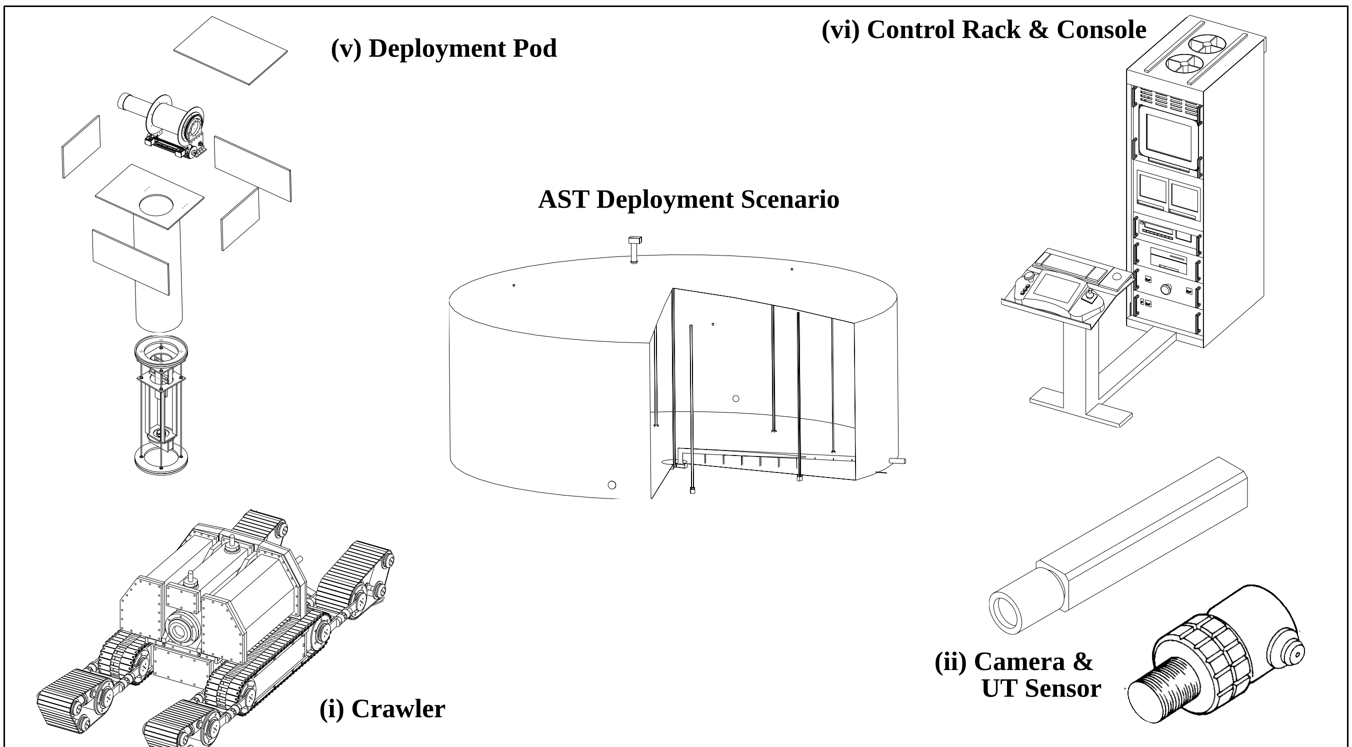

Figure 1 : *Neptune* system overview

necessary infrastructure outside the tank and on-board the robot would have been excessive, again leading to an overly bulky and heavy vehicle and tether system. The purging approach was also ruled out, because it would have required a fairly sizeable tether system (supply and return air lines) resulting in a very large and heavy tether management system atop the tank. The most viable alternative was that of pressurization. By providing a pressure differential w.r.t. the outside, the electronics and motor/sensor systems can operate under normal conditions internal to the enclosures. Using redundant temperature and pressure sensors and hardware and software safety backups, the system was designed to meet all of the regulations applicable for that class, division and group.

III. System Description

- **Overview**

The *Neptune* system consists of 6 separate entities which are depicted in Figure 1. These are (i) the robot crawler with its magnetically ‘switchable’ tracks, (ii) the on-board vision and ultrasonic (UT) sensors, (iii) the onboard control and telemetry system (not shown), (iv) the on-board and in-tank navigation system (not shown), (v) the deployment system atop the tank, and (vi) the remote operator console and the display and control software. Each of these subsystems is covered in detail in the sections to follow.

The robot crawler is deployed from its deployment pod atop the AST, and it navigates on the tank floor and walls using an OEM tank-internal acoustic positioning system (SHARPS from Marquest) [7]. On-board camera and UT sensors provide visual and steel-plate thickness feedback back to the operator. The system can operate in a teleoperated and a closed-loop fashion, which can be monitored using the synthetic bird’s eye view generated on the host computer’s graphics display which runs a commercial 3D graphics rendering software package (IGRIP from Deneb).

- **Robot Crawler**

The robot crawler shown in Figure 2 is made up of a set of anodized aluminum pressure-proof enclosures to house the controller-, power- and telemetry electronics, the UT-system electronics, and the camera and light system as well as the navigation transponders and their electronics.The track-driven locomotors are separate enclosures housing motors and transmissions which are connected to the rest of the system via a steel-braided teflon hose and connectors. The entire system can be pressurized and thus all volumes can be monitored with a single computer and redundant sensing systems. All interconnection wiring is run through the back end-plate holding all enclosures together. The tether system consists of a custom electro-optical cable (BIW) which is connected to the robot via a swivel connection to allow the robot to make sharp upward transitions without scuffing or bending the cable. The electro-optic umbilical consists of a single-mode fiber, redundant power conductor pairs and drains, all encased in impermeable filler and surrounded by braided Kevlar and a tough abrasion-resistant polymer coating. Custom electro-optic connectors (D.G. O’Brien) on either end of the cable insure easy maintenance and assembly in the field.

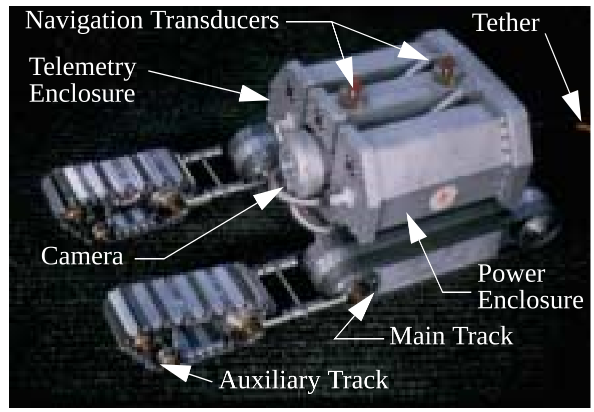

Figure 2 : *Neptune* in-tank crawler robot

The track locomotors consist of an internal in-line motor/ planetary system driving a pair of dual-output bevel gearbox shafts which in turn drive the sprockets that engage the tread (see Figure 2).

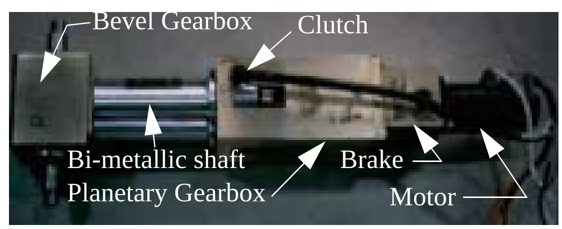

Figure 3 : Tread-drive and magnetic switching actuator

The actuator also has a bi-metallic clutch-actuated in-line concentric drive shaft which allows it to engage and disengage a permanent magnet circuit which takes advantage of a bi-metallic tread to magnetically attach the crawler to the steel plates. The principle is depicted in Figure 4, and is similar to that used in magnetic dial-gauge stands used on milling beds. A bi-metallic shaft can be turned in order to close/open a magnetic circuit, causing the magnetic flux to go around the magnet (no magnetic attraction) or through the resting surface (magnetic holding effect). By properly sizing the magnet shape, pole area and tread-piece cross-section, the desirable holding forces can be generated to allow the crawler to be fully supported on vertical and upside-down surfaces without the need for permanent magnets.

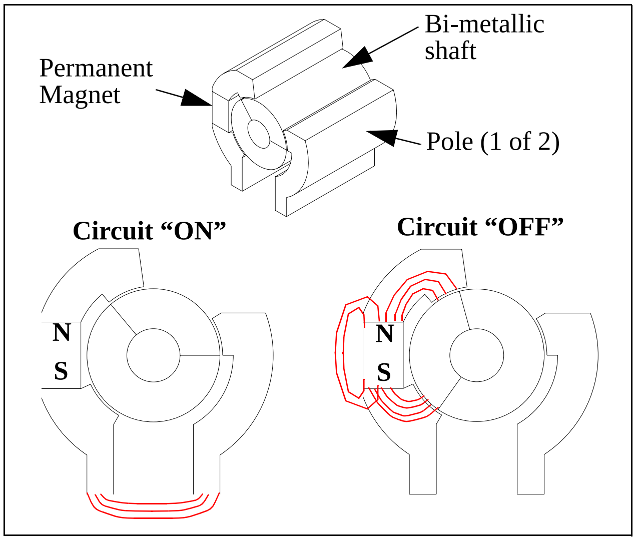

Figure 4 : 'Switchable' magnetic circuit principle

A set of auxiliary permanent magnet treads in the front of the crawler allow the crawler to make the transition from the floor onto vertical walls (Figure 2). The auxiliary tracks are passively hinged and are slaved to the locomotor drive sprockets. These auxiliary treads are used to ease and insure a successful transition despite surface conditions, varying friction properties and track shapes. The reason for not using permanent magnets on all the treads is based on the experience that they tend to attract all magnetic material they drive over, especially oxides (i.e. corrosion flakes!), eventually reducing their magnetic holding capacity. The presence of a 'switchable' magnetic tread also eases turning and maneuvering, which is known to be a problem in many tracked magnetic vehicles with aspect ratios (length/width) greater than unity.

- **Telemetry and Electronics**

The robot communication is accomplished using a proprietary custom-designed miniature computer-controlled single-mode fiber-optic telemetry system. A highly miniaturized dual- wavelength, single-mode fiber system was designed based on commercially available components and integrated on a custom PC board to fit inside the enclosures. The telemetry system operates with two separate lasers (1330 nm and 1550 nm), and is capable of a 1.6 Gbyte transmission rate, 4 fully bi-directional full-analog video channels, 4 bi-directional 19.6KBaud serial channels and 16 bi-directional channels of digital and analog I/O. The telemetry board system is integrated onto a microprocessor board for complete monitoring and switching purposes, as shown in Figure 4.

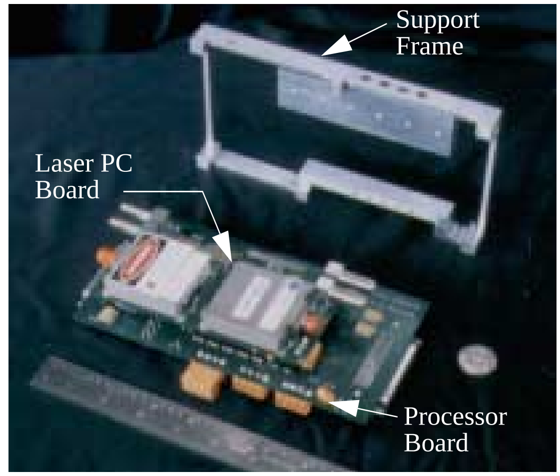

Figure 5 : Fiber-optic telemetry and micro-controller systems

The on-board microprocessor is based on the Motorola 68HC11 8-bit microprocessor monitoring the telemetry system and on-board sensors, while also controlling HP stepper motor-controller chips to drive the motors for the tracks. Communication to the control console is via dual asynchronous serial communications between the crawler and an identical topside micro-controller/telemetry system.The topside microprocessor communicates with the host computer via serial link. The host computer is a high-power Sun SPARC IPX computing and display engine to allow for operator display and planning and control functions.

The entire crawler runs on a 48 VDC power bus generated from 300VDC supplied through the tether. Other needed voltages are generated internally using DC-to-DC converters. All switching is done using solid state relays, namely for powering up/down the locomotors, cameras and other equipment. UT data and the camera video are directly transferred to the topside using the two dedicated analog video channels supplied as part of the telemetry system.

- **Sensors**

The sensor suite used on the crawler consists in part of a miniature color CCD camera (SONY) aided by a low-temperature set of tuned halogen or LED lights mounted on a custom-made PC-board, to illuminate the path in front of the vehicle to allow the teleoperated tracking of weld seams in clear fluids (alcohol to No.2 heating oil) (see Figure 9).

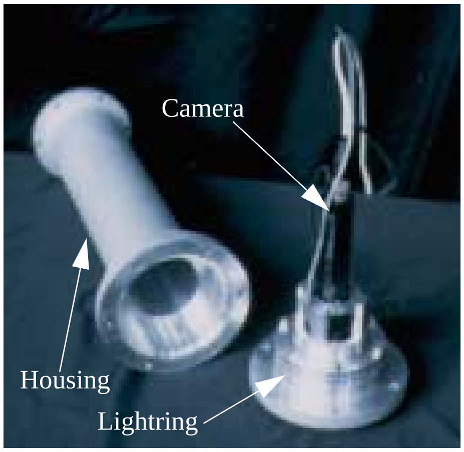

Figure 6 : *Neptune's* camera and light system

The ultrasonic measurement system, multiple-echo piezo-ceramic gauges working on the pulse-echo principle, is attached to the rear of the vehicle and consists of a set of two in-line transducers mounted on a towed self-levelling trolley. These transducers and their associated UT electronics are off-the-shelf components that were integrated into the system and will work in a wide variety of fluid viscosities (gasoline to filtered crude) (Figure 9).

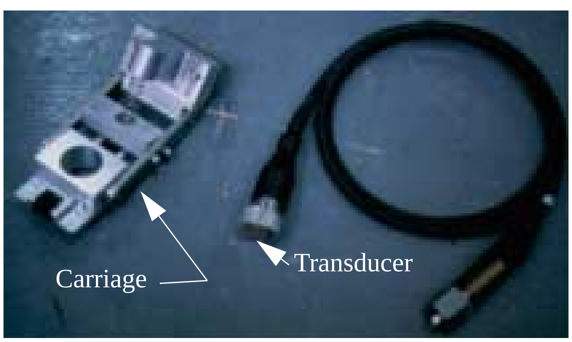

Figure 7 : UT sensor head and carriage

UT data and visual feedback will be continuously logged and stored for later retrieval and post-processing for analysis and reporting purposes.

- **Navigation System**

The navigation system is based on a modified commercially available acoustic positioning system, which uses time-of-flight of sound in liquids in order to triangulate the position of the transceivers mounted atop the robot crawler. The navigation net consists of (at least) three transducers, such as the one shown in Figure 9, hung into the tank from the tank-dome and immersed into the petroleum product.

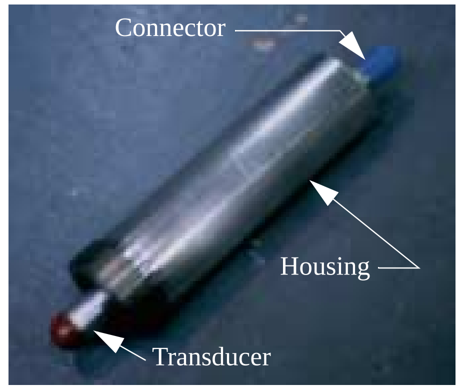

Figure 8 : *Neptune's* navigation net transponder

Their sound impulses are received and returned by the two transceivers atop the robot, allowing a topside computer system to triangulate the location of each transceiver, giving the operator and controller feedback as to the position and heading of the crawler within the net and thus within the tank. This position feedback is transmitted to the host computer to allow for display, planning and control functions of the crawler.

- **Connectors and Tether**

The tether was based on design principles prescribed by the NEC for 'extra-hard usage' temporary equipment. It thus represents a key component since it is the life-line that allows the use of temporary powered equipment in Class I environments. The tether was made with a petroleum resistant outer jacket, housing a single-mode fiber and 6 pairs of 16-ga. power conductors in a filled matrix strengthened through a Kevlar braid to allow a rating to 500 pounds continuous and 2,000 pounds breaking strength.

The connectors were custom-designed for us and rely on knowledge gained in underwater connectorization over the last 45 years. The innovation was that it was the first fully-rated hybrid single-mode fiber connector on the world market in 1993. The design is proprietary, yet copies or alternate designs can now be obtained commercially.

- **Deployment Pod**

The deployment pod consists of an aluminum structure which can be attached to the manway of a tank, holding the winch and deployment cage for the vehicle (see Figure 9). The winch system consists of a sealed and pressurized geared motor and control electronics system, driving a winch-drum and a slaved level-wind system to handle the 500 feet of electro-optic umbilical. A mercury power slipring and an optical slipring allow the transfer of power and data through the rotating cable drum. The tether passes through the deployment cage, which consists of a set of linear and rotary bearing stages to control the bending radius of the electro-optic tether and any cable scuffing on the inside of the tank's manway penetration. The entire deployment pod is sized to hold the entire robot/winch system for transport and subsequent installation atop a (typically 60 foot tall) AST using a crane. The winch drum and level-wind are sized to hold the full tether length with 5 full layer wraps. Much design effort has gone into the winch system as it represents another critical subsystem, seeing as it sits completely immersed in the vapor-zone of the tank's contents. Certified components such as the motor and the power slipring were used, while the pressurization scheme safeguards the motor and control electronics.

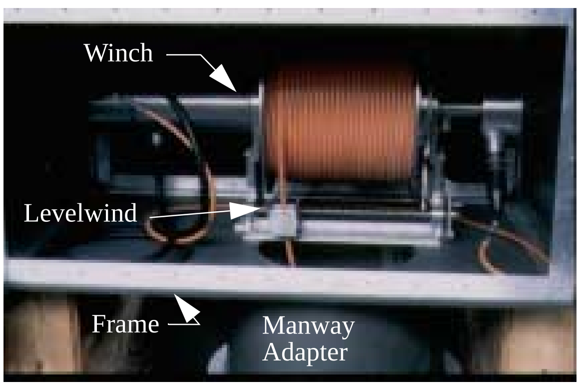

Figure 9 : *Neptune's* deployment pod system

The winch control electronics are also custom and are again based on the 68HC11 microprocessor. The winch motor is a stepper-motor controlled in speed-mode, with absolute position gathered through a battery-backed resolver and speed-to-position counter and memory chip system. Communications to and from the remote console are via a serial cable. Typically forward/reverse motions and the desired speed are the commands, and position/velocity and system pressure and temperature are the feedback to the console.

- **Control Console**

The control console consists of host-computer system, power conditioning system, TV monitors and telemetry interface system mounted into a 19" rack, with a remote portable control console housing the robot control joystick, the kill-button and a touch-screen display for remote control and display purposes.

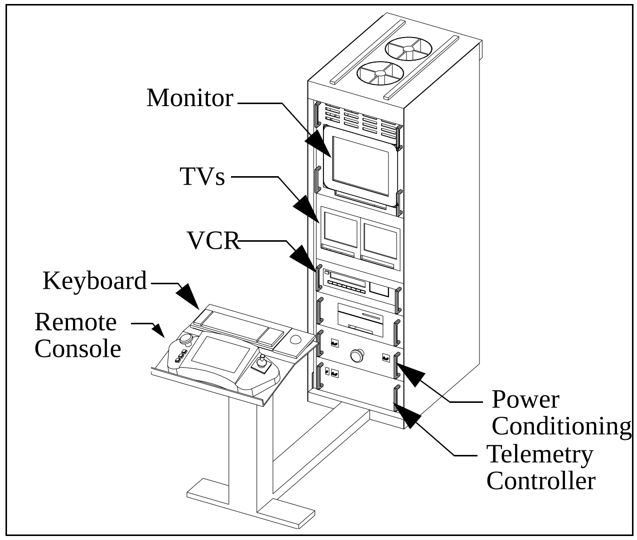

Figure 10 : Operator control station

The complete system is depicted in CAD in Figure 10, with the portable remote console shown in Figure 11.

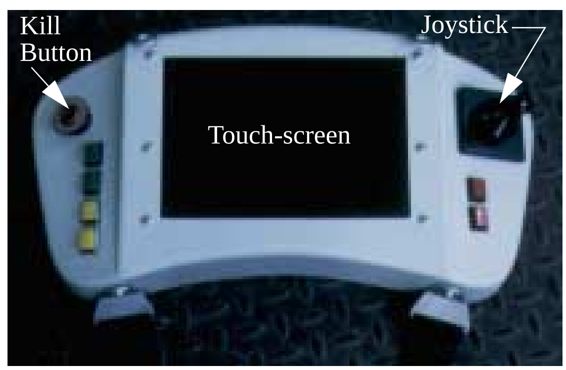

Figure 11 : Portable remote control console

The host computer is a SUN SPARC IPX system, which is used to drive the display, planning and control portions of the overall system. Custom planning and control software is integrated with a commercially available three-dimensional graphics rendering package in order to create a synthetic display of the robot inside the tank, while plotting desired and actual trajectories (see Figure 12). Views can be altered at will, giving the operator the ability to have a bird's eye view. Other information such as system temperature and pressure are monitored by the software and displayed in the form of gauges and sliders. Any anomalous condition is reported to the operator to allow immediate remedial action to be taken, such as shut-down or a systems check.

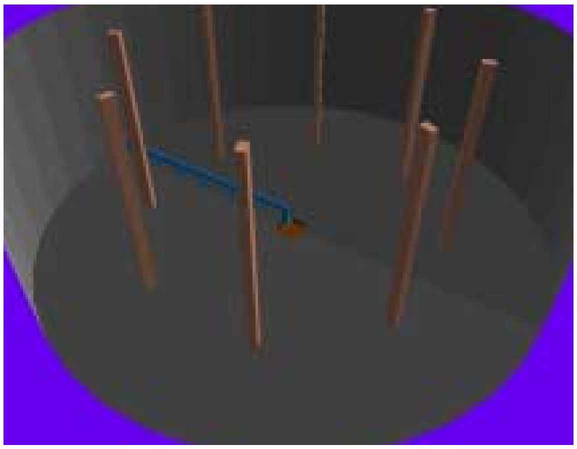

Figure 12 : *Neptune's* synthetic 3D AST display

The remote console is used to display critical information to and from the SUN host computer, should the operator not be sitting in front of the control rack. Eventually the post-processing and real-time display of steel-plate thicknesses could be displayed on the SUN monitor, but for now it is logged and processed on a separate IBM-based computer.

IV. Experimental Results

The *Neptune* system is currently undergoing testing in a water tank to test all seals, navigation, UT and video systems, as well as the locomotion on steel floor- and wall plates. Current results indicate that the system achieves a steady state operating temperature of $40^{o}C$ over a 10-hour operating period in $25^{o}C$ water. In addition, the frictional characteristics of the tread drive and alignment requirements has required some sprocket modifications. Overall the magnetic switching circuit operates properly with holding forces about 85% of calculated. The software is reliable and has been operating without interruption over the past weeks.

The *Neptune* system has been successfully demonstrated to the US Army Corps of Engineers and industry interests (Exxon, Shell, Mobil) in January of 1995 in a water tank in Paulsboro, NJ. Interest was strong enough to warrant pursuing certification for the prototype and continued demonstrations, while signing up manufacturing concerns to develop commercial prototypes of the system.

V. Agenda

We will engage a certification agency (such as FM or UL) for a multi-month certification process, after which *Neptune* will be used in the field to test and demonstrate its capabilities in real-life AST inspection tasks - probably as early as the fall of 1995. Once certified, an OEM equipment manufacturer will take over the commercial production of the system, and provide the robot system to the project's industrial partner to enable a completely new type of inspection capability in the petroleum tank inspection/service industry.

VI. Acknowledgments

This project is being sponsored by the US Army Corps of Engineers and Raytheon, Inc. under contract #DACA88-93-D-0004-0002. The author also wishes to acknowledge the contributions of Brian Albrecht in the area of the magnetic locomotor design, and Bryon Smith in the area of the telemetry and controller electronics design. The *Neptune* system has several patents pending in the U.S., Europe and Japan.

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