Neptune: Above-Ground Storage Tank Inspection Robot System

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Abstract

The Neptune *system is a mobile robot system used to remotely inspect above-ground storage tanks (ASTs) containing petroleum products.* Neptune *ascertains the state of corrosion of the floor and side-walls 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. The complete system is comprised of (i) a robot crawler vehicle suitable for classified locations which carries visual and ultrasonic sensors, (ii) a deployment pod atop the tank which lowers and retrieves 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 such hazardous environments, classified as Class I, Division 1, Group D.*

1. Introduction

The *Neptune* system was conceived to provide a more cost-effective and timely solution for the problem of inspecting hard-to-reach areas in ASTs - namely the floor plates and the first eight feet up the inside walls. These inspections are spelled out by the API inspection guideline standard 653 [2], which dictates the frequency, type and location of tank-inside inspections to determine the integrity of the tank in the face of corrosive processes.

1.1 Inspection Task Requirements

The need for periodic AST inspection is mainly due to the corrosive processes present in single-shell steel ASTs. These tanks are typically located inside 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. Thus only external corrosion and weld areas can be inspected with equipment available today [4], while internal corrosion and the entire tank bottom are currently inspected via human entry. These methods require that the tank be emptied, cleaned and vented [5] before a human inspector can gain access into the tank and perform the inspection with hand-held tools. This approach takes a tank out of commission for at least 2 weeks, resulting in a substantial operational loss for the owner/operator of a tank farm. The *Neptune* system obviates the need for temporary decommissioning of the tank, while providing the inspection data quality and statistically representative data density required by the API's standard 653 [2]. There certainly are pipe-crawlers ([7], [8]) and sewer-line inspection/cleanup systems ([9], °[10]) in operation today, but none have the combined capabilities *Neptune*, nor are they rated for the environments *Neptune* is targeted for: immersion in explosive petrochemical products. The only related system currently patented, relies on emptying the tank first and the use of human operators inside the tank for cleanup purposes [11].

The *Neptune* system will 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 steel-plate thickness measurement sensor array. We are currently only targeting open-, floating- and closed-roof tanks filled with such petroleum products as kerosene, gasoline, jet-fuel and other light-crude derivatives. However, the system will ultimately be able to also inspect internal floating-roof tanks which represent 40% of all ASTs in the US.

1.2 Design for classified environments

The biggest challenge for the system design was to conceive of a system able to remotely fit through the 20" to 36" diameter manway openings atop these tanks, and to insure it could be certified for operation in these environments. The requirements spelled out by the NFPA [1], NEC [3], FM and UL, clearly state that the certification needed would be for Class I, Division 1, Group D, which implies (i) deployment in flammable and combustible gas or fume environments - Class I, (ii) operation in areas where the flammable and combustible 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 main 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 pressurize the enclosure(s) 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 necessary infrastructure outside the tank and in-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 inside the enclosures. Using redundant temperature and

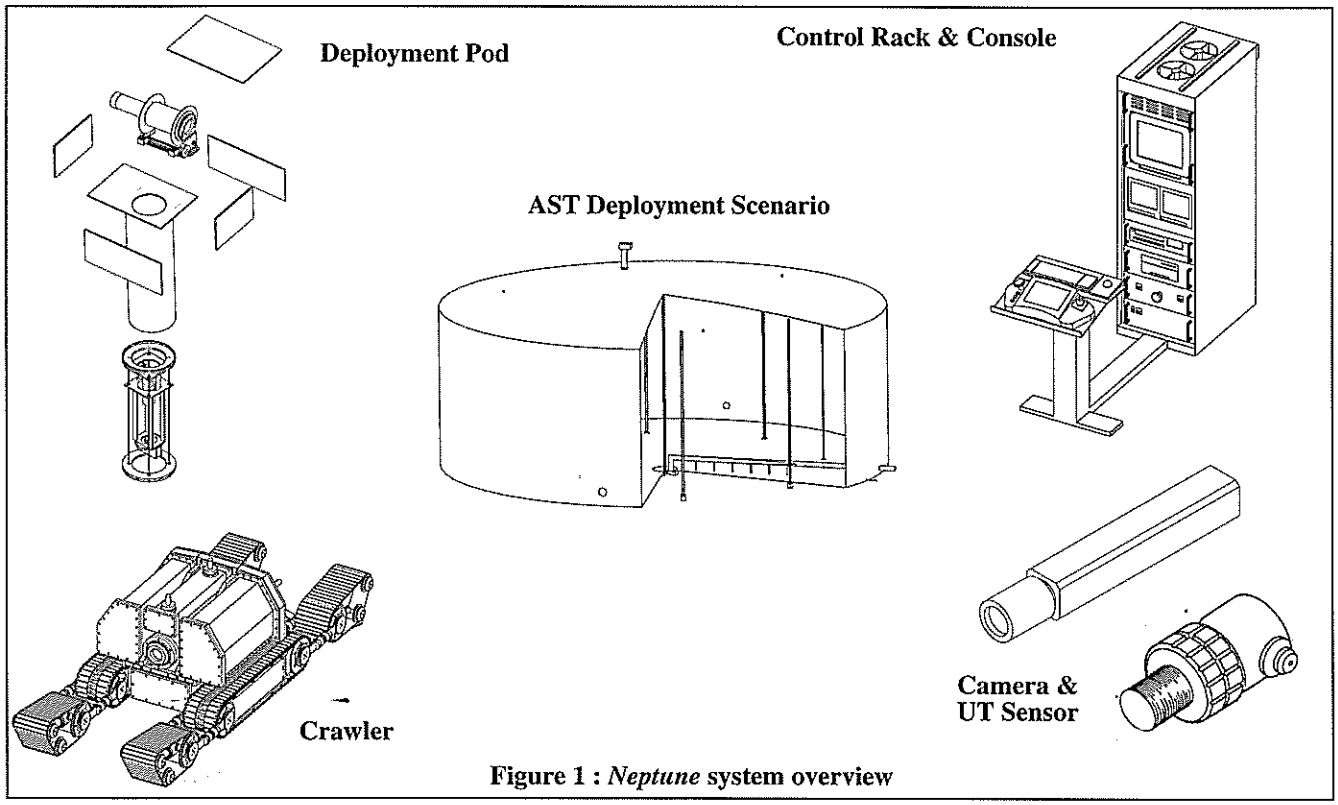


Figure 1 : *Neptune* system overview

pressure sensors and hardware and software safety backups, the system was designed to address all of the regulations applicable for that class, division and group.

2. System Description

2.1 Overview

The *Neptune* system consists of six separate entities, four of 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.

2.2 Deployment and Operation

The robot crawler is deployed from its deployment pod atop the AST, and it navigates on the tank floor and walls using a tank-internal acoustic positioning system. On-board camera and UT sensors provide visual and steel-plate thickness feedback/measurements back to the operator. The system can operate in teleoperated and computer-controlled closed-loop modes, which can be monitored using the synthetic bird's eye view generated on the host computer's graphics display using a commercial 3D rendering package (IGRIP™ in our case).

The system will be operated in teleoperated mode using a joystick console during deployment and retrieval. During the scanning phase on the tank floor/walls, the operator uses a mouse to pick a 4-sided polygon surface which the robot has to scan. The planner lays out the grid pattern and sends the desired trajectory to the execution module which brings the robot to the starting position and continues servoing the crawler position. The control strategy used on the crawler is to use PID crawler heading control to point the crawler back towards the desired path, with the treads controlled in simple velocity PID control mode.

The 3D graphics display is used to supervise the crawler's scanning operation. Embedded in the graphics software are routines that check for potential collisions and chafing of the tether along known tank obstacles (such as columns and pipes), using a simple n-dimensional quasi-static discrete chain model for the tether and then performing collision checking along its arc-length. Tether-payout is controlled using a closed-loop PID controller based on the known crawler position, a catenary tether model and a comparison to tether-length payed out. The operator is always able to override the closed-loop control for the crawler and the winch at any time in case of emergency or the desire to operate in teleoperated mode.

2.3 Robot Crawler

The robot crawler shown in Figure 2 comprises 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 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 light 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 on either end of the cable insure easy maintenance and assembly in the field.

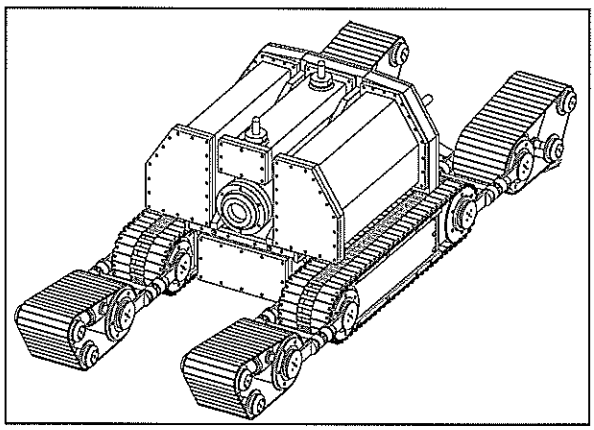


Figure 2 : *Neptune* in-tank crawler robot

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. 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 3, and is similar to that used in magnetic measurement stands 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).

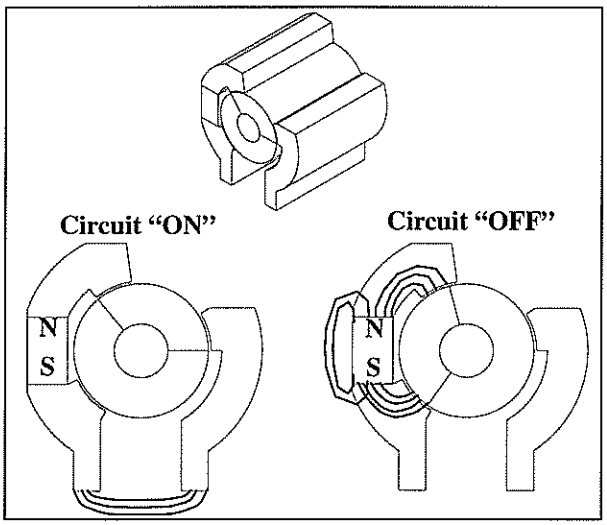


Figure 3 : 'Switchable' magnetic circuit

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 inverted surfaces.

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. 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.

2.4 Sensors

The sensors used on the crawler consists in part of a miniature color CCD camera aided by a low-temperature set of tuned halogen or LED lights to illuminate the path in front of the vehicle to allow the teleoperated tracking of weld seams. The ultrasonic measurement probe will be attached to the rear of the vehicle and will consist of a set of 8 in-line transducers mounted on a magnetic-wheel self-levelling trolley. The system is currently being designed using commercially available components and will be integrated onto the crawler by the end of the project. UT data and visual feedback will be continuously logged and stored for later retrieval and post-processing for analysis and reporting purposes.

2.5 Electronics and Telemetry

The telemetry system is a custom design developed at the Field Robotics Center (FRC). 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 is characterized by a 1.4 Gbit/sec transmission rate, two duplex 60MHz analog video channels, two duplex high-speed (10MHz) serial communication channels, and copious analog/digital I/O. A simplified system block diagram of the system architecture is shown in Figure 4.

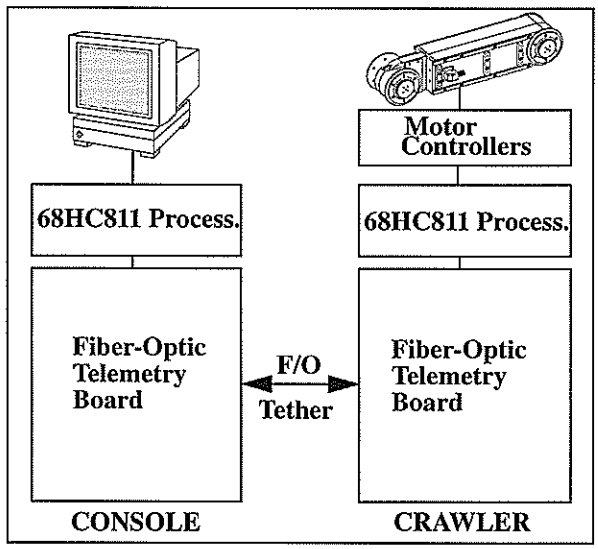


Figure 4 : Telemetry/Controller System Diagram

The on-board controller is based on the Motorola 68HC811 8-bit microprocessor monitoring the telemetry system and on-board sensors, while also controlling HP HCTL-1100 motor-controller chips to drive the motors for the track locomotors. Communications are via dual asynchronous serial lines between the crawler and an identical topside micro-controller/telemetry system. The topside microprocessor communicates with a host

computer via serial link. The host computer is a high-power 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 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.

2.6 Navigation System

The navigation system is based on a modified commercially available acoustic positioning system [6], 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 hung into the tank from the tank-dome and immersed into the petroleum product. 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.

2.7 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 5).

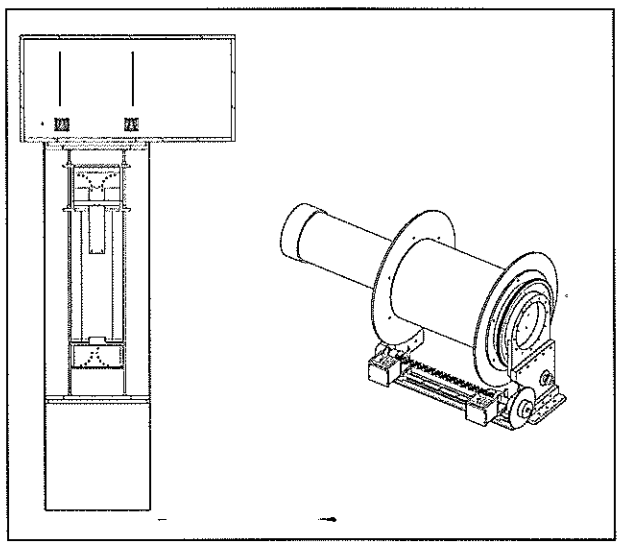


Figure 5 : Winch & deployment pod x-section

The winch system consists of a sealed and pressurized geared motor and control electronics system, driving a winch-drum and a slaved level-wind 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 thus avoid 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 monitored using an externally mounted TV camera and light system, peering through a plexiglass viewport mounted atop the deployment pod. 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 petroleum contents. Certified components such as the motor and the power slipring were used, while the pressurization scheme safeguards the control electronics.

The winch control electronics are custom-made and are also based on the 68HC811 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.

2.8 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. The complete system is depicted in Figure 6. The host computer is a Sun SPARC IPX CPU, which is used to drive the display, planning and control portions of the overall software. 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. Views can be altered at will, giving the operator the ability to have a bird's eye view. Other information such as temperature and pressure are monitored by the system 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.

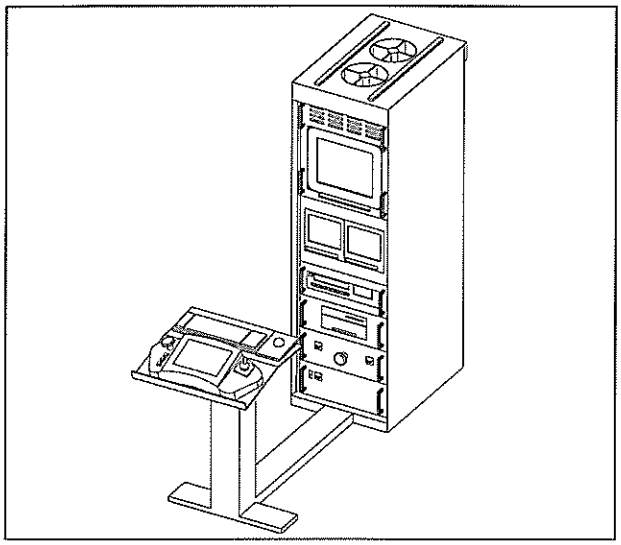


Figure 6 : Remote control console and rack

The remote console is used to display critical information to and from the SUN™ host computer, should the operator not be situated 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, yielding an operator display such as the one shown in Figure 7, showing robot position, plate thickness contours and elevation maps.

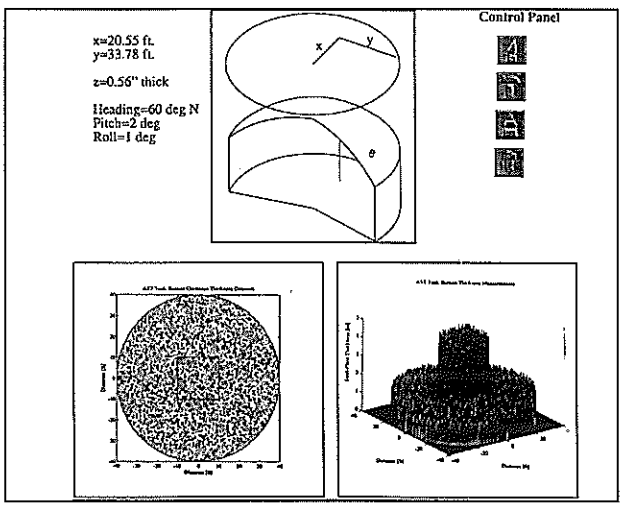


Figure 7 : *Neptune's* ultimate operator display

3. Agenda

The *Neptune* system is currently under construction, and is expected to be completed in the spring of 1994. After a demonstration to the project sponsors, the system will be delivered to a certification agency (such as FM or UL) for a multi-month certification process, after which it 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 1994. Once successful, a commercial partner will take over the commercial production of the system, and provide the robot system to the project's industrial partner allowing them to offer a completely new type of inspection capability in the petrochemical tank inspection/ service industry.

4. Acknowledgments

This project is being sponsored by the US Army Corps of Engineers and its industrial partner 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 patents pending in the U.S., Europe and Japan.

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