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ROBOTIC SYSTEMS FOR THE HIGH LEVEL WASTE TANK FARM REPLACEMENT PROJECT AT INEL

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ABSTRACT Westinghouse Idaho Nuclear Company (WINCO) is specifying and designing a new high level waste tank farm at the Idaho National Engineering Laboratory (INEL). The farm consists of four underground storage tanks, which replace the existing tanks. The new facility includes provisions for remote operations. One of the planned remote operations is robotic inspection of the tank from the interior and exterior. This paper describes the process used to design the robotic system for the inspection tasks.

INTRODUCTION

The new site is being specified to include four 1890 m3 (500,000 gal), 18.3 m (60 ft) diameter underground storage tanks. Each tank is housed in its own secondary containment vault and the entire facility is covered by a weather enclosure to facilitate maintenance operations. The tanks contain an acid solution used to dissolve nuclear fuel rods, making the environment radioactive and corrosive. The new facility design includes provisions for remote maintenance and inspection operations. RedZone Robotics, Inc. has undertaken the design of a robotic system to carry the inspection equipment. The design effort began with a parametric study and engineering analysis that evaluated the facility design and possible future inspection requirements. After taking these parameters into consideration, ideas for the robotic system were proposed and evaluated. The final design selection consists of two separate robots: a wheeled mobile robot for the tank interior, and a cylindrical gantry robot for the tank exterior. A formal design effort was initiated at RedZone following the parametric study and is currently 60% complete. The remainder of this paper describes the requirements, concept selection process, and final design.

INSPECTION REQUIREMENTS

The first task in this study was to identify the inspection tasks (or requirements) for the new tank farm. RedZone met with WINCO and the architectural engineering firm, ICF Kaiser Engineers to review project documentation and gain an understanding of the inspection process required for the new tanks.

The inspection of the new tanks is driven by a Resource Conservation and Recovery Act (RCRA) requirement to verify tank integrity. This verification is primarily accomplished by tank level monitoring and sump liquid detection. These sensing methods provide quick detection of large losses of tank contents through leaks, but slow seepage is more difficult to detect. Slow seepage is detected by checking tank integrity with a robot inspection system.

It was determined that visual inspection would be the primary method of inspection to detect slow seepage. Specific areas, such as welded areas are more likely to corrode than others. Visual inspection of the interior and exterior walls, coiling coils, and the tank dome is essential. If seepage is detected visually on a non-occluded tank surface, additional analysis with an ultrasonic transducer (UT) provides direct measurements of weld integrity and tank wall thickness. UT inspection of welds and surfaces is not planned as a routine inspection. However, UT inspection capability is a design requirement for the robotic system.

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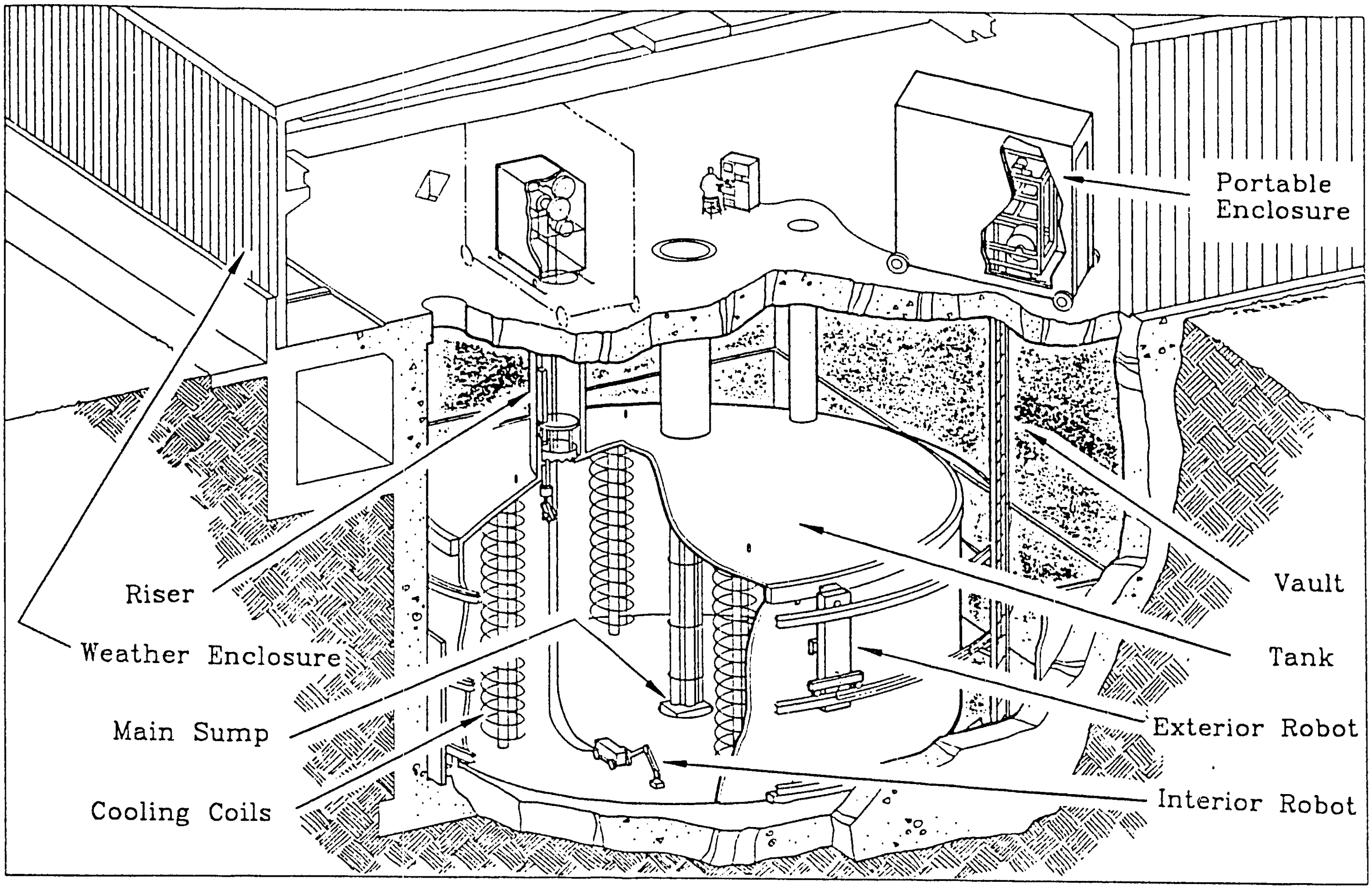

Figure 1: Tank Facility With Inspection Robots Installed

Washdown is also a required task. Surfaces must be adequately clean for the visual inspection system to function. Additional tasks may eventually include repair work on these surfaces.

TANK FACILITY PARAMETERS

A rendering of the tank facility is shown in Figure 1. Key features of the facility (for remote inspection) include:

- The **weather enclosure** provides protection from the elements, allowing year-round access to the tanks.
- The **portable enclosure** provides containment for remote operations. A manipulator and a small crane are permanently mounted inside. The inspection robots are deployed from this enclosure.
- Each tank is housed in an individual square **vault**. The four vaults are arranged in a square, with a sample cubicle located at the intersection of the vaults.
- Eleven **cooling coil** towers are located inside each tank. The cooling coils are obstacles to the robot and require visual inspection.
- The main **sump** is located at the center of each tank. The floor of the tank slopes down to the sump to ensure complete drainage. Additional sumps are located outside the tank in the vault.

Facility parameters, such as weather enclosure, inspection port size and location, and ceiling height, significantly influence the robot design. Through negotiations between robot and tank designers, the optimal facility parameters can be achieved. The final set of parameters is summarized in Table 1.

Table 1: Tank Farm Facility Parameters:

Parameter	Value
Tank Inner Diameter	18.3 m (60 ft)
Tank Height	7.3 m (24 ft) to roof bottom, 9.4 m (31 ft) to roof dome peak
Vault Size	20.7 m (68 ft) square
Tank Floor Slope	2 % down to sump
Tank Sump Region	0.9 - 1.2 m (3–4 ft) diameter at center
Exterior Inspection Ports	Two 0.9 m x 1.2 m (3 ft x 4 ft) ports
Exterior Inspection Port Locations	Opposite corners of vault
Bottom Knuckle Region - Exterior	0.9 m (3 ft) above base of tank
Internal Inspection Ports	Five 0.61 m (24 in) diameter ports
Internal Cooling Coils	11 towers total, each with 1.5 m (5 ft) diameter spiral coils
Minimum Weather Enclosure Ceiling Height	8.91 m (29 ft 3 in)
Portable enclosure exterior dimensions	6.1 m (20 ft) long x 3.4 m (11 ft) wide x 5.5 m (18 ft) high
Portable enclosure crane	1814 kg (2 ton) capacity, 3.4 m (11 ft) lift height
Exterior radiation level in the vault	4000 Rad/hr (tank full)
Interior radiation level	10 - 200 Rad/hr (tank empty)
Temperature	Tank contents are maintained at 7.2° - 35 °C (45 – 95°F)

Table 2: Robot Specifications:

Parameter	Specification
End Effector Positioning Accuracy	±0.025 m (1 in)
End Effector Positioning Repeatability	±0.0032 m (1/8 in)
End Effector Positioning Stability	$\pm 7.9 \times 10^{-4}$ m (1/32 in) with a settling time of 10 seconds
Speeds	Continuously variable between 0.025 and 0.051 m/s (0.1 and 2 ips)
Maximum Payload Weight	22.7 kg (50 lb) at tool mounting plate
End Effector Dimensions:	
High Res. Camera	Cylinder, 0.051 m (2 in.) diameter, 0.305 m (12 in.) length
Ultrasonic NDE	Cube, 0.152 x0.152 x 0.279 m (6 x 6 x 11 in)
Visual Feedback	Overview camera(s) sufficient to view robot and end effector in operation
Audio Feedback	Required from each robot
Power System	UPS with sufficient capacity to allow safe shutdown of the robot in event of power failure
Safety	• 5:1 safety factor for load bearing components • No single or multiple point failure may result in inadvertent contact with the tank with a contact pressure of greater than 34 kPa (5 psi) • Redundancy must be provided for recovery of the robot

Table 2: Robot Specifications, continued:

Parameter	Specification
System Life Span	50 years
Maintenance Periods	Annual, 5 year, 10 year
Number of Operators Required	1 Person
Operator Shift	4 hours
Exterior Robot Materials	To withstand *occasional* exposure to 6 molar oxalic acid 6 molar nitric acid Turco Cleaning Compound 4502 at temperatures to 71°C (160°F) and pressures to 138 kPa (20 psi)
Interior Robot Materials	To withstand exposure to 6 molar oxalic acid 6 molar nitric acid Turco Cleaning Compound 4502 at temperatures to 71°C (160°F) and pressures to 138 kPa (20 psi)

ROBOTIC SYSTEM SPECIFICATIONS

The system specifications are based on the inspection requirements and the tank facility design. The robot system specifications are summarized in Table 2.

CONCEPTS

Many ideas were considered during conceptual design, and three concepts were ultimately evaluated for the inspection tasks; a long reach manipulator, a cylindrical gantry type robot, and a mobile robot. In this section, each concept is described, and the evaluation criteria used to select the final concepts are outlined.

A. Long Reach Concept

The long reach concept is a telescoping boom deployment, used to position a multiple degree-of-freedom manipulator. The manipulator is used to position the end effector or payload.

The long reach arm is shown fully extended in Figure 2. At full extension, the deployment measures about 15.5 m (51 ft) from the weather enclosure floor to the manipulator's first pitch joint. The manipulator is capable of scanning a 2.7 m (9 ft) radius around the deployment point. The whole system is deployable through a .51 m (20 in) outer diameter riser. The stowed manipulator and vertical deployment are just under 6.1 m (20 ft) in length, allowing delivery by the overhead crane, but not by the portable enclosure crane.

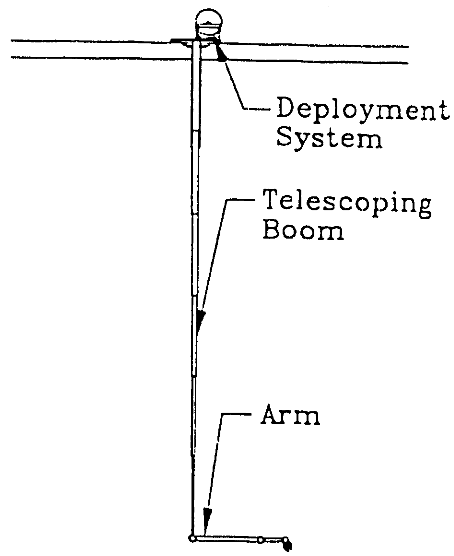

Figure 2: Long Reach Concept

B. Tracked Concept

Operation of the robotic system is simplified if the robot's motions closely match the motions required for inspection of the tank surface. Based on this idea, the track concept employs a cylindrical gantry-type system shown in Figure 3. Inside the vault, three horizontal rails run concentric to the tank at the top, center, and bottom. Vertical rails allow the robot to travel from one pair of horizontal rails to another, either the top and center, or the center and bottom. The robot scans the upper or lower half of the tank and can also move the end effector vertically and radially. The horizontal rails remain in the vault; all other equipment is deployed from the weather enclosure. This concept is tailored to the exterior requirements and is not capable of performing interior inspections.

Two deployments, one through each exterior inspection port, are necessary for scanning the tank to ensure that the robot can be pulled back to the deployment hatch by its tether in the event of a failure. The robot scans ±90° of the tank wall (i.e. one half of tank perimeter) in each deployment. For deploying the robot, there is a gap in each horizontal track under each inspection port. The robot is mounted to the deployment cart, which rides on the vertical rails and contains a small segment of horizontal track, fitting into the gap. The robot and deployment cart are guided into the vault until the rail segment is aligned with the vault rails. The robot drives onto the horizontal rails and begins inspection.

C. Mobile Vehicle Concept

The mobile vehicle is an alternate concept for performing inspection of the floor, primarily inside the tank. This concept provides the maximum coverage of the tank floor and is shown in Figure 4. This system has the UT and/or visual end effector mounted in its base, looking down at the floor. The vehicle examines a weld by driving over it. The robot is also equipped with a camera system to allow visual inspection of all the components on or near the base of the tank, such as cooling coils and/or the sump system. Other applications include inspection of the secondary containment floor and vault sumps on the exterior of the tank.

The deployment system for this concept is a winch-type mechanism, which lowers the robot through the penetration to the tank floor and

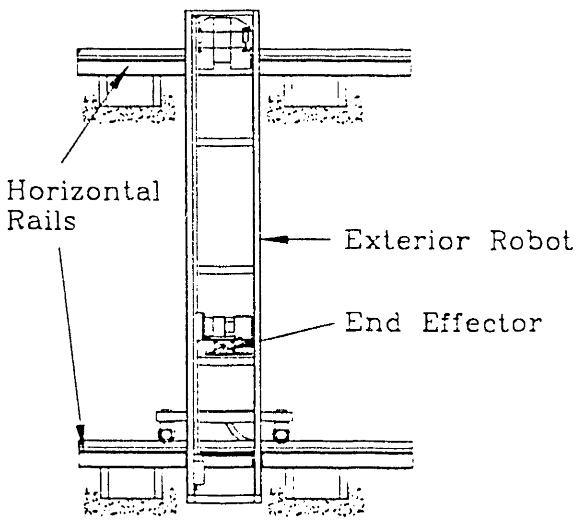

Figure 3: Tracked Concept

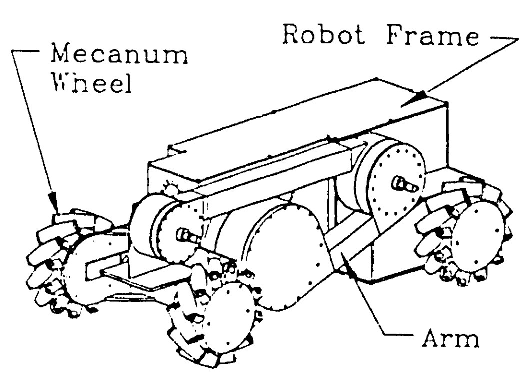

Figure 4: Mobile Vehicle Concept

Table 3: Concept Comparison on External Inspection Tasks:

Task	Need	LR	TS	MV
Visual inspection of external walls	Required	YES	YES	SOME
UT weld inspection of external walls	Required	YES	YES	NO
Visual inspection of secondary containment	Required	YES	YES	SOME
External surface weld repair	Potential	YES	YES	NO
External sump clearing/inspection	Potential	SOME	SOME	YES
LR = Long Reach	TS = Tracked System	MV = Mobile Vehicle		

Table 4 : Concept Comparison on Internal Inspection Tasks:

Task	Need	LR	TS	MV
Visual inspection	Required	SOME	N/A	YES
UT of welds on bottom of tank	Required	SOME	N/A	YES
Washdown bottom of tank	Required	YES	N/A	YES
Washdown internal walls	Required	YES	N/A	YES
Visual inspection of internal walls	Required	YES	N/A	YES
Visual inspection of cooling coils	Required	SOME	N/A	SOME
Internal sump inspection	Required	SOME	N/A	YES
Internal sump clearing	Required	SOME	N/A	YES
Visual inspection of internal dome	Potential	SOME	N/A	SOME
Retrieval of dropped objects	Potential	SOME	N/A	YES
Internal surface weld repair	Potential	SOME	N/A	SOME
Internal equipment repair	Potential	SOME	N/A	SOME
LR = Long Reach	TS = Tracked System	MV = Mobile Vehicle		

retracts it when the inspection is complete. The deployment system is also equipped to perform tank wash down and to monitor the robot's position.

EVALUATION

The three concepts are compared on the basis of inspection requirements, and other key characteristics used for evaluation. The inspection robots must be capable of performing all required tasks, and also as many potential tasks as possible. Tables 3 and 4 indicate whether a particular concept performs the inspection tasks fully, partially or not at all. In each table, "YES" indicates that the concept can meet the requirement, "SOME" indicates that the concept partially meets the requirement, and "NO" indicates that the concept does not meet the requirement. Note that the tracked system only applies to exterior inspection and is not considered for the interior.

A. System Considerations

In addition to the ability of the robot to meet the inspection requirements and specifications, other factors were considered in selecting the final concept. These factors influence the design, fabrication, operation, and maintenance of the system. A list of system considerations is presented below:

- Operating/human factors
- Safety/collision avoidance
- Decontaminability

- Retrievability (System must be recoverable from the tank under all circumstances).
- Maintenance
- Inspection area coverage
- Cabling (Cabling should be robust, protected and redundant or replaceable in the event of cable failure. Concepts that minimize cable bending and possible contamination are advantageous).
- Deployments per full tank inspection (Fewer deployments per inspection are preferable).
- Ease of deployment
- Accuracy/repeatability
- Payloads
- System complexity (Concepts which are less complex are easier to design, fabricate, operate, and service).
- System cost
- Speed of inspection (Systems that cover larger inspection areas per unit time are preferable).

Each of these considerations is examined in Table 5 with respect to the three concepts. Evaluating these selections is somewhat subjective, due to the nature of the design process. The rating system used assigns 1 to the best system for a given characteristic and 3 to the worst system.

Table 5: Concept Evaluation

Characteristic	LR	TS	MV
Operating/human factors	2	1	3
Safety	3	1	2
Decontaminability	2	1	3
Retrievability	1	2	2
Maintenance	2	1	2
Coverage	1	2	2
Cabling	2	3	1
Deployments per inspection	3	2	1
Ease of deployment	2	3	1
Accuracy/repeatability	2	1	2
Payload	3	1	2
System Complexity	3	2	1
Cost	3	2	1
Speed of inspection	3	1	2

LR = Long Reach | TS = Tracked System | MV = Mobile Vehicle

B. Conclusions:

External Inspection: In the exterior region between the tank and vault, the concept best suited to the inspection requirements is the tracked deployment system. This system provides equivalent inspection capabilities to the long reach system, but has some inherent advantages in operation, safety, accuracy and repeatability. In addition, the tracked concept is simpler to implement and operate than the long reach because it requires fewer degrees-of-freedom (3 versus 7). The resulting design is shown in Figure 3. The mechanical system consists of the following elements:

- The **Robot Assembly** carries the end effector that performs the inspection of the tank exterior and vault. Either visual or UT end effectors are used for the inspection. Other potential uses of the robot include retrieval of dropped items and tank repair.
- The **Storage/Deployment System** serves as a storage location for the system when not in use and provides the mechanism to deliver the robot from the weather enclosure floor down to the horizontal rails.
- The **In-Vault Equipment** consists of rails that the robot rides on during deployment and inspection.

Internal Inspection: In the tank interior, determining the best concept is more difficult. Because the requirements for internal inspection are not well defined and likely to evolve over the facility's life span, an adaptable system is the best selection. A mobile vehicle system provides the maximum coverage of the tank floor and is easily adaptable. The resulting design is shown in Figure 4, and consists of the following elements:

- The **Deployment system** delivers the position/washdown system and robot into the tank and serves as a storage location for the system when not in use.

- The **Position/washdown system** serves three functions. First, a spray nozzle mounted at the end of a telescoping boom allows tank washdown before the robot is lowered to the floor. Second, a positioning system automatically tracks the robot on the floor to provide accurate position information. Third, an overview camera mounted with the positioning system provides a view of the robot on the floor.

- The **Mobile robot** performs the inspection of the tank floor, wall, sump, and knuckle region. Inspection is accomplished using either visual or UT end effectors. The interior robot is also usable on the tank exterior for inspection of the secondary containment floor and vault sumps. Other potential uses include; retrieval of dropped items, sump or tank repair, or operations on other tanks, such as heel removal.

SUMMARY

This paper demonstrates the technique used to select a conceptual robot design. The basic sequence is:

A. Determine tasks

B. Determine constraints

C. Use tasks and constraints to develop specifications

D. Propose several potential concepts

E. Evaluate concepts against the specifications.

The detailed design of these robots is currently 60% complete.

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