Development of Remote Operated Vehicle Prototype for Dry Stainless Steel Storage Canister for Used Nuclear Fuel

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INTRODUCTION

Industry stakeholders including the Nuclear Regulatory Commission (NRC), National Laboratories (e.g., Los Alamos National Laboratory, Idaho National Laboratory, etc.), the Electric Power Research Institute (EPRI), Dry Canister Storage System (DCSS) manufacturers and nuclear power providers have performed evaluations that show that under certain conditions, the DCSS's used to store spent (used) nuclear fuel (SNF) are potentially susceptible to chloride-induced stress corrosion cracking.

Due to the lack of a permanent repository facility, DCSSs will need to be utilized for longer periods than their original licensed design life, at their existing independent spent fuel storage facilities (ISFSIs) or at an interim site. With this new time frame in mind, the NRC must license and renew licenses at these locations. To do so, the NRC will require that the facilities perform inspections according to codes and standards that are in process. Currently, there are no generally accepted (and preferable) audit protocols or aging canister management standards in place that account for current realities.

Robotic Technologies of Tennessee (RTT) and Tennessee Technological University (TTU) are working with these nuclear industry stakeholders to develop a miniature remote manipulation tool to support DCSS inspections. This work has resulted in a "proof of concept" ROV to performing NDE of DCSS's without removing the canisters from the surrounding concrete over pack. These devices must operate in the high temperature, high radiation environment of a DCSS. Anticipated temperatures may reach 80° C (176° F) and radiation doses may reach 1000 R/hr for the duration of the inspection, anticipated to last 10-20 hours or more.

Dry casks are typically constructed in a cylindrical shape with an inner steel canister directly storing the SNF assemblies that is bolted or welded closed, in an outer concrete cask. After loading with SNF, dry casks are stored outside vertically on a purpose-built concrete pad, or horizontally in a concrete storage bunker. An individual SNF storage cask can weigh more than 100 MT (220,000 pounds) and be more than 15 feet long and 6 feet outside diameter. There are more than 50 different types of dry casks produced by about a dozen manufacturers approved by NRC for general use in the United States.

DCSS's targeted for testing and/or examination include Areva's Nuclear HOrizontal Modular Storage (NUHOMS®) system, NAC's Magnastor® and Holtec's International's HI-STORM® system. These manufacturers generally have different models with slightly different configurations. This accounts for the majority of the variations. In addition, once placed in the field the canisters containing the spent nuclear fuel often lean to one side or another. In other words, there are many slight variations in the field that will need to be anticipated so that the ROVs are able to address these variations.

DESCRIPTION OF THE ACTUAL WORK

This project developed and tested a remotely-operated mobile robot scaled to fit the DCSS based on all-pneumatic adhesion systems. The device incorporated a failsafe retrieval strategy to ensure recapture and reuse of the robotic system. This device is referred to as the Miniature Suction Mobile Inspection Platform (M-SMIP). The M-SMIP is able to carry NDT payloads of up to 20 pounds and payload volumes of 60 in³ (not including camera and driving mechanisms which are embedded in body). Two NDE systems were incorporated into the system and included in the testing phase.

Working Principle

The underlying design principle is developed from work on skid-steer climbing robotic system that focus on high-mobility adaptive suspension systems that enables the suspension to achieve a high-range of deformation to allow the system to accommodate significant surface variations. Here, the suspension refers to the connecting mechanism between adhering forces or sealing members and the chassis. During operation, surface variations include obstacles on the climbing surface such as welds, transverse / longitudinal stiffeners, transitions between intersecting surfaces and traversing curved surfaces. This would include the ability to travel on concave and convex surfaces, over seam welds and navigate around support rails.

Description of Design Concept

An overview of the current proposed concept is provided here. The underlying concept is based on an adaptation of a miniature mobile climbing robot design for manufacturing tasks [1] with a fundamental transition from magnetic adhering force to suction adhering force. An overview of the prototype concept is shown in a CAD model in Figure 1. The designed system consists of a miniature mobile vehicle with wheel or endless-track type propulsion mechanism and uses suction to generate stabilizing forces while operating in climbing conditions. The suction is generated in a suction chamber through the use of a fan or pump. The suction chamber is relatively fixed to the vehicle chassis and moves with the vehicle chassis. A seal is created around the suction chamber through an adaptive sealing mechanism that spans the lateral sides of the vehicle to fully enclose the suction chamber. Thus, the suction chamber is maintained even as the mobile vehicle passes over significant geometry changes in the climbing surface, for example transitioning between surfaces that are orthogonally opposed. The adaptive sealing mechanism is constructed passive mechanism with built-in elasticity to maintain contact with the climbing surface. This allows the vacuum chamber to change shape as needed to accommodate changes in the climbing surface. It creates the need to seal between the links of the sealing mechanism, but this is more readily achieved since there is control over the material and surface finish of the links.

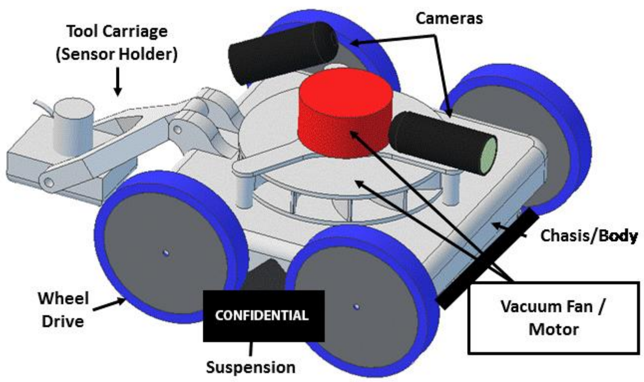

Figure 1: Overview of M-SMIP system

The M-SMIP consists of five primary parts as labeled in Fig. 1; the integrated chassis/body, the drive system (wheel drive), the surface-sealing suspension system, the vacuum plenum- rotor-drive motor, and tool carriage. Three primary drives are required, left/right drives and the compressor drive. Encoded inputs on the left-right drives are optional for automatic behaviors or kinematic feedback and were evaluated as part of the project. Operator feedback is provided primarily through one or more on-board camera (See Fig. 1).

Description of Design for manufacture and assembly
Of the five primary components, four (Integrated chassis/body, surface-sealing suspension system, and plenum rotor) are fabricated from ABS using a fused-deposition manufacturing tool. The relatively low stress conditions and resolution requirements of approximately 1 mm were met. The wheel drives and rotor drives are purchased components and relatively inexpensive. The camera and non-destructive inspection tools represented the majority cost of the system components. An alternative design to the onboard vacuum rotor and motor was tested and proved suitable, to place the vacuum outside of the tank and pull a small flexible tube to the M-SIMP, connect through a flange and produce vacuum in the M-SMIP vacuum chamber.

Description of how the system operates
The system is operated remotely through an operator interface with feedback kinematics. Here, the robot controller is placed in the operator control box located external to the tank. A control tether connects the robot to the external control box (see schematic of operator pendant, power, control box tether, robot). The tether contains drive inputs for the motors, camera and transducer feedback. These components are shown in Fig. 2. The tether is unified with protection sleeve and contains a light-weight tensile-carrying member to allow pulling on the cable for tether management.

The operation here considers a vertical storage tank with nominal four inch tall vent at the top of the compartment as generally shown in Fig. 2. The operator assembles the M-SMIP and places the mobile crawler with bridge through the upper vent portion. The operator pulls a mechanical cable to deploy the bridge at the separation point taken from video feedback. The operator then leaves the vent area to perform the task remotely. S/he will use the controller to drive the M-SMIP and can view the machine through on-board cameras or potentially a camera located at the vent entrance. Diagram 4 shows the M-SMIP traveling along a path defined by the operator to perform the task. The operator will use the visual feedback to identify key internal landmarks and then select an inspection path based on this initial planning stage. The M-SMIP is then driven to a series of vertical longitudinal runs along the inner cylinder and data is collected on wall thickness or visual observations during this procedure. During the vertical inspections along uniform sections of the cask, the M-SMIP operates in a semi-autonomous mode, maintaining constant speed, recording inspection data at fixed spatial intervals and watching for obstacles. This allows the operator to focus on the primary duty on supervising quality of inspection data and managing the robot during transition phases. The operator is also responsible for managing slack in the tether on an as-needed basis. The driving and inspection tasks can be conducted by a two-technician team as needed.

<u>Description of the task</u>
The inspection task is broken down into four primary tasks, (1) insertion/installation, (2) navigating surfaces, (3) inspection and (4) retrieval. These will be discussed in turn.

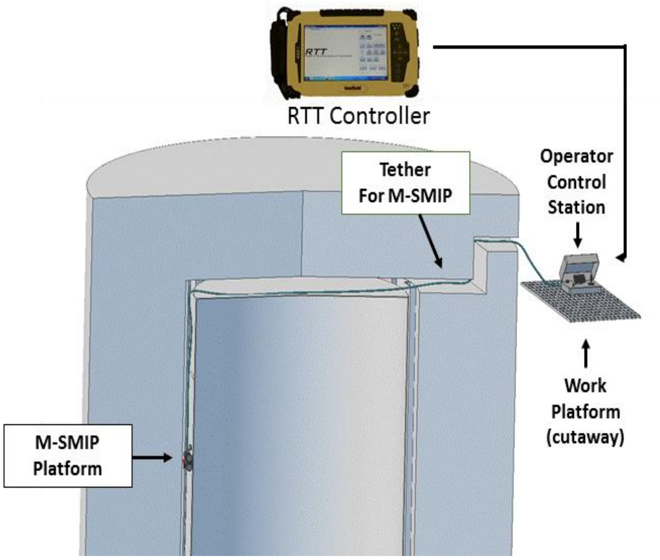

Figure 2: Cross sectional view of storage cask with representative M-SMIP deployed)

4.3.1 Insertion/installation: The insertion task is the first operation and involves placing the M-SMIP into the entry point of the tank (venting location) for navigation to the central operating location (top surface of the internal cylinder). The insertion operation is dependent on the specific structure of the DCSS and conditions. Samples of this are demonstrated in the field test section presented below. For more versatile installation tasks, the system employs a small bridge that is initially placed on the nose of the M-SMIP. This bridge is carried by the M-SMIP through the vent and released to provide a simple transition between the outer and inner cylinder walls. The bridge is released through a simple compliant linkage and is retrieved at the end of the task through a cable extending to the exterior of the cask.

4.3.2 Navigating surfaces: The second major task follows insertion and covers the primary traversal operations that occur throughout the inspection process. For vertical tanks, this traversal processes occurs on the top surface of the inner cylinder, along the vertical walls of the inner cylinder, and transitions between these vertical and top surfaces. The M-SMIP does its primary steering and or alignment along the top surface, and operates in a fairly linear fashion during the transition from horizontal to vertical surface, and during a vertical surface run. However, steering capability is retained in the M-SMIP at any time during its operation. The transition between the vertical and horizontal conditions are a key feature of this design and result from the suspension design that provides a high mobility sealing surface for the suction chamber over a wide range of surface geometries.

4.3.2(a) Steering: The M-SMIP is a skid-steer type mobile robotic (MR) system. This steering mechanism is well documented for climbing purposes by the proposers with specific models that consider simultaneously the design parameters, energy required to perform specific paths, and characterization parameters to provide accurate real-time estimates of robot position and orientation [2].

4.3.2(b) Surface transitions: The transition between the vertical and horizontal conditions are a key feature of this design and result from the suspension design that provides a high mobility sealing surface for the suction chamber over a wide range of surface geometries. Analytical models have been developed to consider further the contact forces during a transition state where contact forces between the robot and climbing surface provide a prediction of the total payload capacity and stability [3]. The operator is located remotely and operates the system primarily through video feedback. Therefore the transition operations and the adaptive characteristics of the M-SMIP operate in a passive mechanical fashion.

4.3.2(c) Tractive forces and Payload: The M-SMIP provides its primary adhering forces through vacuum pressure generated by an on-board fan, the robot chassis and a compliant seal created by the trackless suspension system Sample tests on the prototype M-SMIP demonstrate a tractive force of 50 lbs with corresponding payload of 20 lbs when operating on a dry to moderately damp steel surface with a machine weight of 5 lbs.

4.3.3 Conducting the inspection operation: Due to the radioactive environment, the coordination of the inspection operation with the M-SMIP will primarily be conducted by the remote operator with inspection data (response and feedback from transducers, video equipment) collected while the M-SMIP is driven along the tank surfaces. The flaw detector, recording equipment or other equipment is located external to the tank and allows real-time monitoring of this data. This allows the operator to determine if certain areas of the structure need to be revised during a typical outing. Cable management is also performed by the external remote operator. Cable management consists of two primary tasks: 1) providing sufficient cable into the tank or removing excess slack as needed and 2) visually observing the cable location relative to the M-SMIP during operation to avoid crossing the cable or indicating times needed for slack removal.

4.3.4 Equipment retrieval: Once the inspection operation is complete, the M-SMIP and associated inspection equipment is retrieved from the storage tank. The retrieval process is coordinated in a similar manner to the insertion process. Cable slack is removed, the M-SMIP is driven to the top of the inner cylinder and then moved over the transition bridge and up and out of the storage tank through the vent access used for entry. The transition bridge is removed mechanically with the attached cable.

4.3.5 Design for radioactive environment: The M-SMIP is designed to handle a range of humid, wet, muddy or dusty conditions. With respect to radioactivity protection measures, traditional remote operated systems are designed to have a long-term operational life through radiation hardening. The M-SMIP takes an alternative approach. The system is designed to be very small, lightweight and accommodate tight passage ways through creative chassis design. The majority of the M-SMIP mechanical portions are constructed using additive manufacturing of ABS or similar plastics. The on-board electronic portions are limited, and to the degree possible, are embedded in the plastic chassis components for extra protection. The 3D printed designs achieve 2 goals: 1) low-cost, easily reproduced designs made for as little as one use (one cask inspection), and 2) readily adapt design to changing cask conditions depending on manufacturer.

4.3.6 Range of NDT Sensor Technology: The initial fielded M-SMIP incorporates two inspection technologies:

- Eddy current. This technique is capable of detecting damage, including stress corrosion cracking (SCC). However, it is necessary to correlate the eddy current response to the damage present. This can be accomplished with the aid of a series of samples with known damage. Quest Integrity has experience using waveform analysis to correlate raw inspection data to surface integrity.
- Visual inspection through onboard camera

RESULTS

Two M-SMIP systems were developed and tested, with tests occurring first on mock-up storage cask with cutaway portions and then complete storage casks. The M-SMIP test systems retained primary aspects of the M-SMIP design described above, but one system was based on suction for generating adhering forces and the second used embedded permanent magnets for generating adhering forces. The tests were conducted in two stages, first on a mock-up of a representative DCSS device with cutaway portions, and then tests within complete storage casks. The first round of tests confirmed size, remote operation and transitioning between surfaces (horizontal to vertical, and back in multiple orientations to accommodate travel through different venting configurations). These tests included the 90 degree transitions when coning into a vent and transitioning to run down along the canister. The second round of tests were to evaluate performance under realistic conditions.

Summary of testing activities

Testing activities occurred during June 2015 through September 2015. A summary of the primary test results is provided here.

Tests on mock-up canisters with cutaway in vent region
The M-SMIP prototypes were tested first on a mock-up of the DCSS with a cross-section cutaway in the vent and vertical region. The cutaway allowed easy viewing of system during operation. The M-SMIP prototypes were then tested on a DCSS consisting of concreate overpack liner with vertical cask with the spent-fuel removed.
Evaluation of the Magnet-based M-SIMP:
The magnet-based M-SMIP ability to transition two ninety degree curves and traverse to the concrete overpack liner. It demonstrated good operator control, ability to maneuver to multiple locations within the liner and was readily returned to the vent for removal. The Magnet-based M-SMIP performed equally well in the cutaway mock-up and in the complete DCSS. Figure 3 shows testing of the magnet-based M-SMIP in the cutaway mockup while Figure 4 shows testing in the actual DCSS.

Figure 3: Magnet M-SMIP operating in cutaway mock-up

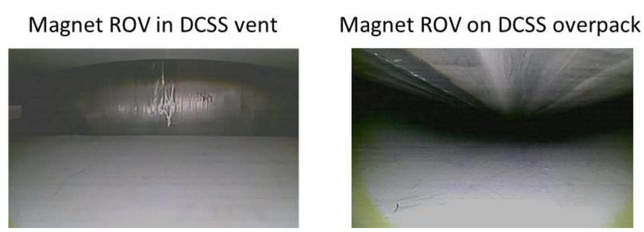

Figure 4: Magnet M-SMIP operating in actual DCSS

Evaluation of the Suction-based M-SIMP:
Suction M-SMIP transitioning succeeded in certain areas and revealed challenges in others. The Suction M-SMIP was able to successfully transition 90 degree corners on the mock-up cutaway (see Fig. 5), but failed to maneuver around two sharp 90 degree corners in the vent because the vacuum hose would bind on the sharp edges. It should be noted that the actual DCSS had two 90 degree corners in the vent while the mock-up only had one. This demonstrates variability that is expected in the different DCSS units. As a solution, the team created a “corner assist” device consisting of a small chamfer made from PVC inserted remotely to the first edge in the vent allowing the vacuum hose to easily slide over the edge. With this modification, the suction M-

SMIP was able to access and navigate along the liner of the overpack as shown in Fig. 6. Figures 4 and 6 demonstrate the view from the M-SMIP of the DCSS during an inspection.

Figure 5: Suction M-SMIP operating on cutaway mock-up

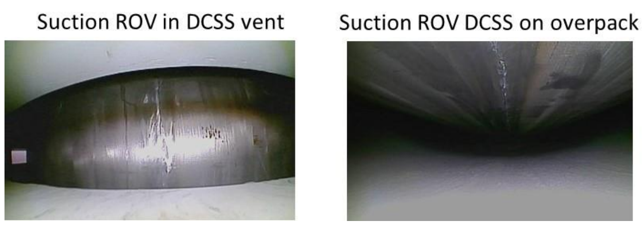

Figure 6: Suction M-SMIP operating in actual DCSS

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