ReTRIEVR, A LONG-REACH ROBOT FOR TANK OR SILO WASTE RETRIEVAL

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ABSTRACT

The ReTRIEVR acronym stands for REvolving Turret Reeled cable Incremental link Extending Vacuuming Robot. This long-reach slender robotic arm is being developed in support of waste removal activity at the US Department of Energy’s Fernald Site. ReTRIEVR is deployed from a gantry structure to break-up and vacuum waste from the Silo-3 site. Silo-3 is an 80-ft (24-m) diameter, 35-ft (10-m) high domed structure housing powdery, caked, or granular metal oxide waste byproducts from processing concentrated uranium ore in the early days of the U.S. nuclear program. The primary opening for retrieval activity is through a 20-inch (0.5-m) access hole in the center of the Silo-3 dome.

The ReTRIEVR (patent pending) robotic system comprises a segmented link-mast (~ 60-ft (18-m) long) with an industrial master-slave robot on the mast end. Each mast-link measures approximately 17 inches (0.4-m) in diameter by 10-ft (3-m) in length. A hinge along each link permits clamshell closure around the working cables. Adjacent links are joined by transverse hinge and actuator connecting pins. Active articulation is achieved by extending and retracting the hydraulic actuator. The end of the ReTRIEVR features a six degree-of-freedom, dexterous force feedback robot. The arm can hold and maneuver a vacuuming nozzle, and other tools that may be required to assist in waste retrieval.

Principle advantages of this approach are:

- The segmented, clamshell mast enables the system to be deployed and contained in a more compact structure than traditional long-reach arm designs.
- The hollow mast supports and protects the umbilical cables and the large (8inch) (20-cm) waste conveyance hose.
- The dexterous force-feedback arm can manipulate many common hand tools thereby enhancing the arm’s adaptability within the unstructured tank or silo environment.
BACKGROUND

Silo-3 is an 80-foot (24-m) diameter, 35-foot (10-m) high domed structure housing powdery, caked, or granular metal oxide waste byproducts from processing concentrated uranium ore in the early days of the U.S. nuclear program. Concerns for the integrity of the concrete structure have prompted efforts to remove the waste and package it for long-term storage. The ReTRIEVR team approach is to vacuum the material from the silo by extending an 8-inch vacuum hose through the 20-inch (0.5-m) opening in the center of the concrete dome. The vacuumed waste material is mixed with grout to produce environmentally stable logs suitable for burial. The delivery device for the vacuuming hose is the ReTRIEVR robotic manipulator developed by Framatome ANP, Inc.

One of the principal design considerations is to avoid or minimize any loading on the dome. To assure no dome loads, a radial clearance of 1-inch (2.54-cm) is required between any ReTRIEVR component and the circumference of the access port. Thus, the effective opening available to the ReTRIEVR robotic arm and the 8-inch (0.2-m) hose is a maximum of 18-inches (0.4-m) in diameter.

Additional ReTRIEVR requirements are:

- To be able to break up compacted and potentially saturated material
- To retrieve miscellaneous debris with up to 20-lbs. lateral force, and 100-lbs. vertical dead lift.
- To vacuum all interior surfaces for removal of visible waste material
- To apply spray fixative to all interior surfaces following the vacuum cleaning.

The DOE has a history of using long-reach robotic arms to remove waste material from tanks and silos. The Gunite tank initiative is one of the better-publicized campaigns. This system relied on the SPAR LDUA. A separate hose-management manipulator was required for this task because the SPAR arm did not have a working channel through its center and there was no room for a hose on the outside of the arm (1). The Grey Pilgram EMMA arm does have a central working channel through the arm, however this approach requires a tall enclosure to support the full length of the arm above the point of entry (2). The Framatome ANP ReTRIEVR arm mitigates or eliminates both of these concerns.

DESIGN DESCRIPTION

The ReTRIEVR system consists of major hardware components as shown in Figure 1. Each of these components is discussed individually.

Mast and Links

The Mast consists of up to 7 link segments - each approximately 17 inches (0.4-m) in diameter. The first two segments are one-piece cylindrical links approximately 5 feet (1.5-m) long. Since the first two segments will always be attached to the Kraft arm, it is more important to build a lighter link than to add complexity and weight associated with the clamshell capability of the remainder of the links. The rest of the links are 10-feet (3-m) long and can be installed by closing the two clamshell halves around the hose and umbilical lines running through the center of the mast (2). The first two clamshell links (nearest the Kraft Robot) are thinner-wall and have smaller hydraulic actuators to minimize the weight on the extended portion of the mast. The upper-most clamshell links are heavier to support the fully extended system. The average weight of each clamshell segment is less than 500 lbs. inclusive of actuators, umbilical

Fig. 2. Link assembly showing clamshell closure feature permitting installation around cables and hoses running through mast center.
cables, hoses, fluid and waste. Each link is hinged along one side in a piano-hinge arrangement and secured closed with a series of captured screws down the other side. This permits the segments to be opened for assembly around the conveyance system tube and the hydraulic and electrical umbilical lines for all lower components.

Adjacent links are attached to each other with a pivot pin on one half and a hydraulic actuator on the other clamshell half. Each mast segment can be articulated relative to the next by up to 45 degrees using the appropriate hydraulic actuator. The hydraulic hose umbilical contains connection points, appropriately spaced along its length, so that each extension segment can be connected as it is added to the assembly. The links have an alignment groove along the full axial length to engage with the turret and provide circumferential positioning registration. The mast is raised and lowered by a winch and held in place with the turret clamp. The upper-most link has a safety collar above the turret clamp to preclude dropping the link through the clamp and into the tank. The safety collar must be in place whenever the turret clamp is opened to assure redundant protection from inadvertently dropping the Mast into the silo.

**Dexterous Hydraulic Arm**

The arm is a Kraft Telerobtics, commercial grade RAPTOR arm with a force-feedback master and a custom forearm to facilitate passage through the insertion sleeve. The arm has a reach of 72 inches (1.8-m), weighs 160 pounds, and has a lift capacity of 200 pounds (3) (Table I). The arm joints are encoded by potentiometers and can be programmed to follow a predetermined path.

<table>
<thead>
<tr>
<th>Manipulator Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degrees of freedom</td>
</tr>
<tr>
<td>Maximum reach</td>
</tr>
<tr>
<td>Lift capacity</td>
</tr>
<tr>
<td>Jaw closure force</td>
</tr>
<tr>
<td>Wrist torque</td>
</tr>
<tr>
<td>Weight in air</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hydraulic Power Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating pressure</td>
</tr>
<tr>
<td>Flow requirement</td>
</tr>
<tr>
<td>Filtration</td>
</tr>
</tbody>
</table>

**Waste Retrieval Nozzle**

The waste retrieval nozzle is mounted to the side of the Raptor arm gripper (See Figure 4) with an actuated sliding attachment. This permits relatively unrestricted operation with the wrist and gripper assembly pointed straight or to the left. Some wrist yaw motion range is sacrificed when the yaw joint is rotated toward the hose. Normally the vacuum-nozzle will extend slightly beyond the gripper for mining activity. If, however, the gripper is needed to break-up clumps, retrieve debris, or to carry other end effectors, such as a tool for loosening compacted material, or the fixative spray tool, the vacuum-nozzle can be retracted to a less obtrusive position.

The vacuum nozzle is designed to introduce the waste material into the vacuum conveyance hose. A screen mesh is attached to the opening to keep large debris out of the waste stream. The nozzle also features a carbureted design that assures a mixture of air and waste is introduced to the hose and minimizes the possibility of clogging the hose inlet.
Two air nozzles also are included to break-up clogs and other material in front of the vacuum opening, and to direct the material into a pile near the end of the mining operation for more effective vacuuming. Valves for the air nozzles can be remotely actuated from the control station.

**Turret/Clamp Assembly**

The Turret/Clamp Assembly provides rotational motion about the central vertical axis of the silo opening, and clamps the upper-most link in place at all times, except when the mast is being inserted or removed from the silo. The Turret/Clamp Assembly also includes an 11-ft (3.4-m) long rotating protective sleeve. This sleeve extends through the non-rotating outer seal that joins the Silo to the Gantry-Enclosure. The Turret/Clamp Assembly is mounted onto a pre-positioned interface plate that forces alignment with the Silo access hole.

The Turret/Clamp central sleeve also serves as an attachment point for the mast Pan-Tilt-Zoom (PTZ) video camera inside the Silo, and for the cable reeling assembly above the central sleeve.

**Cable/Hose Reel Assembly**

The Cable/Hose Reel Assembly consists of a reel for the arm and link umbilical cable/hose bundle, and a cable winch that lifts and lowers the mast. The winch cable also provides a continuous tether through the links to the Kraft-Robot. The reel cable/hose bundle and the winch cable compete with the conveyance hose for the area near the center of rotation. The entire assembly is mounted to the rotating Turret/Clamp approximately 18-ft (5.5-m) above the turret opening to allow introduction and removal of link and vacuum hose segments.

The reel is coupled to the cable winch motor through a slip-clutch such that the umbilical is under continuous light tension and cannot unwind as the mast is raised or lowered.

All of the control valves associated with the link hydraulic cylinder controls and any other remotely controlled valves within the mast (pneumatic or hydraulic) are located inside the umbilical cable reel. This permits access and replacement or repair, if required, while the arm remains in the Silo. It also minimizes the number of hydraulic and pneumatic swivel channels required in the reel supply lines.

The Cable/Hose Reel Assembly includes the swivels and twist cable connections and festoon cable management components to permit the turret to rotate freely over the full range of rotation.

**Auxiliary Tools**

The primary tool developed for this project, other than the vacuum nozzle, is the hydraulic de-lumper. (See Figure 5) This tool is patterned after large tunnel mining tools, however the blades are conventional carbide bit course-tooth saw blades. The saw blades are aligned in two offset...
rows and are driven by a reversible hydraulic motor. The blades turn at about one revolution per second (fairly slow) but can exert a high degree of force considering the size and weight constraints for the system. The de-lumper tool is also reversible to allow discharge of any unmanageable debris. Other tools may include pneumatic chisels, augers, or hand tools. Almost any tool weighing less than about 50 pounds and fitted with a universal robotic T-grip can be grabbed by the manipulator and operated as an extension of the control station operators arm.

**Auxiliary Tool Hand-Off**

The 20-inch (0.5-m) diameter auxiliary Silo opening is to be used to pass auxiliary tools in to the Kraft-Robot. Auxiliary tools can include various hand tools for agitating, or breaking up the waste material. This eliminates the need to retract ReTRIEVR back into the gantry enclosure for tool change. Segmented poles can be joined to lower the tools more than 10-ft (3-m) into the silo. After the robot has clasped the tool, the pole can be unhooked and removed from the silo. The tool-hand-off pole also can be used to accept solid debris that the Kraft-Robot may retrieve from the waste pile (small tools, wire, tape, etc.).

The auxiliary opening is about twenty feet (6-m) away from the center of the silo dome. This requires several segments to be placed in the silo and over one fifth of the material to be mined before any auxiliary tools can be accessed through this opening. A six-inch (15-cm) opening however is available within 6-ft (2-m). of the center opening. An alternative method for accessing tools during the early stages of mining may be to hang the tools from their power tethers through the six-inch opening. The tethers can be introduced into the silo and fished back into the gantry enclosure through the center opening before the mast is introduced. After coupling the tools, the tethers with tools attached can be lowered back into the silo where the Kraft manipulator can access them even during the early stages of the mining process.

**Hydraulic System**

The hydraulic system provides the fail-safe motive force for both the link cylinders and the Kraft-Raptor-Arm. The Raptor-Arm has seven hydraulic servo-valves that control the six joints plus the gripper of the dexterous robotic arm. These valves are located near their actuators inside the arm and are controlled by the Remote Servo Driver (RSD) mounted in the base of the arm. A single hydraulic supply and return line supplies hydraulic pressure to the Kraft arm header. A 27 pin electrical cable provides control demand signals to the servo valves. A potentiometer position feedback signal is provided to each servo amplifier to close the joint servo loop. If a fault condition occurs in the arm, its hydraulic supply can be turned off in the reel so the arm will hang limp, and can be extracted safely from the silo for repair.

The mast cylinders are controlled by “zero-leakage” valves in the reel. Thus, if a fault condition occurs, or if the system is to be shutdown, the mast will not move. If there is a valve failure, the mast lines can be bled from the reel assembly to relax the mast and allow extraction for system repair.

**Video**

Video viewing is key to success of the operation. Two color cameras are used for in-Silo views of the ReTRIEVR operation. A Pan/Tilt/Zoom (PTZ) camera is mounted to the turret sleeve with the cables routed between the seal and the sleeve. (See Figure 6) After insertion into the Silo, the camera can be rotated out of the mast path with a long-handled pole. If this camera needs to be changed during operation, the mast must first be removed. The failed camera can then be removed with a pole, repaired or replaced, then re-installed onto the Turret/Clamp sleeve. If the camera cables need replacing, replacement cables can be dropped in the annulus between the sleeve and seal, hooked with a pole through the sleeve, connected to the camera, then have slack taken up as the camera is lowered to its sleeve mount.
A second fixed-position zoom camera is located on the Kraft-Robot to view the gripper area, and the vacuum nozzle. Both cameras have redundant integral lights and a pneumatic line to blow clear air in front of the lens.

MINING STRATEGY

The team believes the Silo-3 is full to within a few feet of the top of the dome. The plan is to begin mining the waste with a manually manipulated hose and possibly with reduced vacuum to make enough of a cavity to introduce the Kraft arm. A spherical or cylindrical cavity will then be mined as the Kraft robot is introduced into the silo. As much as possible, the material is to be removed from the top to minimize arm impact loading from a "cave-in" of undercut material. The return air path must be verified before increasing the vacuum rate to prevent excessive pressure loading of the Silo structure. After the first link is fully inserted, the first mast joint will be articulated and the turret rotated. The mining strategy is to vacuum as much material as can be reached from a fixed mast position with the dexterous arm, then move the turret for a full 360 degree sweep, then articulate and/or insert the Mast.

This sequence is repeated until most of the waste is removed from the Silo. The waste material will be mixed with grout for long-term stabilization and packaged for off-site burial. After the bulk of the material is emptied, an air-sweeper will aid the final removal until no waste material is visible. A fixative spray will then be fogged into the silo to seal any remaining loose contamination. The silo is to remain in this preserved state until site work priorities allow the structure to be completely demolished and removed for low-level waste burial.

IMPLEMENTATION PLAN

The system is in final design stages, and fabrication is more than 80% complete as this paper is submitted. Initial mockup testing was scheduled to occur in Fall, 2000 with site delivery and waste removal beginning in 2001. The project however is currently under a stop-work-order for issues unrelated to the ReTRIEVR technology. As of the time this paper was submitted, neither the schedule, nor the new project prime contractors have been named. The ReTRIEVR developers however hope to be able to deploy the system for its intended purpose when the task is resumed.

ALTERNATIVE APPLICATIONS

Although ReTRIEVR has been primarily developed for the Silo-3 application, the design lends itself to other forms of waste removal requiring conveyance through an arm with strict contamination controls. Instead of dry caked material, the material could be hard or wet and could be mobilized with a slurry pump and the waste transported back through the arm.

Initially, the Silo-3 application was intended to transport all waste through a coiled conveyance hose managed on a reel. Due to excessive flow losses, this proved unsatisfactory for the vacuum system but may work well for a pumped system.

The manually incremented, segmented mast drastically reduces the enclosure demands over alternative long-reach arms. The simple capture and two-pin link unions make insertion and withdrawal relatively simple. Although the arm is designed for reliable operation, if failures do occur, practically all failure scenarios are “fail-safe” such that extraction is assured.
CONCLUSIONS

The ReTRIEVR long-reach manipulator represents a creative and effective technological approach to waste removal from tanks and silos like the Fernald Silo-3. Key features are:

- The segmented, clamshell mast enables the system to be deployed and contained in a more compact structure than traditional long-reach arm designs.
- The hollow mast supports and protects the umbilical cables and a large (8-inch)(20-cm) waste conveyance hose.
- The dexterous force-feedback arm can manipulate many common hand tools thereby enhancing the arm's adaptability within an unstructured tank or silo environment.
- The system is essentially fail-safe. Although the design should function without failure or maintenance problems throughout the mining job, practically all possible failure modes allow relatively simple recovery for system repair and return to service.

REFERENCES
