Mobile Manipulation and Survey System for H-Canyon and Other Applications across the DOE Complex-17309

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ABSTRACT

The Nuclear & Applied Robotics Group (NRG) at the University of Texas at Austin is leading a team of university, industry, and national lab partners to develop and deploy a mobile manipulation and survey system for the H-Canyon Air Exhaust (CAEX) tunnels. Since the 1950s, these tunnels have connected Savannah River's nuclear chemical separations facilities to a terminus of sand filters. The tunnel must be periodically inspected. The conditions are harsh: 30+ mph air flow, acid vapors, alpha contamination, high beta and gamma dose, uneven floor surfaces, small entry port, obstacle debris, "muddy" paths, standing water, and overhead obstacles. Since 2003, 5 crawlers have been deployed to inspect the tunnel with sufficient but limited success. Thus, H-Canyon provides an opportunity to develop and deploy a more robust system adhering to the notion of Multi-user / Multi-use (Mu^2) in which a system is developed to complete a particular mission, but designed to maximize its extended use (multiple missions, locations, operators, etc.). Previous deployments provide a set of experiences upon which to learn and build. The environment is challenging and representative of other envisioned scenarios across the national nuclear complex. This paper reviews the history of system deployment into H-Canyon, the lessons learned from these experiences and then derives the requirements that will drive a 3 year effort to develop and deploy a system for H-Canyon inspection and other missions. The paper then concludes with a summary of technologies that enable a path to a functional prototype based on the current conceptual solution. This examination of available technologies and remaining technological gaps can assist the client in assessing the risk associated with proposed development and the range of application possible with a delivered functional prototype.

INTRODUCTION & BACKGROUND

H-Canyon began operations at the Savannah River Site (SRS) in 1955 and is the only hardened nuclear chemical separations plant still in operation in the United States. The H-Canyon Air EXhaust (CAEX) tunnels connecting the facility to the sand filters must be periodically inspected, but conditions are harsh. Since 2003, 5 crawlers have been deployed with various levels of success and in several sections of the over 300 meters of tunnels of H-Canyon. In 2015, the Recovery Crawler (RC) was deployed to either retrieve the toppled 2014 Inspection Crawler (IC) or move it out of the inspection path. It was able to move the IC out of the inspection path and return home, but the IC (and its predecessors) are no longer operable. The RC was retrieved but cannot provide the minimum (or desired) inspection capabilities. [2]

Fig. 1: Images from inside the CAEX Tunnel: (left) a view from the 2015 Recover Crawler (RC), (center) a close up of the deterioration of a tunnel wall, and (right) an image of the tipped over 2014 Inspection Crawler (IC) in the muddy debris under a duct. [1]

After the mission, the SRS team concluded that they require a system with more robust method for traversing the unknown and ever-changing terrain. Mission risk must be reduced and better methods are needed to view behind the hanging ducts and pipes. Furthermore, there is a desire to develop:

- a more comprehensive suite of sensors capable of providing data beyond simple video imaging including radiation survey data, collect soil/water samples, structural images via NDT techniques such as neutron radiography, and environmental data;
- collect Simultaneous Localization And Mapping (SLAM) data and other sensors used for navigation to develop better models of the CAEX tunnel;
- perform more comprehensive inspections;
- integrate SLAM and radiation data for analysis and visualization; and
- perform all these activities in real-time.

Even for the base requirements, a developed system will require higher costs than the customer prefers and more advanced technical capabilities than those used in past efforts. To address this need, the University of Texas at Austin (UTA) has assembled a team to develop and deliver a mobile manipulation and survey system to SRS. This paper reviews the lessons learned from previous efforts, the requirements the proposed system, available technologies (and remaining gaps), and the preliminary conceptual design for the functional prototype developed over a three year project. A key secondary goal of the system is to have Multi-User Mult-Use (ME^2) capability spanning EM & DOE Complex needs and thus it reviews potential uses beyond the CAEX tunnel.

PREVIOUS CAEX TUNNEL INSPECTION EFFORTS

Critical to the success of this project is the inclusion of individuals at Savannah River National Laboratory (SRNL) who have been actively involved in the development and deployment of remote vehicles and crawlers to inspect the CAEX tunnel since from

2003 [1] and continuing today [2]. This section reviews previous efforts in order to derive project requirements (both needs and desired) presented in the next section.

Fig. 2: Approximate location of tunnels (green and yellow dashed) and access points.

The air exhaust tunnels run under H-Canyon and continue through to the sand filter. After the filter, it travels through more tunnel to the fans and out the stack. To illustrate the challenge, note the total length of the green line (see Fig. 3) is 300 meters of tunnel with limited access points. Due to acid used to process the nuclear materials, acid vapors in the air stream have degraded the air tunnel concrete walls (Fig. 1). For this and other reasons, SRS is required to perform periodic inspections to evaluate the tunnel's structural integrity. To complete this task, SRNL has performed 6 partial inspections with 5 different vehicles (see Fig. 3). The conditions in the tunnel are challenging:

- 50 km/hr (30 mph) wind flow,
- Acid vapors,
- Alpha contamination (millions of dpm/100 cm^2),
- Dose Rates: beta & gamma (est. range: 10-1,000 mRem/hr),
- Highest recorded beta dose: 970 mrem/hr),
- Highest recorded gamma dose: 890 mrem/hr),
- Uneven floor surfaces with debris and obstacles,
- Obstacles include previously deployed vehicles,
- Air ducts through the tunnel that must be inspected (See Fig. 5), and
- Pooling water as deep as 13" in some areas.

The approach for the first three inspection efforts was similar. The systems were all small, lightweight, tethered, low cost, and used a tele-operated pan-tilt-zoom camera. These systems were only deployed in areas close the H Canyon building. The three vehicles all were eventually stuck and are obstacles future systems must contend with. However, all three vehicles successfully collected information on the structural integrity of the tunnel as required. The areas inspected by each previous effort are shown in Fig. 4.

In 2014, a more sophisticated Inspection Crawler (IC) was developed to extend the capabilities to inspect the walls more effectively around the air ducts and other obstacles. The system was still low cost (<$75K), and tele-operated. It featured larger tires; robust tether for power, video, and retrieval; a scissor lift; extendable mechanical slide; and two pan-tilt-zoom cameras. The IC was able to inspect approximately 100 meters of tunnel before failing when falling debris prevented the retraction of the mechanical slide. This resulted in a high center-of-gravity resulting in the system tipping over when operators drove the platform (See Fig. 1).

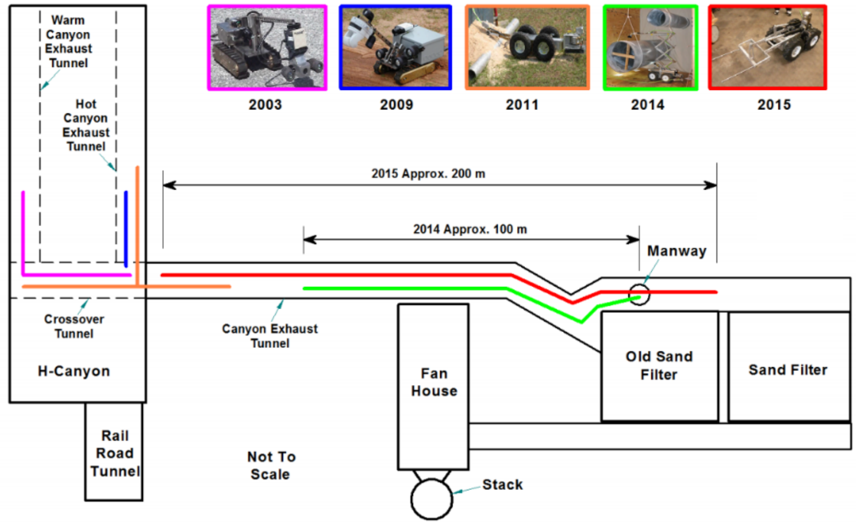

Fig. 3: Approximate areas in CAEX tunnel inspected using each mobile system.

To recover the IC, engineers at SRNL developed a Recover Crawler (RC) capable of up-righting the IC in order to continue inspections and move the system out of its desired path. Although the system was not designed to perform detailed inspection, it would attempt to do so before its retrieval and decontamination. In addition to the retrieval fork mechanism, the system had similar features to the 2014 system, but designers – based on lessons learned – added pitch/roll sensors as well as additional beta/gamma dosimeters. The RC was able to upright the 2014 crawler, but the IC was unable to perform any additional inspections. The RC was then able to traverse approximately 200 meters of the tunnel collecting some useful images from areas never before inspected as well as images of the previously deployed vehicles. The system was retrieved and decontaminated, but was unable to perform inspection behind the air ducts.

Fig. 4: 2014 inspection crawler in a cold test environment.

For every inspection, the client requested the engineers develop a low-cost, low-tech solution due to the high risk of not retrieving the system. And in each case, the choice contributed to the loss of the system. The core lesson learned here and in other deployments in nuclear environments across the globe is that a *proper investment in hardware and software is necessary to not only ensure the mission can be completed, but also to assure the system can be retrieved*.

REQUIREMENTS FOR CAEX TUNNEL INSPECTION

From previous inspection attempts – and the lessons learned from them – the team determined the system requirements which were broken down into the 7 key technical categories defined in DOE's recent solicitation [4] to develop solutions robotics applications across the DOE complex.

1. **Remote access and ability to maneuver within a high-hazard, physically challenged, confined, and unstructured space.**
   a. Largest entry port is a 30" inner diameter pipe in the ceiling. Desired outer diameter of system is 27".
   b. The crane hook used to lift items into the tunnel is 58" above the access port.
   c. Capable of maneuvering through 6" to 12" of moist floor debris that has a consistency of a dense, wet, slippery, cohesive powder described as "oily peanut butter."
   d. Must maneuver past of debris, obstacles and water puddles up to 13" deep.
   e. High values for contamination of alpha as well as gamma/beta dose.
   f. Robust to acid vapors in air.
   g. Robust to high wind speeds in tunnel.
   h. Access extremely small or hard to access locations within the tunnel itself as required for comprehensive inspection.
   i. Deployed system must provide lights (no lights in tunnel).
2. **Non-Destructive Testing and Evaluation**
   a. Future integrity inspections will require more sophisticated NDT testing methods to assure the 18" – 24" thick walls of reinforced concrete are sound.
   b. Must determine the concrete density of the walls.
   c. Capability to measure surface hardness of the underlying concrete surface.
3. **Imaging, Surveying, Mapping and 3D Rendering**
   a. Hi-resolution images are necessary and required to analyze the structural integrity of the walls and ceiling.
   b. Dosimeters required for all deployed systems.
   c. Frequent radiation measurements and surveys provide further information on the integrity of both the CAEX tunnel and the H-Canyon facility.
4. **Manipulation and End-effectors**
   a. Ability to relocate a camera in the Cartesian space to view all the walls.

- b. The camera must have pan-tilt-zoom capability and be placed over a 36” diameter duct. Duct center is 36” from the wall and 36” from the floor.
- c. Ability to collect soil and concrete samples.
- d. Ability to deploy additional sensors or subsystems to inspect extremely difficult locations.

5. **Worker Assistance**
   - a. Provide supervised autonomous behaviors to ensure the system does not tip or collide with obstacles in the environment.
   - b. Perform simultaneous localization and mapping (SLAM)
   - c. SLAM data is necessary to reduce the burden on the operator and better ensure the system safely navigates in the tunnel.
   - d. SLAM data can be correlated and used with radiation and structural data for visualization and analysis.
   - e. SLAM data will be necessary after future inspections to accurately perform quantitative comparative analyses.
6. **Heavy Operations**
   - a. Collect soil and wall samples for later testing.
   - b. Transport NDT and other necessary sensors into the CAEX tunnel.
   - c. Take multiple core bores from wall and/or ceiling for analysis outside.
7. **Task Automation**
   - a. Automate platform point to point moves to reduce the burden on the operator and prevent tele-operator error.
   - b. Automate the manipulator motions to ensure a collision free path is completed to place the camera, sensor, or deployed subsystem is in the desired location
   - c. Automate routine tunnel inspection to allow the tunnel to affordably be inspected at higher frequency without incurring high operational costs.
   - d. Automate the correlation of SLAM data to inspection and camera data for visualization.

A system that meets these requirements must be either radiation hardened or tolerant and use similarly radiation hardened or tolerant tools and sensors. In addition to meeting the requirements correlated above, the system must also:

- Use hi-definition cameras (resolution: 720p minimum, 1080p preferred),
  - o Capability to monitor and record all cameras in real-time
  - o Separate driver cameras viewing forwards and backwards
- Able to perform during and after total immersion in acidic water,
- All joints protected from dirt and water intrusion, and
- Self-righting capability should it tip over in the tunnel.
- Inspection should occur when the canyon is in stand-by mode: typically twice a year lasting 3-5 days.

APPLICABLE TECHNOLOGIES & TECHNICAL GAPS

There is insufficient space in this paper to analyze all the technology necessary to meet the requirements; but, a brief review of select recent technological developments and deployments by the team tasked with delivering a functional prototype are summarized. A table summarizing the remaining technological gaps concludes the section.

Mobile manipulation platform for inventory and inspection of SNM: UTA has previously developed a dual-arm mobile manipulator (VaultBot) for inspection and radiation surveying that meets many of the performance requirements necessary for CAEX tunnel inspection. [6][7][8] The mobile platform is a Clearpath Husky base with a FitPC and inertial measurement unit (IMU) mounted inside the user bay. It has a Sick LMS511 2D LIDAR for mapping and navigation mounted to the front. Two Universal Robotics UR5 industrial manipulators are mounted to a steel bulkhead on the top of the Husky. Various grippers, cameras, and sensors have been affixed to the manipulator arms.

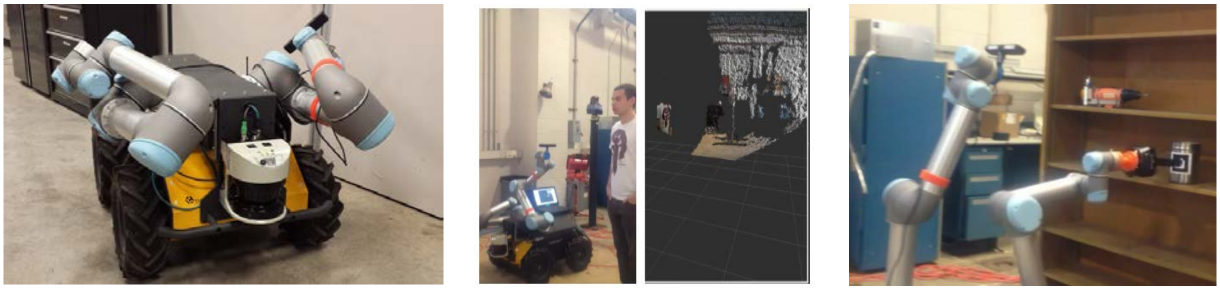

Fig. 5: UTA's VaultBot for inspection and radiation surveying (left) inspecting potentially contaminated personnel (center), and simultaneous visual and radiation inspection of a SNM container (right).

To meet the CAEX application requirements, an improved geometry is conceptualized below and the system can be powered either by a tether (if necessary) to meet the power requirements. But manipulator hardware, control software and human-machine interface transferable technologies. UR manipulators have controller level monitoring of joint position, speed, torque during operation and will emergency stop itself if values outside specified thresholds are detected. This allows UR robots to operate with no safety guarding which decrease concerns related to manipulator collisions with the environment due to localization errors or unsighted objects.

Navigation of mobile system in hazardous, highly uncertain environments: The Center for Intelligent Machines and Robotics (CIMAR) at the University of Florida (UF) has developed several autonomously navigating ground vehicles for a large array of mission applications. [9][10][11] Recent applications have included robotic assisted convoy operations, autonomous patrols where differences between the current environment and the prior-mapped environment can be identified, high speed autonomous navigation, and autonomous systems for range clearance. CIMAR also competed in the two DARPA's Grand Challenges and Urban Challenge. Hardware systems are available to demonstrate this functionality as shown in Fig. 8.

Fig. 6: Autonomous Off-road and range clearing vehicles

The core technologies developed at UF include the development and implementation of the Adaptive Planning Framework (APF) which allows the vehicle to evaluate and select the appropriate sub-system behavior based on the current sensed environment and mission plan; the design and implementation of a JAUS-based architecture which allows the real-time operations of sensing, interpretation and modeling, behavior selection, and behavior execution to occur at a rate of 40 Hz; the development of a motion planning algorithm that uses a predictive temporal method which allows the vehicle to plan its motion based on the current sensed environment and the predicted future environment; and algorithms which simultaneously perform localization, mapping, and object tracking.

Fig. 7: (Left) Modified Pioneer LX with Geiger counter, alpha sensor, & object recognition. (Right) UT Austin's mock storage vault.

Autonomous survey with integrated SLAM and radiation sensor data: Another common but mundane tasks in the DOE complex involves inventory and inspecting of storage facilities for radiation contamination. Operators completing these tasks are exposed to higher than normal background radiation. It is desirable to complete these tasks more comprehensively and with higher frequency than possible using human operators. To address these and other issues, UTA has developed the ability to complete these tests using a fully autonomous mobile manipulator. Full autonomy allows for the system to operate in secure environments without the need for wireless or other forms of electronic communication. [4] Inventory is completed by integrating results from a subset of selected sensors, including barcodes, vision, pose estimation, and radiation signature. Thus, inventory results not only verify the presence of the object, but also if it has moved or exhibits higher than normal radiation emissions. The system is also capable of testing a room for alpha contamination, which is automatically done during any inventory task, but can also be completed more comprehensively as a standalone task. The mobile system has power for 13 hours of operation and can autonomously return to its charging base if power runs low or some other fault is experienced. The system has a full 360° of collision detection and avoidance capability to prevent collisions with unmodelled objects and personnel in a shared workspace.

Demonstrations for inspecting lower shelves have been completed at UT Austin to demonstrate feasibility. A ZipperMast retractable tower was integrated which is capable of reaching up to 8 feet to inspect higher shelves.

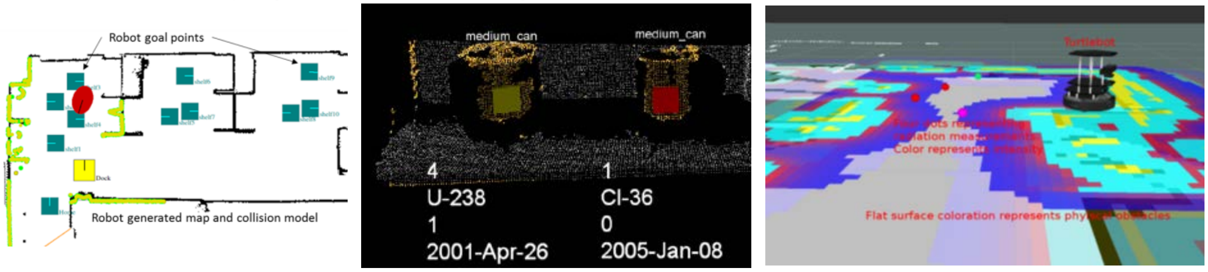

Fig. 8: From left to right: Room map generated by navigation software; overlay of bar code recognition info and 3D object recognition; and radiation map generated using Geiger counter data.

Deployed radiation hardened/tolerant components in functional prototype: A radiation hardened and tolerant version of the ANDROD V-A and VI-A system has previously been developed by UF. Over twelve hundred parts were reviewed for radiation tolerance. The research and development program successfully developed an ANDROS robot capable of operating in environments while accumulating gamma ray doses in excess of 1 Mega-rad. Tracks, O-rings, insulating materials and all plastic components were tested without failure. Watec 906 CCD cameras were irradiated and suffered gradual degradation until detail disappeared at 126 Krads. Radiation hardened cameras are expensive (>$30,000). The low cost (<$1000 dollars) tested camera gradual image degradation, and easy replacement indicated their use was feasible. Activity analyzed on 2 hardened SA 3865 microcontrollers to replace the originals. Similarly the university redesigned the Servo Amplifiers, the DC/DC converters and the A-D converters. The Polaroid ultrasonic transducer (PID607281) was irradiated to determine its ability to operate in radiation fields and it was unaffected by ionizing radiation dose in excess of 2 MegaRads. A RADFET transducer developed by REM allows the operator to track the dose to specific components online as a function of time. Thus UF redesigned and replaced all electronic control components found susceptible to radiation doses below a required threshold.

Functional prototypes for access to hard to reach areas for inspection: FIU STEM students developed a crawler inspection platform/mechanism for the inspection of high level waste storage double shell tanks and waste transfer lines to Hanford's Waste Treatment Plant (WTP). To do this FIU developed a magnetic miniature rover that will travel through the refractory air slots. The refractory air slots range from 1 inch to 3 inches in width and provide a complex maze to navigate through, including four 90° turns to reach the center of the tank. Based on the constraints, a design for a magnetic miniature rover was developed that traverses through the refractory pads upside down along the primary tank floor and provide video feedback. Traversing upside down along the tank floor allows simplifies obstacle avoidance.

Fig. 9: Debris in refractory air slots, mock-up test bed and maximum pull force testing.

Developed functional prototypes using ROS for DOE applications To maximize re-use, simplify validation, and improve collaboration, the team utilizes the Robot Operation System (ROS). [14] ROS includes many of the capabilities required by DOE-EM robotics use cases including 3D perception, navigation in unstructured environments, dexterous manipulation and supervised autonomy.

Use of robotic system for Non-Destructive Testing (NDT): Environmental threats (underwater oil spills, nuclear power plant accidents, inspection of stored material, etc.) have invigorated renewed interest in fielding radiography in severe operating conditions. Any particle type can be combined with a wide range of digital detectors to image almost any object in extreme environments. Manipulators can be implemented as the combined motion control and manipulation system for neutron/x-ray imaging tasks, providing advanced motion capabilities and imaging techniques that are difficult to achieve with linear and rotary stages, such as helical scans or rotations other than along a Cartesian axis. Also, robotic systems allow for a single system for various types of imaging applications instead of dedicated machines for each imaging purpose. A robot can freely produce almost any movement pattern required; hence, the system will not be restricted to what imaging capability it can produce. In-depth repeatability tests have been performed at UTA as well as extensive MCNP analysis which demonstrate that the robot’s repeatability and survivability are sufficient. [16] Copies of the developed hardware system exist at both UT Austin and LANL which have been used with both portable sources and neutron beams generated from a reactor.

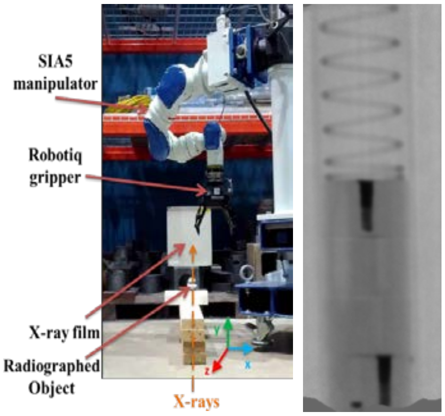

Fig. 10: Neutron radiography and X-ray cartography experiments at UT.

Verification and Validation of a functional prototype: An industrial partner provides the team with capability to adequately perform verification and validation for the delivered system. For example, Areva recently completed a 3 year program for the development and deployment of RIANA (Robot for Investigation and Assessment of Nuclear Areas). The machine has been developed to assist in the dismantling and inspection of nuclear facilities. The robot is equipped with 3D and thermal cameras to reconstitute its environment in real time. Its laser vision enables it to identify and negotiate its way around obstacles as well as position itself precisely within a confined space.

Fig. 11: AREVA's RIANA

RIANA's was developed using the Actin software operating system originally developed for NASA to simplify the interface between space robots and their human controllers. The robot's Human-Machine Interface allows RIANA's controllers to intervene while the device is in the middle of a chore. In fact RIANA's work can be conducted without requiring the presence of an operator – an optional guidance program allows the robot to find its own way to work on a site autonomously. The robot was designed so that after any break in communication the robot can autonomously return to its last known location.

Summary of available technology and remaining gaps: The documented efforts above provide many of the capabilities necessary to succeed in the CAEX tunnel, but challenges remain. Note, the efforts of SRS are not included in this table as they are not a part of the design team. However, for many gaps, their input will be used to address the gap and reduce developmental risks.

Table 1: Technical capabilities and gap relative to CAEX tunnel inspection application

Color key:	N/A	🟥 Gap! (to be addressed)	🟨 Exists (but incompletely)	🟩 Exists! (adoption necessary)

Necessary Technical capability	UT	UF	FIU	Areva	Gap
Mobile Platform Navigation					
In uncertain environments	🟨	🟩	🟨		🟩
In radiation environments	🟨		🟨	🟩	🟩
In 14” water					🟥

30” port access			🟨	🟨	🟨
Capability to right platform after tipping					🟥
Mobile Manipulation					
Non-contact visual and radiation survey	🟩				🟩
Integration of SLAM and radiation sensor data	🟩	🟨			🟩
Exchange tools/sensors at the end-effector	🟨		🟨		🟨
Coordinate motion planning with mobile platform	🟩				🟩
Transitional autonomy (tele-operation to full autonomy)	🟩				🟩
Secondary systems for comprehensive inspection					
Compact mobile platforms			🟩		🟩
Integrate sensors with mobile platforms.	🟩	🟩	🟩	🟩	🟩
Radiation and integrity sensors					
Visualization using High resolution cameras	🟩	🟩	🟩	🟩	🟩
Radiation sensing for remote systems (alpha, beta, gamma)	🟩			🟩	🟩
Robotic NDT capabilities	🟨				🟨
Use of NDT technology to analyze structural integrity		🟩			🟩
Core sample collection	🟨				🟨
Radiation Hardening, Tolerance, and Shielding					
Quantification of radiation requirements		🟩		🟩	🟩
Component testing for radiation hardening tolerance		🟩			🟩
Sleeving/shielding for radiation and other contamination	🟨	🟨	🟨	🟨	🟨 [1]
System Integration					
Developed functional prototypes for nuclear environments	🟨			🟩	🟩
Develop systems using hardware/task agnostic SFW (ROS)	🟩	🟩	🟨		🟩
Verification and Validation of Functional Prototype		🟨		🟩	🟩

FUTURE RESEARCH OBJECTIVES & AVAILABLE TECHNOLOGIES

The team has proposed a hybrid mobile platform capable of maneuvering using wheels, treads or articulated legs. The treaded legs can fold back into the platform providing a compact system that can be deployed via a 30” (76 cm) manhole and lowered using a chain hoist in extremely windy conditions. The manipulation platform will include a proven industrial manipulator with a 1 meter reach and 5 kg payload to extend the system’s inspection, survey, and collection capabilities via a set of

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[1] All team members have extensive experience in this area, but the possibility of contamination due to system’s location in a pool needs further investigation.

interchangeable end-effectors or flexible gripper. The delivered system will include a suite of radiation sensors and core sampling capabilities to perform structural analysis of the tunnel. To ensure the entire tunnel can be inspected, the system will be able to deploy and retrieve smaller customized sensors or robotics systems which further increase the system’s ability to meet its mission and maximize its access to the entire inspection area.

Fig. 12: The proposed multi-purpose crawler for comprehensive inspection of the CAEX tunnel. The platform can move via wheels, tracks or legged locomotion.

Mounted on this system are the sensors and manipulation capabilities together with the necessary radiation hardened components. The approach developed here focuses on application to the H-Canyon Exhaust Tunnel environment. Related to mobility, the primary requirements are:

- maximum dimension of 27” to fit through manway access,
- self-righting capability should it tip over in the tunnel,
- capable of maneuvering through 6" to 14" of moist floor debris that has a consistency of a dense, wet, slippery, cohesive powder, and
- perform during and after total immersion in acidic water.

The mobility platform will contain cameras on articulated arms for inspection, mapping, and navigation and sensors for non-destructive measurement of concrete wall and ceiling density. Reliably maneuvering through an environment covered in a variable amount of moist floor debris is the significant challenge that must be addressed.

Fig. 13: MEISTeR [17]

A robot similar to the proposed configuration has been built by Mitsubishi Heavy Industries for application in the Fukushima Daiichi nuclear power station. The robot, shown in Fig. 16, is named the "Maintenance Equipment Integrated System of Telecontrol Robot" (MEISTeR). It is a remotely controlled dual-arm system that was developed for tasks such as vacuuming up radioactive material, using an abrasive jet to scrape off a thin layer of a contaminated surface, and concrete core sampling. The MEISTeR is an impressive system. The dual seven degree-of-freedom arms provide a good capability to perform a wide variety of tasks. The dual tracks on each side provide the propulsive means, but there is a concern as to how well it can perform relative to the requirement to maneuver through 6" to 14" of moist floor debris or water. So while this system provides confidence in the architectural approach, a different mobility design will be undertaken in this proposal.

We note also that much work is being done by other agencies such as DARPA in developing new mobility concepts. Most of this work focuses on humanoid type mobility. This may be the best approach in the long run, but is impractical today as these systems are not able to right themselves if they tip over.

CONCLUSIONS

This paper reviews the requirements of a system that can inspect the CAEX tunnel at SRS and then reviewing the technologies available from the team assembled to deliver a functional prototype to SRS in three years. An overview of the available technologies is then used to determine what technological gaps still remain. A summary of the proposed concept is then briefly presented.

Fig. 14: The hardware and software developed for CAEX tunnel inspection is broadly applicable to address other DOE-EM needs including (top left) Fukushima type events, (top central) Decontamination and Decommission tasks, (top right) tank inspection, (bottom right) response to contamination events such as the barrel release at WIPP, (bottom center) routine inspection of SNM storage facilities, and (bottom right) challenging inspection and clearing tasks such as the PUREX storage tunnels in eastern Washington. [3]

For the H-Canyon exhaust tunnel, the relevance and benefits are clear. The fully functional system will provide remote and complete access to a high-hazard, physically challenged, confined and unstructured environment that DOE is mandated – both legally and ethically – to routinely inspect. Furthermore the team proposes to develop these tools in a modular fashion using ROS – an open source framework for advanced robotics R&D. Thus the developed technologies will be available to help solve a broad range of DOE-EM challenges such as those shown in which in turn provide a set of application agnostic technologies spanning the entire DOE-EM mission and DOE complex.

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ACKNOWLEDGEMENTS

The author would like to thank DOE-EM and the NEUP IRP program for funding this effort. The author would also like to thank our project collaborators: AREVA, Savannah River National Lab, University of Florida, and Florida International University. This paper is largely derived from the proposal submitted by this team, and thus their inputs were essential for this manuscript.