Contract No:

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy (DOE) Office of Environmental Management (EM).

Savannah River Site H-Canyon Collaborative Advanced Technology Demonstration (ATD) Program Review - 18313

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ABSTRACT

The purpose of the Department of Energy-Environmental Management Office of Technology Development's (DOE-EM TD) Science of Safety (SOS) Robotics Initiative is to pull innovative commercial off the shelf (COTS) and near ready technologies to the field to expedite remaining EM mission clean up and enhance worker safety. A goal of this program is to demonstrate to DOE facilities the value of these available new technologies and their potential uses to solve difficult problems. In support of this goal, the Savannah River Site (SRS) H-Canyon Air Exhaust (HCAEX) tunnel biannual inspection task has been selected to demonstrate and evaluate the benefit of pulling advanced technology solutions to EM facilities. This is a highly collaborative task facilitated by SRNL and engaging SRS H-Canyon facility stakeholders, National Laboratory robotic and concrete inspection SMEs and university robotic and sensor researchers.

Presently, the SRS HCAEX tunnel inspection consists of a visual examination to evaluate the structural integrity of the tunnel. Personal access is prohibited in the tunnel due to extreme conditions, thus the examination is accomplished remotely by deploying cameras mounted on a robotic crawler deployed into the tunnel. While the ability to see inside the tunnel in recent years has been highly valuable, it is desirable to have a better understanding of the environment to support a more thorough structural analysis and for long term planning purposes. This higher order of understanding can be accomplished through advanced COTS sensors and tools and those currently in development and near ready. The advanced technologies selected for demonstration will be evaluated for hosting on the FY19 HCAEX tunnel inspection crawler platform.

The HCAEX ATD task is expected to be performed over a two-year period with year one now concluding. At WM2018, we presented the H-Canyon stakeholder's high priority inspection and remote handling needs, the collaboration team and the planned process of developing an integrated solution [1]. This presentation will review the initial scope and inspection needs, then discuss the past year's progress to address these needs. The discussion includes the results of the Concrete Integrated Product Team (CIPT) formed to evaluate promising concrete NDE inspection technologies and a LiDAR based tunnel mapping sensor suite solution. Highlighted in the discussion will be the engagement and pulling of university developed research and development to include student engagement through the formation and hosting of the SRNL Robotics and Sensors Intern team and collaboration with MSIPP funded Robotic Arm Concrete NDT Inspection University researchers. Lastly, the path forward to complete the demonstration will be presented.

INTRODUCTION

The United States Department of Energy - Environmental Management (DOE-EM) clean up mission is projected to require in excess of $200B and require several decades to complete with many of the most daunting technology challenges remaining. A recent EM review by the Secretary of Energy Advisory Board (SEAB) highlighted the need for investment in technology development including robotics and remote systems as a means of accelerating the mission. The DOE-EM Office of Technology Development (DOE-EM TD) responded to this recommendation with a Robotics Initiative. As part of the initiative, the EM TD Robotics Roadmap has been developed which identifies DOE-EM facility needs and high value solutions to expedite cleanup and enhance worker safety. Additionally, as part of the strategic direction of the roadmap, it is desired to pull these technologies to the DOE facilities to demonstrate and evaluate the usefulness and effectiveness of advanced robotics, remote systems and related technologies in the field.

While commercial robotic and remote system industries have made tremendous strides in recent years, EM application of these systems is challenged by the lack of demonstrated robustness and reliable performance in harsh, unknown and hard to reach environments. Additionally, operating facilities focused on meeting schedules have a "*no room for failure*" paradigm and thus turn toward low risk (a.k.a. low tech) hardened and proven technologies providing no incentive for technology development. To promote the development of a robust robotic capability and to demonstrate the benefits of pulling advanced technology solutions to DOE-EM facilities, the DOE EM TD initiated the SRS H-Canyon Collaborative ATD. The mission of the ATD is to provide an enhanced robotic and sensor inspection of the SRS H-Canyon Air Exhaust (HCAEX) tunnel in FY19. Currently the H-Canyon facility conducts a bi-annual visual inspection of the SRS H-Canyon Air Exhaust (HCAEX) tunnel, the ATD scope is to supplement the required biannual video inspection with advanced sensors and tools to demonstrate the viability and benefits of pulling advanced technology to the field. The technologies selected for the ATD support the H-Canyon identified priorities and are also DOE EM complex high value needs as identified by the DOE Robotics Roadmap [2].

BACKGROUND

SRS is in the southeastern United States where it covers approximately 777 square kilometers and employs over ten thousand people. The primary mission of the site from the 1950s to the 1980s was to produce nuclear materials for national defense. SRS used five nuclear reactors, two chemical separations facilities, a tank farm, and support facilities for this mission. In the late 1980s, the SRS mission changed to include maintaining the Tritium stockpile and environmental management and cleanup at the SRS. SRNL is located at the SRS and has provided technical support to SRS facilities since operations began in the 1950s.

Fig. 1 - H-Canyon Facility with tunnel locations noted

H-Canyon is a chemical separation facility at the SRS. The H-Canyon exhaust air is routed to a crossover tunnel and carried to a large sand filter through the H-Canyon Air Exhaust (CAEX) tunnel, Fig. 1. The tunnel is below grade and made from reinforced concrete. Presently a biannual visual inspection of the SRS HCAEX tunnel is required to assist in the evaluation of the structural integrity of the tunnel.

The HCAEX tunnel is a harsh, difficult to access environment where human entry is not allowed, Fig.2. The tunnel exhausts nitric acid vapors with an air flow of over 50 km/hr. This caustic exhaust air has caused concrete erosion which releases grit into the air flow creating a sandblasting effect in the tunnel. Additionally, the concrete grit has littered the floor with a slick mud-like debris making it difficult to gain traction with robotic platforms and creating uneven floor surfaces. Also present are alpha contamination and beta-gamma dose rates up to 10 mSv/hr (10 to 1,000 mR/hr) and several types of physical obstacles to include step changes, ducts and standing water.

Fig. 2 - Standing water in CAEX Tunnel

Since 2003, six visual inspections of the tunnel have been performed using various crawlers as shown in Fig. 3. Early deployments were performed in the cross over tunnels below the building and more recent deployments have captured the tunnel from the building to the sand filters. At this time, video of most of the tunnel wall and ceiling surfaces has been collected except for those blocked by obstructions, mainly duct work. It is desired to obtain video of all surfaces along with higher quality video of the entire tunnel to better understand the erosion that is taking place. Video acquired thus far has been very useful in gaining a high-level understanding of the tunnel environment and how it is changing. Additionally, the video has helped identify tunnel obstacles for future inspection planning [3]. Terrain in the tunnel has been very difficult to navigate; four of six deployments have resulted in the crawler not being retrieved from the tunnel, Fig 4.

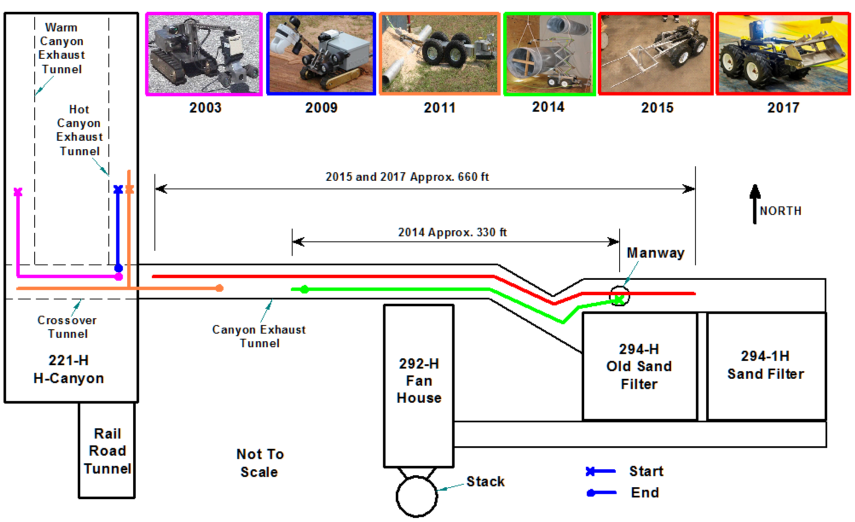
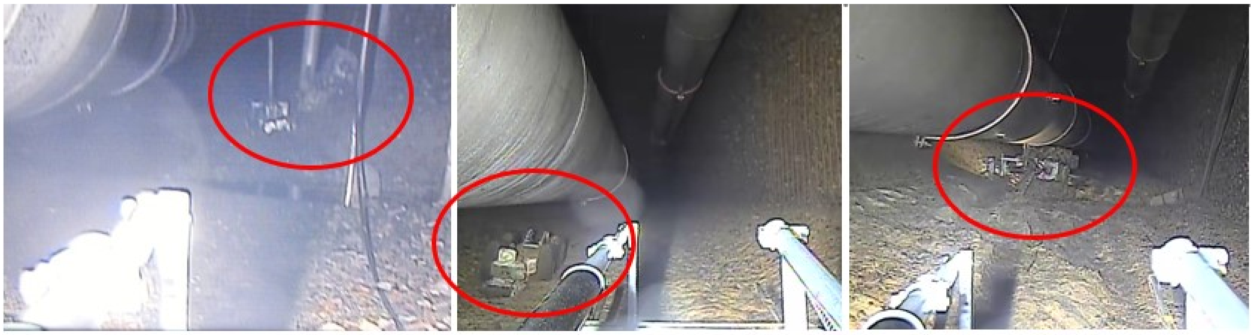


Fig. 3 – H-Canyon Inspection Crawler and Path History



2003 & 2009 Crawlers 2011 Crawler 2014 Crawler

Fig. 4 – Inspection crawlers still in tunnel.

DESCRIPTION

The ATD was designed to be a highly collaborative task facilitated by SRNL and implemented in partnership with government and university subject matter experts and the engagement of SRS H-Canyon facility stakeholders, Table 1. Technical collaborators include experts in the fields of robotic development for harsh environments and experts in concrete structural inspection techniques. This collaboration leverages current DOE-EM TD funded academia and EM Lab work to support the enhanced inspection.

Table 1 - ATD Collaborating Organizations

DOE EM TD ATD Technical Collaborators
DOE National Labs: • *Savannah River National Lab (SRNL)* • *Los Alamos National Lab (LANL)*
US Army Engineering Research & Development Center (ERDC)
Integrated Research Project (IRP)-EM-1, "***Nuclearized Robotics for Integrated Mapping***" Universities: • *University of Texas at Austin (UT Austin)* • *University of Florida (UF)* • *Florida International University (FIU)*
Minority Serving Institutions Partnership Program (MSIPP) Project, "***Smart Tel-Operated Robot Systems for Nondestructive Testing of Concrete Structures***": • *North Carolina Agricultural and Technical State University (NC A&T)*

Identification of Advanced Technologies of Interest

H-Canyon stakeholders to include facility program management, structural integrity design authorities and engineers, and DOE-Savannah River were engaged to develop and finalize a prioritized list of H-Canyon enhanced inspection needs. Recent partial visual inspections of the tunnel have shown a notable amount of concrete erosion along the tunnel walls, Fig. 5; high priority needs focused on concrete characterization to support an enhanced structural integrity evaluation and for long term planning purposes. Technologies deemed to be of highest priority included concrete related NDE structural examination and high accuracy 3-D mapping to determine tunnel concrete erosion rates, Table 2. These technologies were also identified in the DOE EM roadmap as having broad applicability across the complex and as such were selected as technology goals for the ATD.

Fig. 5 – Recent tunnel inspections showing concrete erosion and exposed rebar

Table 2 - Stakeholder identified characterization data of high priority

H-Canyon Enhanced Inspection Needs – Top Priorities		
Need	***Priority***	***Description***
1	High	***Non-destructive Examination (NDE) Concrete Mapping*** Sensor/system to measure concrete tunnel wall, ceiling and floor thickness. • Data shall show rebar, concrete density, and concrete thickness to within +/- 6.35mm (+/- 0.25“) • Data shall include relative position +/-25.4mm (+/- 1.0”) with reference to tunnel landmark (corner, pipe hanger, access port, etc.) • Solution may include multiple pieces of equipment
2	High	***Accurate 3-Dimensional Mapping of Tunnel*** The goal is to create an interior tunnel map that can be compared to future tunnel maps. In particular, it is desired to measure the amount of surface area that has been eroded between mappings. • surface accuracy +/- 6.35mm (+/- 0.25“) or better • sensor range greater than +/- 4.6m (15.0’) • map tunnel from robot point of view • Advanced feature: ability to map behind duct work • Advanced feature(s): demonstrate ability to compare two mappings and determine difference in surface depth; provide this information in user-friendly format

Funding Overview and Modified Scope

Due to funding constraints, the original scope to develop and add the selected sensors to a robust inspection platform for deployment as part of the April 2019 inspection was modified. New scope focused on leveraging currently funded DOE programs and work in progress, Table 3, to identify and develop "proof of concept" solutions.

Table 3 - Leveraging Existing Programs to Address Funding Constraints

Leveraging of Existing Programs to Develop "Proof of Concept"
DOE EM HQ: "Science of Safety Robotics Program" • University Integrated Research Project (IRP) which included a LiDAR mapping component • Funded two SRNL Graduate Student Interns from the DOE EM IRP to "pull" LiDAR solution to SRS
DOE EM MSIPP • University Project which included a concrete inspection device deployed using a robotic arm • Sponsored two SRNL Summer Interns who worked on a LiDAR sensor suite development
SRNL R&DE Technology Development Funds & Existing Materials • LiDAR, 4K Cameras and existing hardware for development

Development of Enhanced Solutions

Two technical teams were created to further the modified scope. The Concrete Integrated Product Team (CIPT) was formed to identify and evaluate sensors and methods to obtain HCAEX enhanced concrete characterization data meeting the stakeholder identified priorities. A 3D mapping team was formed to develop a proof of concept solution which included pulling LiDAR technology developed under a university IRP to SRS.

Concrete Integrated Product Team (CIPT)

The CIPT team included H-Canyon stakeholders, facility management, concrete SMEs and R&DE robotic and sensor SMEs. Scientists and structural integrity experts from SRNL, SRNS, LANL and the Army Corps of Engineering participated. An in-depth identification of potential concrete inspection solutions was completed by the team. Solutions for consideration were commercial off the shelf (COTS) or near ready, Technology Readiness Level (TRL) 7-9. Sensors and methods were evaluated on performance, usefulness of data acquired for structural integrity evaluation, and the feasibility of a tunnel deployment given the unique access challenges and environment. Due to the depth of the tunnel underground (~4.9m (16')) surface inspection was not considered an option, however alternate solutions to a tunnel inspection were encouraged and discussed. NDE of the tunnel concrete is preferred by the H-Canyon stakeholders however collection of samples was considered.

The CIPT identified ultrasonic inspection devices deployed using a robotic arm to be the most feasible NDE solution. Such instruments can provide the high value data desired for an enhanced structural integrity evaluation to include wall thickness, location of rebar and structural deformities. In the evaluation of potential ultrasonic devices, the Pundit Live Array Pro was identified as having potential to deliver desired results. The Pundit device possesses sixteen points of potential surface contact which has the potential to perform when on the uneven eroded tunnel walls.

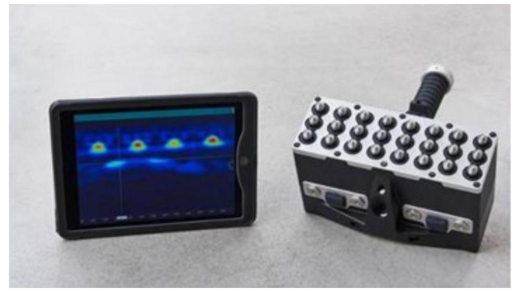


Figure 6 - Pundit Live Array Pro concrete inspection instrument

To further the feasibility evaluation and development of a robotic deployed concrete instrument, work performed under the MSIPP funded university project "Smart Tele-Operated Robot Systems for NDT of Concrete Structures" is being leveraged. The Pundit vendor and MSIPP professors and students were hosted at SRNL for a day of testing with the Pundit device. A January 2019 meeting is planned at the NC A&T robotics and concrete labs with representatives from the CIPT and Pundit for further discussions on robotic arm deployment.

Figure 7 - Concrete Inspection Instrument deployed using a robotic arm

Tunnel 3D Mapping

Mapping of the tunnel is of interest to better understand the tunnel environment such as a quantitative understanding of the rebar exposure and obstacle locations. Of particular interest is the ability to determine the tunnel wall erosion rate for long term planning. Conceptually it is thought that high accuracy 3D mapping scans acquired at different points in time can be collected and compared to determine the rate of erosion. Several DOE programs were leveraged to develop a proof of concept LiDAR centric modular sensor suite that could be remotely deployed into the tunnel by a crawler.

In 2018, SRNL R&D Engineering formed and hosted a Robotics and Sensor summer intern team to develop and test a LiDAR centric 3D mapping sensor suite. A goal of the project included pulling LiDAR research developed at the UT-Austin laboratory funded under a DOE EM IRP to a field proof of concept solution. The intern team was comprised of four robotic engineering students sponsored through the SRNL and DOE MSIPP intern programs, two of which worked on the UT-Austin IRP LiDAR development, Fig. 8.

The intern team was tasked with the following objectives:

- Design and development of a 3D mapping sensor suite capable of merging LiDAR acquired point cloud data with high res camera images
- Incorporation of an Inertial Measurement Unit (IMU) to assist with positioning in the GPS denied tunnel environment
- Development of a user GUI for the remote control and viewing system
- Development of the sensor mounting hardware for hosting on a crawler
- Design and build of a test bed simulating tunnel conditions
- Testing of the sensor suite on a crawler platform in the test bed

Fig. 8 – SRNL Robotic Sensor Intern Team (left to right) Julian Benitez (MSIPP UPR), Conor McMahon (UT-Austin, IRP team), Stuart MacVean (SRNS President), Manual Losada (MSIPP FIU DOE Fellow), Christopher Suarez (UT-Austin, IRP team)

To facilitate rapid sensor integration, software coding and user GUI development, the Robot Operating System (ROS) was employed as the development platform. ROS is a set of open source software libraries and tools that assist with the building of robot applications. ROS includes drivers for many sensors, state-of-the-art algorithms, and powerful developer tools. Sensors selected for the summer intern solution were chosen based on possession of ROS drivers and associated sample code. Additionally, the ROS 3D Robot Visualizer (rviz) tool was employed during development.

3D Mapping Sensor Suite Development

The developed sensor suite included a planar LiDAR sensor for depth imaging, two Panospheric 4K cameras, and an inertial measurement unit to aid in base localization, Figs. 9 - 11. The LiDAR is actuated to rotate about the vertical axis, which allows for the team to gather 3D mapping data. These rotating planar scans can also be fused with the camera and IMU data to generate colorized internal maps of the tunnel.

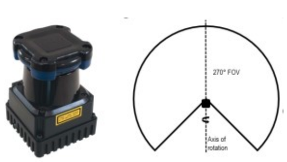


Fig. 9 - Hokuyo LiDAR and it's FOV and applied rotational axis

Fig. 10 - Two 4K Kodak PIXPRO SP360 Panospheric Cameras

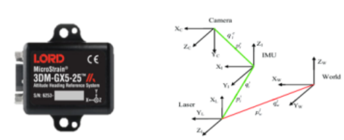


Fig. 11 - Micro strain IMU (left) and transform data (right)

The team developed a mounting fixture for the sensor suite which maintained defined geometry between the sensors and allowed for the suite to be affixed to a crawler test platform, Fig. 12. The mount holds the LiDAR sensor, two 180-degree cameras on either side and the LiDAR servo on the center. The sensor mount was designed using CREO and printed in the R&DE Additive Manufacturing Lab.

Fig. 112 – 3D printed sensor suite (left) suite hosted on test crawler (right)

3D Mapping Software

The supporting software was developed iteratively over the summer and leveraged prior research conducted at UT-Austin, which facilitated the stitching of LiDAR scans, the fusion of the sensor data, and algorithms to provide in-situ navigation feedback to the operators of the crawler, Fig 13. A Graphical User Interface (GUI) was developed to allow the user to set the rotational speed of the LiDAR, perform a scan, and register and save the 3D generated cloud after a scan is done. The software provides the desired ability to map and perform degradation measurements and offers the operator improved situational awareness. The improvement in awareness reduces risks of the robot becoming stuck or disabled inside the tunnel.

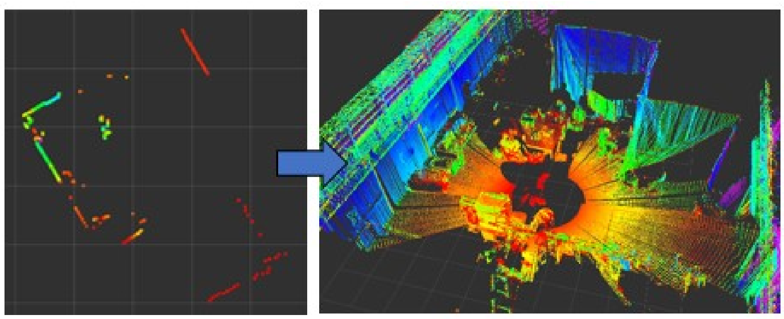


Fig. 123 - Raw 2D LiDAR intensity scan (left) and generated 3D point cloud (right) after stitching

3D Mapping Sensor Test Bed

A test mockup of a 4.9m (16') section of the tunnel with simulated eroded walls was designed and materials were procured for its assembly. The test bed included the ability to change the tunnel width with millimeter precision to simulate erosion to acquire data to test scan comparison algorithms, Fig 14. To simulate the degraded concrete surface of the tunnel walls without adding a lot of weight to the test bed, sheets of faux stone are to be used on the inner walls, Fig 15.

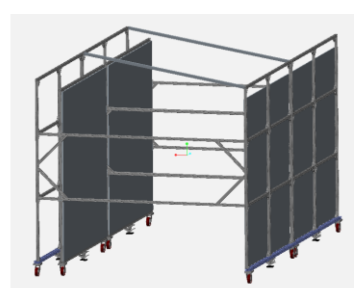


Fig. 14 - Tunnel Mock-up Design

3D Mapping Sensor Performance

To test the performance of the developed sensor suite, faux stone wall was scanned using the Hokuyo LiDAR based sensor suite (~$5.2k) and a high-performance FARO scanner (~$60k) and the scans from the two systems compared, Fig. 15. The average distance from the Hokuyo cloud and the nearest point in the FARO cloud was 1.75 mm; 98.8% of points in the Hokuyo cloud were within the target accuracy of 6 mm (~.25") of the FARO.

Fig. 15 - Faux stone used to simulate concrete walls for

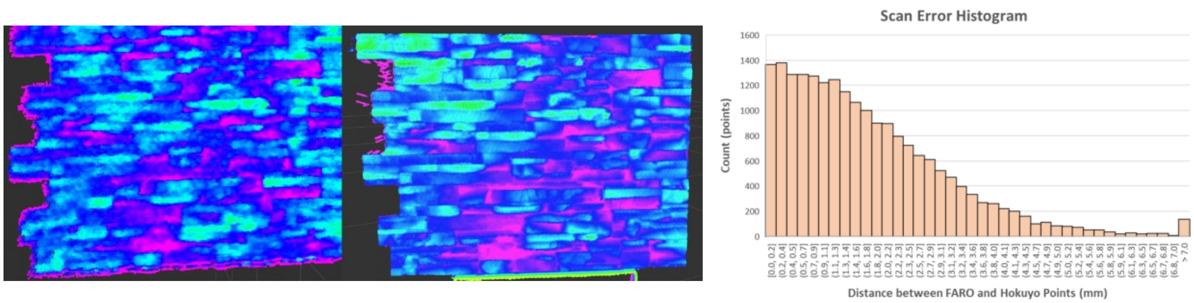


Fig. 16 - Hokuyo LiDAR (Left) FARO Focus LiDAR (center) histogram of the distance between the Hokuyo and FARO scans across all cloud points (right)

Student Team Accomplishments

The intern team was able to develop and incorporate a sensor suite into a fixture that is mountable on a crawler for remote 3D mapping. Developed software produced promising mapping results from the sensor suite, additionally the developed modular software design using ROS enables alternate sensors to be easily incorporated into the suite. The sensor suite tunnel test bed was designed, and procurement initiated. The developed sensor suite provided a successful proof of concept to the stakeholders.

ATD Current Status

Current work on the development and demonstration of enhanced tunnel inspection technologies includes a combination of facility supported tasks and continued leveraging of DOE programs.

LiDAR on a Stick

The successful development of the intern sensor suite and demonstrated proof of concept has led to an H-Canyon funded project to deploy a LiDAR system into the tunnel via a pitot tube to perform mapping at a single location. A successful deployment into the tunnel would demonstrate the ability of LiDAR to perform as needed in the harsh conditions. Presently, an evaluation as to whether to deploy a commercial LiDAR and software package or a field harden intern sensor suite is being performed. A final solution may include both. Deployment of the student solution would require application of the software QA process to the prototype software and data certification. Deployment of the LiDAR sensor will be via a pole into the 16' long pitot tube. Previous deployments of high resolution cameras have been performed via the pitot tube port; the LiDAR deployment pole will be based on previous camera pole designs, Figs. 17 & 18. The LiDAR system to include the deployment pole and remote control system will be developed in early 2019 with a late summer deployment planned.

Fig. 13 - Pitot Tube Port Camera Pole

Fig. 18 - Pitot Tube Port Camera View

Concrete Inspection via Robotic Arm

Further evaluation and development of deploying concrete inspection instruments via robotic arm is being performed. CIPT representatives are preparing to visit the NC A&T robotics and concrete inspection laboratories in January.

CONCLUSIONS

Although original ATD scope modifications were required due to funding constraints, progress has been made on the original goal to identify high value advanced sensors for demonstration and use in a field scenario. LiDAR will be introduced and evaluated as an inspection technology through the LiDAR on a stick project. SRNL will continue evaluation of concrete inspection instruments and development of remote and robotic deployment methods for the devices via robotic arm.

In conclusion, DOE EM and SRS have many challenges in hazardous environments that will require new or different remote systems. The goals of these new systems are to enhance worker safety and to realize a cost savings by expediting remaining EM mission clean up using advanced technologies. The purpose of the ATD is to demonstrate and objectively evaluate the benefit that can be obtained through investments in state of the art technologies. This collaborative effort is expected to result in development of technology with a broad applicability across the DOE complex and demonstrate the value of such investments.

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