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Savannah River Site H-Canyon Advancing Technologies for Remote Inspections – 20345

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ABSTRACT

In 2017, the DOE Environmental Management Office of Technology Development (DOE-EM TD) sponsored the H-Canyon Advanced Technology Demonstration (ATD) to demonstrate to DOE facilities the value of using new commercial-off-the-shelf (COTS) and near-ready technologies to solve difficult problems and enhance worker safety. The DOE Savannah River Site (SRS) H-Canyon Air Exhaust Tunnel (HCAEX) inspection task was identified as representative of the hazardous, human denied environments which could benefit from advanced technologies. The HCAEX underground concrete tunnel is visually inspected biannually using a camera mounted on a remotely operated vehicle (ROV) designed and built by SRNL. While tunnel images have provided valuable visual information, it is desirable to have a higher order of understanding of the environment to support a more thorough structural integrity (SI) analysis and for long term planning purposes.

As part of the ATD, the Concrete Integrated Product Team (CIPT) was formed to identify and evaluate available sensors and methods mature enough to remotely obtain tunnel concrete characterization data of high value and with a high probability of success. The team included SMEs and H-Canyon stakeholders in the field of concrete, nondestructive examination (NDE), structural integrity, sensors and remote systems from SRNL, SRNS, LANL, DOE-SR and the Army Corps of Engineering. The CIPT completed an in-depth identification of customer concrete inspection needs and potential technology solutions. Sensors and methods were evaluated on performance, data usefulness, cost and the feasibility of a successful deployment given the unique tunnel access challenges and environment. Two technologies were identified as promising by the CIPT for near term demonstration and evaluation: LiDAR (Light Detection and Ranging) 3-dimensional (3D) mapping and remote robotic deployment of NDE instrumentation. Laser spectroscopy to characterize tunnel surface chemical changes was also of interest, but presently cost prohibitive.

This paper will include a discussion of the two efforts underway to evaluate and implement the CIPT recommendations. First, the status of the November 2019 deployment of LiDAR at a single location into the tunnel is presented. This initial deployment provided the team a learning curve and lessons learned on the challenges of tunnel deployment to include remote operation and data collection, stabilization of the sensor in high air flow (~30 mph), ability to achieve a tolerance accuracy of 0.25-inches, and the probability to identify change in tunnel dimensions over time.

Secondly, a discussion on the development of the Robotic Arm Concrete Inspection Test Bed capable of deploying NDE instruments to examine custom concrete forms will be presented. Concrete forms simulating the rough concrete surfaces, strength, composition and potential structural defects that can be found at our DOE EM facilities have been designed and built for the test bed. Two state-of-the art concrete NDE instruments have been identified as having potential to work on rough concrete walls, they are being tested and characterized as to their ability to provide desired structural integrity data to include wall

thickness and defect identification on the developed test beams. Lastly, lessons learned, and the path forward 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. In 2019, the DOE-EM Office of Technology Development released the DOE-EM TD Robotics Roadmap [3] which identified EM facility needs and potential high value technology solutions to expedite cleanup and enhance worker safety. While commercial instrument, sensor and robotic system industries have made tremendous strides in recent years, DOE-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.

The strategic direction of the Robotics Roadmap included the recommendation to introduce technologies to the DOE facilities to demonstrate and evaluate their usefulness and effectiveness in the field. The DOE EM TD initiated the SRS H-Canyon ATD as one such demonstration. The original H-Canyon ATD scope was to supplement the required 2019 camera inspection crawler with advanced sensors and tools, however, due to funding and time constraints, alternative demonstration paths for the technologies were identified and are the subject of this paper. In November of 2019, H-Canyon sponsored the first deployment of LiDAR into the tunnel and in FY19, SRNL sponsored development of the Robotic Arm Concrete Inspection Test Bed to include characterization of promising new concrete NDE technologies. Remote 3D mapping and concrete NDE technologies were identified as having broad applicability and high value across the DOE complex by the DOE EM TD Robotics Roadmap. At the Savannah River Site, H-Canyon stakeholders identified remote concrete NDE as the highest priority technology inspection goal to enhance bi-annual SI evaluation of the tunnel.

BACKGROUND

SRS H-Canyon Air Exhaust (HCAEX) Tunnel

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.

Fig 1 - H-Canyon Facility with tunnel locations noted

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, 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 3.

Fig 2 - human denied tunnel interior view

Fig 3 - Standing water in HCAEX tunnel

Since 2003, seven visual inspections of the tunnel have been performed using various crawler. 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. Video acquired thus far has been very useful in gaining a high-level understanding of the tunnel environment and how it is changing. Additionally, it has helped identify tunnel obstacles for future inspection planning [4]. Terrain in the tunnel has been very difficult to navigate; four of seven deployments have resulted in the crawler not being retrieved from the tunnel.

LIDAR TUNNEL DEPLOYMENT

Background

LiDAR 3D mapping technology was selected as having a high probability of deployment success into the tunnel and as having potential to provide useful quantitative results. LiDAR has matured significantly in the past 10 years and the DOE complex has been developing a competency in 3D technologies for training and planning. The ability to use this technology to understand hazardous remote environments is frequently limited by deployment methods into the environments and the hazardous nature of the environment to electronics and instrumentation. LiDAR is an improvement over the visual camera inspection in that it provides measurable data of interior surfaces and artifacts.

Deployment Plan

The tunnel pitot tube location was selected for the initial deployment of the LiDAR as SRNS has previous experience deploying cameras and instrumentation into the tunnel via these 6" pipes, Figs 4, 5 & 6, and because there is ample visual data at this location for comparison to LiDAR results. Deployment at the pitot tube location is a precursor to a potential deployment of a LiDAR system on a future tunnel inspection crawler.

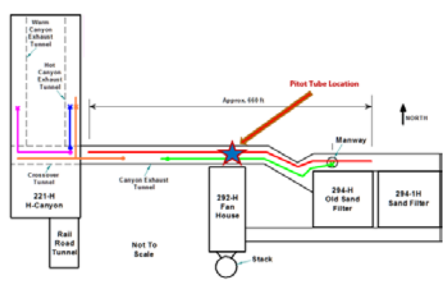

Fig 4- tunnel pitot tube location

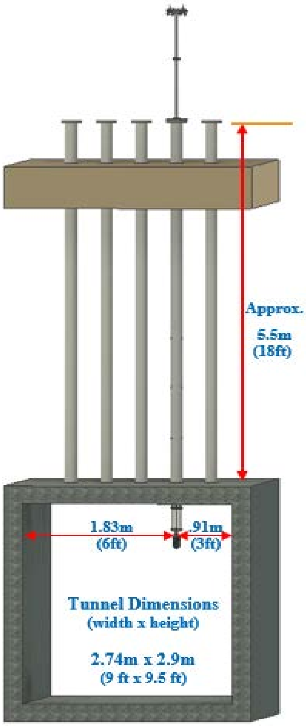

Fig 5 - Conceptual LiDAR system shown inserted into 2nd pitot tube from right with tunnel dimensions noted.

The data acquisition plan included deploying the LiDAR system into the tunnel over a two-day period. The first day, three (3) LiDAR scans would be collected at each of three (3) different tunnel heights, (low, center and high) Fig 7, to obtain a baseline set of scans. The second day, six (6) LiDAR scans would be collected at each of the three (3) heights. The purpose of the two sets of data was to determine if the denser point cloud obtained by combining 6 scans versus 3 scans provided a benefit when evaluating results and to determine the ability to repeat a 3D map collection for comparison to the baseline results of the first day.

Fig 6- View of pitot tube from inside tunnel. Photo obtained by inspection crawler.

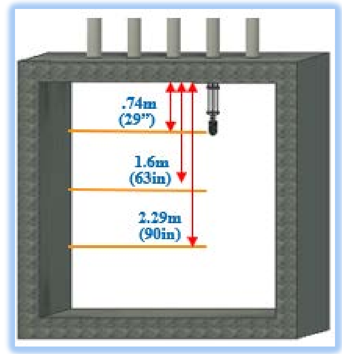

Fig 7- Three scan heights employed to reduce shadowing in results.

Method

A custom-built LiDAR on a Stick (LiDS) system was procured from James Fisher Technologies to perform the 3D mapping at the pitot tube location, Fig 8. The primary system components included a Leica BLK360 LiDAR imaging scanner mounted on a pole for insertion into the tunnel and a data and power box located above ground at a control station for remote operation. The pole fully assembled is 7.87m (25.8ft) and weighs about 91kg (201 lbs). The BLK360 LiDAR is mounted at the end of the pole and is powered by a circuit that replaces the battery to enable powering by an above ground supply. The pole is designed to accommodate three scanning heights in the tunnel to reduce shadowing in the results and to provide for a higher density point cloud (3D map). Additionally, at the tunnel end of the pole are four (4) dimmable LED light strips for illuminating the light deprived environment and whose intensity is controllable from the above ground control station. Wi-Fi access points are mounted at the top and bottom of the pole to bridge the communication network from the underground LiDAR to the above ground remote-control station. Centralizing wheels are located on the lower portion of the pole for scanner stabilization in the high air velocity of the tunnel.

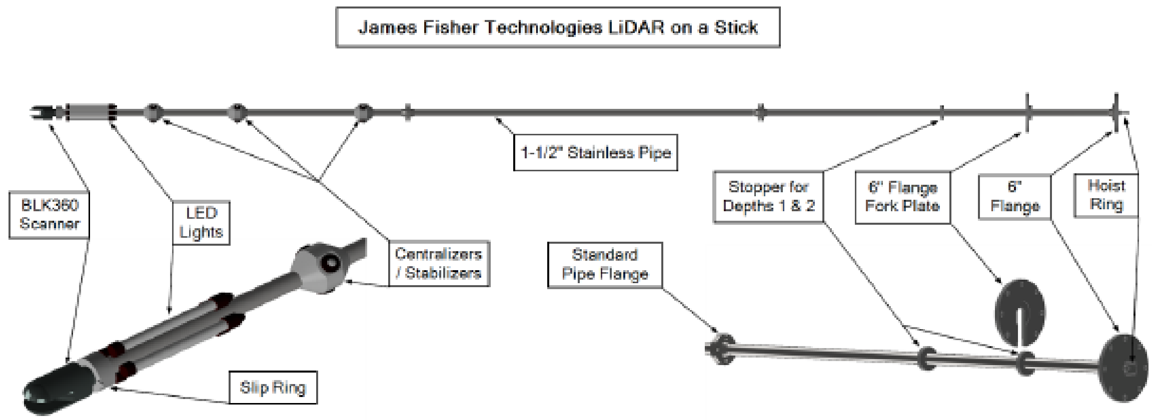

Fig 8 - Custom procured LiDAR on a Stick (LiDS) system

The LiDAR system selected for the pole deployment was the Leica BLK360, Fig 9. This system captures a full-color panoramic image overlaid with the high-accuracy point cloud. The LiDAR is controlled remotely using an iPad Pro running the Autodesk Recap Pro Mobile. Scan data collected on the iPAD Pro is then uploaded to ReCap Pro on a Windows PC where point cloud data can be registered and, if desired, exported in the common a common industry format for further processing. The BLK360 was selected primarily for its small footprint, near scanning ability and low cost for the features and specifications provided. The unit has an IP54 rating which is not the robustness desired for our environment, however, no other options were available.

Fig 9- Leica BLK360 LiDAR

Deployment

On Monday November 4, 2019, SRNL R&DE along with H-Canyon Operations, Engineering, QA and Radcon, SRS Rigging, and on-site JFT technical support deployed the custom procured LiDAR on a pole inspection system into the H-Canyon Exhaust Tunnel, Fig 10. The LiDAR which was mounted on a 25' pole was lowered by crane through a 6" pitot tube into the tunnel, Fig 10. One the first day, the LiDAR scanner successfully collected the planned 3 scans at each of the 3 heights providing for a baseline data set. At the end of the day, the LiDAR was lowered to the lowest position in the tunnel allowing for the pole flange to cover the pitot tube opening to secure the system overnight.

Fig 10- LiDAR system being lowered into H-Canyon tunnel pitot tube.

The second day planned scans were unable to be obtained due to an overnight system failure. After a series of troubleshooting efforts including contacting the Leica LiDAR vendor, the unrecoverable error was traced to the BLK360 LiDAR unit.

Leica BLK360 LiDAR Post Deployment Troubleshooting

Under the Leica service agreement, the company offered to send a replacement BLK360 should we return the failed unit for troubleshooting at their facility; however, the device had been introduced into a radiological and chemical environment, so this was not a viable option. In order to assist in troubleshooting without having access to the device, Leica requested SRNL to download the activity log from the LiDAR and send it to them for failure evaluation. This was acquired the week following the deployment along with several suggested but unfruitful troubleshooting activities. Leica responded after examining the logs that the "Slow Axis Stalled" errors indicate the horizontal rotation axis drives were not working and that they suspect the error was caused by too much strain on the scanner's horizontal rotation axis. Leica stated that the system "is not very over designed and so any additional strain induced by the installed slip rings or wires could very easily cause this error". To emphasize their point, they noted that the system could be operated vertically, but even operating the unit horizontally could harm the LiDAR bearings and motors involved with the horizontal axis rotation.

Acquired Data

The BLK360 acquired both a panoramic photographic image and a 360-degree point cloud during each scan, Fig 11, which are overlaid together in the software to facilitate situational awareness and making measurements. Although the LiDAR panoramic photographic image was limited to the area lit by the pole LEDS, the LiDAR laser surprisingly acquired a point cloud spanning approximately 60m (197 ft) of the tunnel, Fig 12. Within this 60m, there are several obstacles and gross geometry transitions such as height variations, slopes, and tunnel curvature making the acquisition impressive. Although this data is interesting to view, it is the area near the pitot tube which will produce the highest accuracy measurements. Given the rough surface of the walls and the narrow available "viewing" angle of the LiDAR, surface pockets are obstructed from the LiDAR laser as distance increases from the

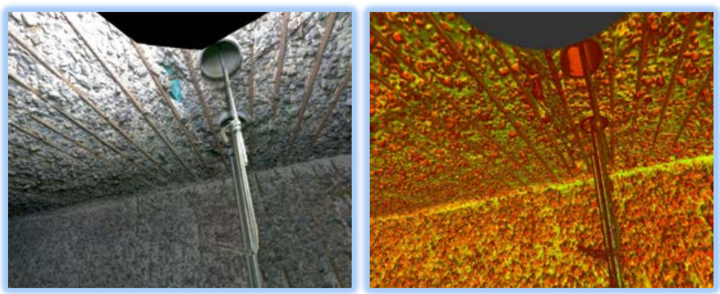

Fig 11 - Scan data, panoramic image (left), 3D laser acquired point cloud (right)

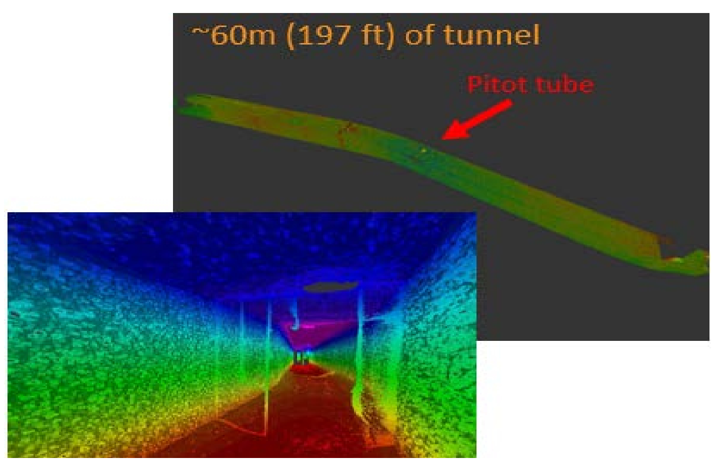

Fig 12- ~60 meters of tunnel point cloud data was acquired (top) interior view of tunnel laser data (bottom) pitot tube location. Additionally, the LiDAR accuracy is a function of distance from the device to the detected surface; manufacturer published accuracy as follows: 6mm (0.236in) accuracy within 10 m and 8mm (.315in) within 20m.

Data Validation

The process to validate collected data during a deployment was developed into a procedure which calls for comparing known measurements of tunnel artifacts to those derived from the collected data, Fig 13. The selected tunnel artifacts identified for this purpose were the geometry of the standard stainless-steel pipes and the SRNS designed stainless steel coupon holder which have documented values, TABLE 1. The nine (9) scans obtained the first day of the deployment were registered (merged) into a single 3D point cloud and the validation procedure applied. Seven measurements were performed from the merged point cloud and validated against the artifacts, TABLE 2. Based on the results, point cloud measurements were within the customer desired .25in tolerance and the collected point cloud data was validated for further usage.

Fig 13- measurement on point cloud taken of Standard SCH 40 6"Pipe for data validation

TABLE 1- Tunnel known dimensions used to validate LiDAR point cloud measurements.

Standard Id	Material	Length (inches)	ID (inches)	OD (inches)
Standard SCH 40 6” Pipe	SS	N/A	6.065	6.625
Coupon Holder	SS 304L	12.375	N/A	N/A
2” 150 # Flange	SS 304 L	N/A	N/A	11

TABLE 2- Comparison of known artifact dimensions to point cloud derived measurements.

Standard *(Inches)*	Measurement *(Inches)*	Error *(Inches)*	Tolerance *(Inches)*	Error in Percentage*	% of Tolerance* *(Accept Limit* -100%)*
Inside Diameter : Pitot Tube Standard SCH 40 6" Pipe					
6.065	6.032	0.033	±0.25	0.54%	13.20%
6.065	6.021	0.044	±0.25	0.73%	17.60%
6.065	6.019	0.046	±0.25	0.76%	18.40%
Outside Diameter : Pitot Tube Standard SCH 40 6" Pipe					
6.625	6.538	0.087	±0.25	1.31%	34.80%
6.625	6.511	0.114	±0.25	1.72%	45.60%
6.625	6.7	0.075	±0.25	1.13%	30.00%
Coupon Holder : Length					
12.375	12.17	0.205	±0.25	1.66%	82.00%

Notes:
1. Error in Percentage* is calculated by taking the error divided by the standard.
2. Percent of Tolerance* is calculated by taking the error dividing by the tolerance, for this calibration only.
3. Accept Limit* is essentially defined as the 100% of the tolerance for this calibration only.

Tunnel Measurements

A custom point cloud was created for the tunnel measurements by merging three (3) scans at each of the deployment heights and only including points located within 30ft of the scanner. The nine (9) scan point cloud created for the data validation provided for a denser point cloud which eased the selection of points for measurements, however it was found to require significant amounts of computing power to process measurements.

Measurements can be made by manually selecting points on the cloud, Fig 14, however this method is prone to human error as the point cloud is comprised of millions of points and it can be difficult to ensure the best point for the measurement is selected. Additionally, given the walls and ceiling are not smooth, it's difficult for single measurements to adequately quantify the overall distances of walls and surfaces. Because of this, the tunnel was divided into cross sections and 3D rectangular boxes encompassing equal dimensions of opposite walls were analyzed, Fig 15. Using Cloud Compare, an open source 3D point cloud processing program, contour maps using the nearest neighbor algorithm were generated on the tunnel walls. The original design width of the tunnel was 2.74m (9 ft). A rough

Fig 14- Example of manual measurements made by selecting points on the cloud

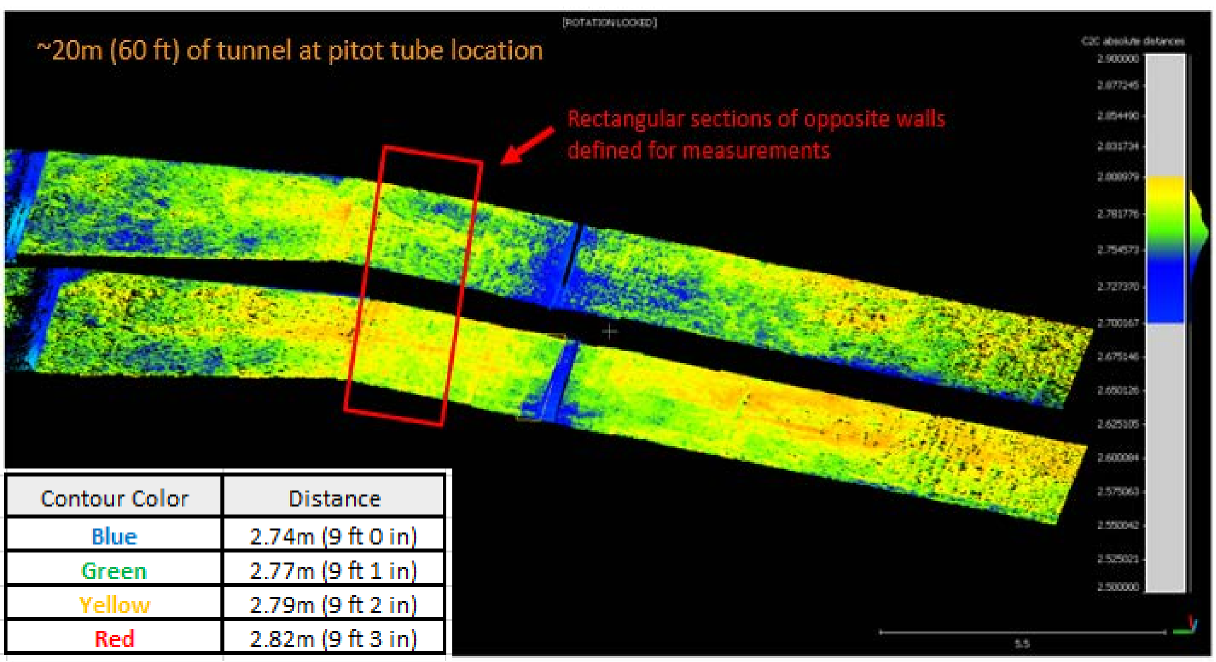

Fig 15- 3D map of tunnel walls within 30m of pitot tube and sectioned to develop distance contour color coded map

distribution of concrete losses can be estimated from the distribution label shown at the right of Fig 15. The deeper blue indicates the original concrete remaining with no loss, however near the pitot tube location the blue may be accounted for by the pole and the concrete holder obstructions.

Fig 16 shows a more focused analysis on the two opposite rectangular sections highlighted in Fig 15. A histogram curve is provided with each contour map showing the normal distribution of distance data. The average distance between to the two segments can be determined by inspecting the histograms. Additionally, these values are important for comparison to future deployment data. As the dimensions of the interior tunnel under current field conditions can be quantitatively measured by point cloud data, concrete loss at current conditions can be calculated. Furthermore, the degradation rate of concrete can be calculated with multiple deployments conduct periodically.

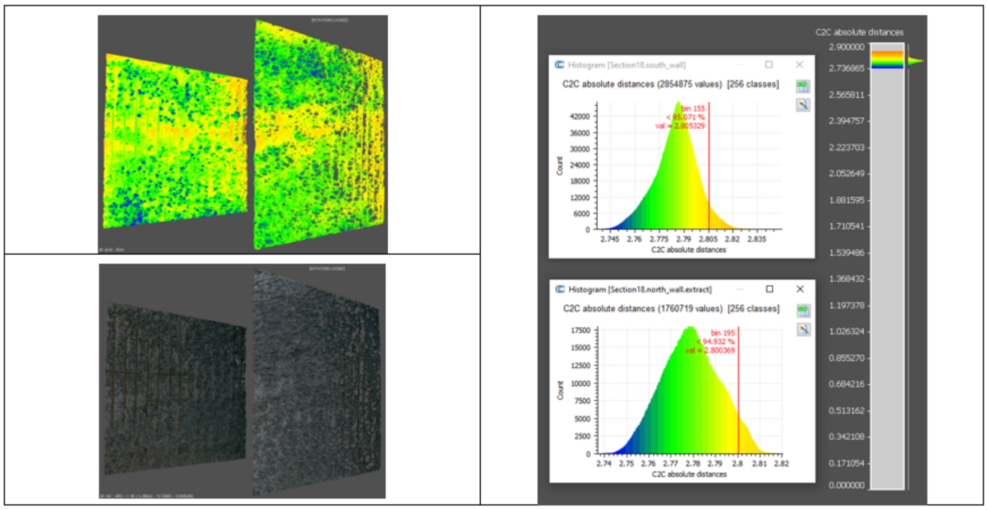

Fig 16- Two opposite sections of wall analyzed for distance data.

ROBOTIC ARM CONCRETE INSPECTION TEST BED

Remote concrete NDE technologies were identified as having broad applicability and high value across the DOE complex by the DOE EM Technology Development Office (TDO). At the Savannah River Site, H-Canyon Exhaust Tunnel (H-CAEX) stakeholders identified remote concrete NDE as the highest priority technology inspection goal to enhance bi-annual SI evaluation of the tunnel. While many useful instruments exist to provide desired concrete structural data, the challenge is deploying them in human denied and hazardous environments. Additionally, NDE instruments are designed for use on smooth concrete surfaces, whereas many older structures and those exposed to hazardous environments such as the HCAEX tunnel, no longer have smooth surfaces.

The Robotic Arm Concrete Inspection Test Bed will enable development and testing of state-of-the-art techniques to evaluate conditions of inaccessible concrete structures. Focus is on the examination of remote concrete structures typically found in DOE EM facilities. The test bed consists of a robotic arm capable of deploying concrete NDE instruments to examine custom concrete forms with known defects. Concrete forms simulating the rough concrete surfaces, strength, composition and potential structural defects that can be found at our DOE EM facilities were designed and built for examination. Two state of the art concrete NDE instruments were identified to be tested and characterized as to their ability to provide desired Structural Integrity (SI) data on the developed test beams and slabs. A collaborative robot arm is being used as they are designed with built in features allowing them to safely operate alongside employees.

Objectives

1) Setup Robotic Arm Concrete Inspection Test Bed
2) Build concrete forms designed to simulate DOE aged facilities
3) Test ability of NDE instruments of interest to collect desired Structural Integrity (SI) data from test forms
    a) Baseline performance with hand deployment
    b) Test ability to obtain baseline performance using robotic arm

Introduction

The goal of this work was to develop and build a test bed to support the evaluation of using a robotic arm to perform remote inspections using concrete NDE instruments. Concrete test forms simulating the rough concrete surfaces, strength, composition and potential structural defects that can be found at our DOE EM facilities were built for examination for use in the test bed.

This test bed can be used for the following:

- to develop techniques and software to perform NDE examination with instruments mounted on a robotic arm
- to design and test custom robotic arm instrument mounts
- to characterize and evaluate state of the art NDE instruments
- to evaluate the ability to acquire desired SI data from test beams
- to evaluate the quality of the acquired data

If the ability to collect the desired data supporting a more thorough SI evaluation can be developed and demonstrated using a robotic arm, the system could be mounted on a crawler for future enhanced remote inspections.

Approach

The implementing team included SRNL R&D Engineering staff, SRNL SMEs in concrete science and inspection technologies and H-CAEX SI stakeholders to optimize the approach and desired results. Two promising state of the art NDE instruments were identified by the CIPT to be included for evaluation and characterization, the Pundit Live Array Ultrasonic Scanner and the Proceq Ground Penetrating Radar (GPR), Fig 17. In addition to providing the stakeholder identified desired data, the selected instruments technologies employed were thought to have potential to work on the rough concrete surfaces found in the HCAEX tunnel and often found in the remote hazardous environments.

Fig 17- State-of-the-art NDE instruments of interest

Basic approach:

1. build the test bed which includes a robotic arm with custom end effector mounts to hold the NDE instruments.
2. Design and build concrete forms simulating the rough concrete surfaces, strength, composition and potential structural defects for testing
3. Collect instrument data on the test beams using traditional manual hand-held methods, then collect the data using the developed test bed robotic arm system, Fig 18.
    a. Data would include instrument performance on smooth, mildly rough and very rough concrete surfaces.

Simplified Test Matrix

CONCRETE INSPECTION PERFORMANCE via Human and Robotic Arm Deployment			
Deployment Method/ Instrument	Concrete Surface		
	Smooth	Mild Roughness (.5" exposed aggregate)	Very Rough (1.5" exposed aggregate)
HAND DEPLOYMENT			
• Proceq Echo Pulse			
• GPR			
ROBOTIC ARM DEPLOYMENT			
• Proceq Echo Pulse			
• GPR			

Fig 18- Simplified Test Matrix

Test Bed

A test bed employing the collaborative UR5 robot arm was designed and built, Fig.19. Collaborative robot arms are designed with features to safely operate alongside people. A custom mount was designed and additively manufactured for the robotic arm to hold the Pundit Live Array instrument. Robotic arm software and rudimentary techniques were developed to apply the instrument against a concrete test pad and the ability to collect data from the Pundit Live Array instrument was demonstrated. The Proceq GPR unit was ordered in early July and was not received until late September, so this system was not tested with the robotic arm. This work demonstrated the need for development of techniques and/or methods to facilitate acquiring instrument results on rough concrete surfaces.

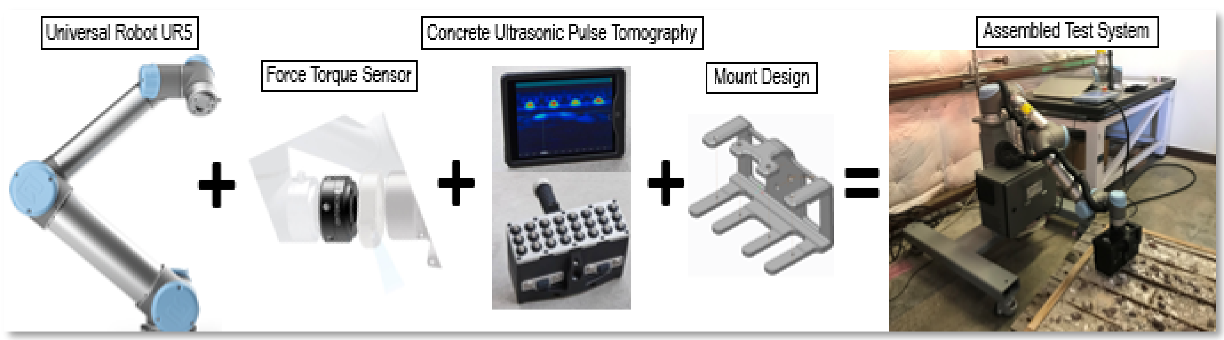

Fig 19 - Test Bed Assembly with Pundit Live Array Instrument mounted

Test Beams and Data Collection

Concrete test beams and forms simulating the rough concrete surfaces, strength, composition and potential structural defects were designed and built for testing. The form design included rebar location and compressive strengths similar to the HCAEX tunnel and are representative of those found at our DOE EM facilities., Fig 20 &21. Initial handheld NDE instrument test data has been collected on the concrete test forms, Fig 22.

Fig 20 – Concrete test beam design (left) and test form (right) with varying surface textures and rebar depth

Fig 21 - Test Forms with varying compressive strengths: 2000 psi, 3000 psi and 5000 psi

Fig 22 - Collection of hand-held instrument data on test beam in field

Accomplishments

Accomplishments to date include:

- Developed Test Bed for evaluating ability to perform remote concrete NDE inspections using a robotic arm, Fig 23
- Developed Test Bed and methodology for evaluating performance of state-of-the-art instruments
- Designed and build custom concrete test forms simulating typical DOE facility concrete
- Ordered and received the Proceq GPR

Fig 23- Robotic Arm Concrete Inspection Test Bed

Future Directions

Facility stakeholders are highly interested in the characterization data that can be obtained using remote concrete NDE technologies. The scope of this work should be pursued to allow for stakeholders to make an informed decision on the feasibility and benefit of a future concrete NDE inspection.

The desired scope includes:

1. Complete the identified objectives to include testing of NDE instruments of interest to collect desired Structural Integrity (SI) data from test forms.
    a. Baseline performance with hand deployment
    b. Test ability to obtain baseline performance using robotic arm
2. Complete characterization and evaluation of the two instruments of interest
3. Develop additional software and deployment technologies if required
4. Develop lessons learned and recommendation for field deployment with team

CONCLUSION

LiDAR acquired data was demonstrated to have significant utility for making high resolution measurements in the HCAEX tunnel for structural integrity consideration. Analysis of the acquired data showed that data could be collected within the customer required .25 in tolerance and tunnel measurements made. Additionally, the potential to determine erosion rate with future deployments is promising. The deployment and subsequent failure of the LiDAR on the second day of tunnel scans, demonstrates the difficultly of deploying off the shelf instruments into remote hazardous environments. A second deployment of the LiDAR is planned for May 2020 and is expected to confirm the ability to obtain a scan at the same location that can be compared to the first scans to determine surface changes and an erosion rate. With advances in collaborative robotic arms to include user friendliness and falling costs, the ability to deploy state of the art instruments into remote areas becomes more of a reality. Many of these new instruments can provide highly valuable data for environmental and structural awareness for integrity analysis and long-term planning. Work to develop these capabilities within DOE has the potential for significant benefit across many facilities across the complex.

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