Inaccessible Penstock Features

Research and Development Office
Science and Technology Program
Final Report ST-2019-7118-01

U.S. Department of the Interior
Bureau of Reclamation
Research and Development Office

September 2019

Mission Statements

Protecting America's Great Outdoors and Powering Our Future

The Department of the Interior (DOI) conserves and manages the Nation's natural resources and cultural heritage for the benefit and enjoyment of the American people, provides scientific and other information about natural resources and natural hazards to address societal challenges and create opportunities for the American people, and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities to help them prosper.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Cover Photograph:

Testing a custom tunnel inspection UAS in a penstock at Center Hill Dam.

Disclaimer:

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<tr><td colspan="7">14. ABSTRACT (Maximum 200 words) The United States Army Corps of Engineers has been working with the University of Pennsylvania’s robotics laboratory over the past several years to develop an unmanned aerial system that can autonomously inspect inaccessible features such as penstocks, draft tubes and tunnels. Reclamation partnered with USACE in 2015 to demonstrate the UAS at Glen Canyon Dam. Since that time, several more demonstrations and tests have been conducted to refine the UAS according to USACE and Reclamation needs.</td></tr>
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Final Report ST-2019-7118-01

Inaccessible Penstock Features

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Acronyms and Abbreviations

3D	three-dimensional
LED	light-emitting diode
LIDAR	light detection and ranging
Reclamation	Bureau of Reclamation
S&T	Science and Technology
UAS	unmanned aerial system/unmanned aircraft system
USACE	U.S. Army Corps of Engineers
USBR	U.S. Bureau of Reclamation
UPenn	University of Pennsylvania

Executive Summary

Inspections are routinely conducted within a hydroelectric facility's internal features. These features include the penstock and draft tube. The penstock is a tunnel that directs water to the generator turbine and the draft tube conducts the water to the outlet on the downstream side of the turbine. Numerous tunnels, pipes and conduits convey water to reservoirs and facilities. These tunnel features range between 4 feet to 40 feet in diameter and curve at angles that inspectors cannot access without special rope access gear and training. In addition, entry into the tunnel often requires special clearances, training and other safety precautions.

The US Army Corps of Engineers (USACE) began research to address this issue in 2012 by partnering the University of Pennsylvania's (UPenn) robotics laboratory. The UPenn lab has long been known for its research on autonomous navigation of unmanned aerial systems (UAS) [1]. The University of Pennsylvania's robotics laboratory have been working to develop a system that can collect useful inspection video and three-dimensional (3D) modeling measurements as well as navigate autonomously without the need for manual piloting.

The Bureau of Reclamation (USBR) partnered with USACE in 2015 to provide demonstration sites for testing and evaluation of the UAS platform. USACE contacted Reclamation for a demonstration facility because it was difficult to find a USACE facility that met the specifications for the demonstration while it was out of service. Reclamation was able to satisfy the need by conducting a joint mission at Glen Canyon Dam (see Figure 1). Additional details about the Glen Canyon test project are outlined in a report submitted by Reclamation entitled Inaccessible Features Inspection at Glen Canyon Dam [2]. This initial collaboration grew into a multi-year partnership of evaluation and feedback.

Since the Glen Canyon demonstration, Reclamation and USACE have continued their partnership including demonstration and testing at Center Hill Dam and participating in annual Reclamation/USACE Collaboration Workshops.

Ongoing testing of the UAS inspection platform has continued at the University of Pennsylvania and at USACE's Center Hill Dam, near Smithville, Tennessee, and a test at the Francis E. Walter Dam, near Bear Creek Township, Pennsylvania. Reclamation attended a Center Hill demonstration in the summer of 2016. Center Hill Dam experienced an extended outage of one of the penstocks due to refurbishment of hydropower unit equipment which has allowed for several years of testing (see Figure 2). However, during one of the scheduled tests, Center Hill Dam was unavailable, so the testing was conducted at the Francis E. Walter Dam (October 2017) (see Figure 3).

Reclamation technical experts continued to provide feedback and specifications for the development of the tunnel inspection UAS after the Center Hill demonstration by discussing progress quarterly and presenting details on the research at USACE-USBR Research Team annual meetings. In addition, during the first Science and Technology (S&T) UAS Research Workshop, Dr. Jim Keller, from the University of Pennsylvania, was a keynote speaker, along

with Reclamation's National Aviation Manager, David Rosser. Listed in Table 1 is a summary of the collaboration that was arranged between Reclamation, USACE and UPenn for this project.

Equipment

The University of Pennsylvania's proposed design for a tunnel inspection UAS includes the following specifications: autonomous real-time navigation, 360-degree data collection oriented to the circumference of the tunnel and sufficient lighting for inspection data collection. The airframe typically uses LIDAR (light ranging and detecting) sensors for positioning. There are also four cameras arranged equidistant around the forward axis. The field-of-view of the cameras allow for overlap. At each camera, a series of LED (light-emitting diode) lights are positioned to provide lighting for the cameras.

Since the beginning of the research, a total of six iterations of the airframe have occurred. With each iteration, the UAS is improved. The first version of the UAS was a quadcopter built with a crash frame. Version two upgraded to a hexacopter and featured two LIDAR scanners for positioning. The third version was another major upgrade to a standardized airframe with a single LIDAR scanner, powerful motors and improved camera resolution. Version four gave minor improvements to the UAS by extending the length of the rotor arms for greater stability. Version five was another major update and gave the airframe more of a landing platform. Finally, version six was a minor update with a repositioning of the LIDAR sensor to make it closer to the center of gravity. Version 1 through 5 airframes are shown in Figures 4 to 8.

Demonstrations

Since Reclamation joined as a collaborator in 2015, there have been nine demonstrations of the UAS capabilities. The demonstrations consist of airframe calibration and testing in a real-world environment. The tests usually last between 1 and 4 days. Seven of the tests were conducted at Center Hill Dam, one test each were conducted at Glen Canyon Dam and Francis E. Walter Dam. Glen Canyon Dam's test area was the Unit 2 penstock. The penstock diameter is steel-lined. The total length of the penstock is about 665 feet with a 285-foot horizontal section and the remainder of the penstock is inclined at a 65-degree angle. In the inclined section, the diameter is 15 feet and in the horizontal section, the diameter is 14 feet.

Center Hill Dam's test area is also a penstock that is similar in diameter and shape to the one of Glen Canyon Dam. The test section at Francis E. Walter was an outlet works tunnel that was a smaller diameter than either Center Hill or Glen Canyon Dam's penstock. In addition, the tunnel trifurcated to a width just slightly larger than the UAS. Because of this, no flights were conducted in the trifurcated sections.

The timeline of all the demonstrations is shown in Table 2.

Method

The concept of the autonomous navigation and the data collection begins with the LIDAR sensor. The LIDAR provides a map of the navigation area and interacts with the cameras and flight controller to prevent collisions and allow the operator to set the navigation position within the cross-section of the tunnel [3]. Images and video are taken of the circumference of the tunnel. This imagery is stitched to create a cylindrical image that is mapped to the tunnel wall (see Figure 9). The video is also analyzed automatically to identify features such as rivets and corrosion (see Figure 10).

Conclusion

While this work is ongoing, the results are close to being finished. Reclamation will continue to collaborate with USACE and intends on participating in a final upcoming demonstration. The value of this work is immense and is requested from all over Reclamation. Once the project is completed and the UAS is made available, it will be able to provide safely-obtained inspection documentation within Reclamation facilities.

Contents

Figures

Tables

References

[1] GRASP Lab, "Vijay Kumar: Robots that fly ... and cooperate - TED Talk," 2012 February 2012. [Online]. Available: https://www.grasp.upenn.edu/news/vijay-kumar-robots-fly-and-cooperate-ted-talk. [Accessed 25 September 2019].

[2] M. Klein, "Inaccessible Features Inspection at Glen Canyon Dam," Bureau of Reclamation, Denver, 2016.

[3] T. Ozaslan, G. Loianno, J. Keller, C. J. Taylor, V. Kumar, J. M. Wozencraft and T. Hood, "Autonomous Navigation and Mapping for Inspection of Penstocks and Tunnels With MAVs," *IEEE Robotics and Automation Letters,* vol. 2, no. 3, pp. 1740-1747, 2017.

Appendix A – Figures

Figure 1: UAS penstock inspection test at Glen Canyon Dam in 2015

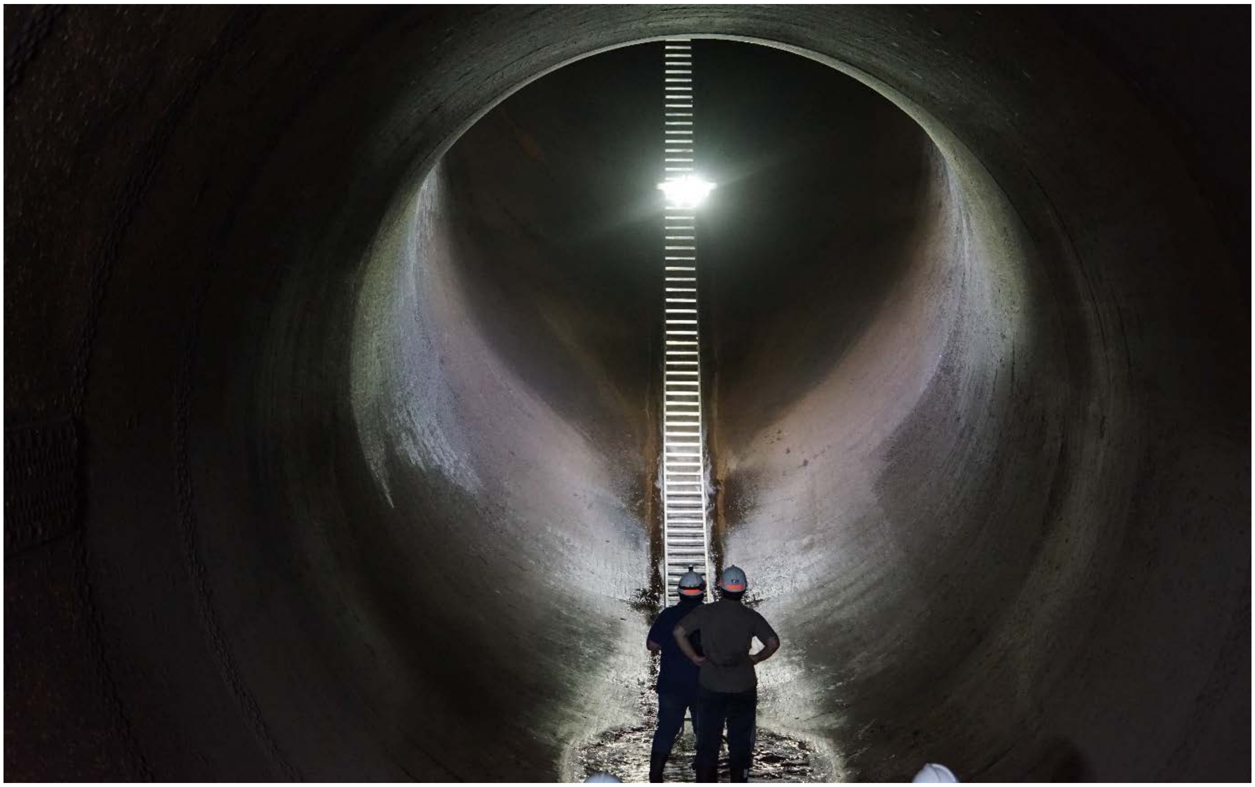

Figure 2: UAS Penstock inspection test at Center Hill Dam in 2016

Figure 3. UAS tunnel inspection at Francis E. Walters Dam in 2017

Figure 4. Tunnel Inspection UAS Version 1

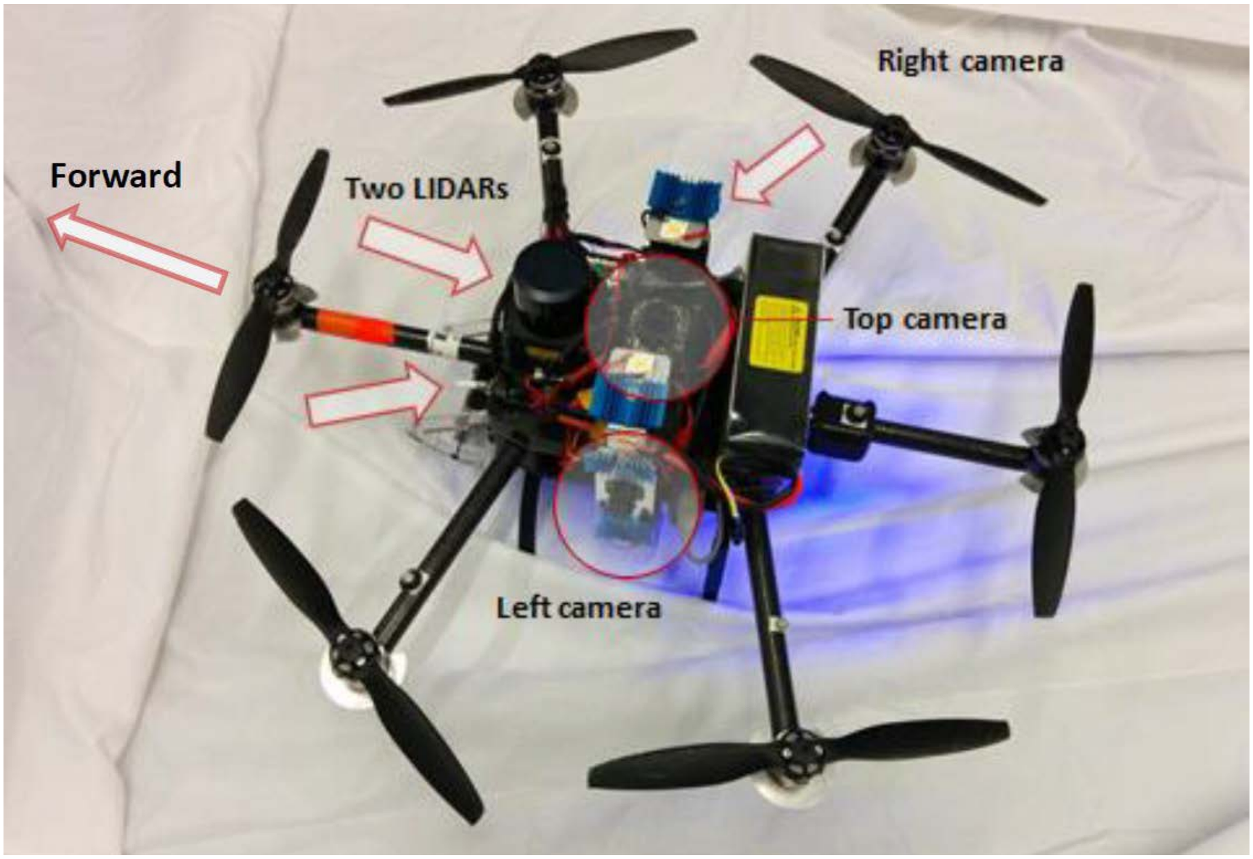

Figure 5. Tunnel Inspection UAS Version 2

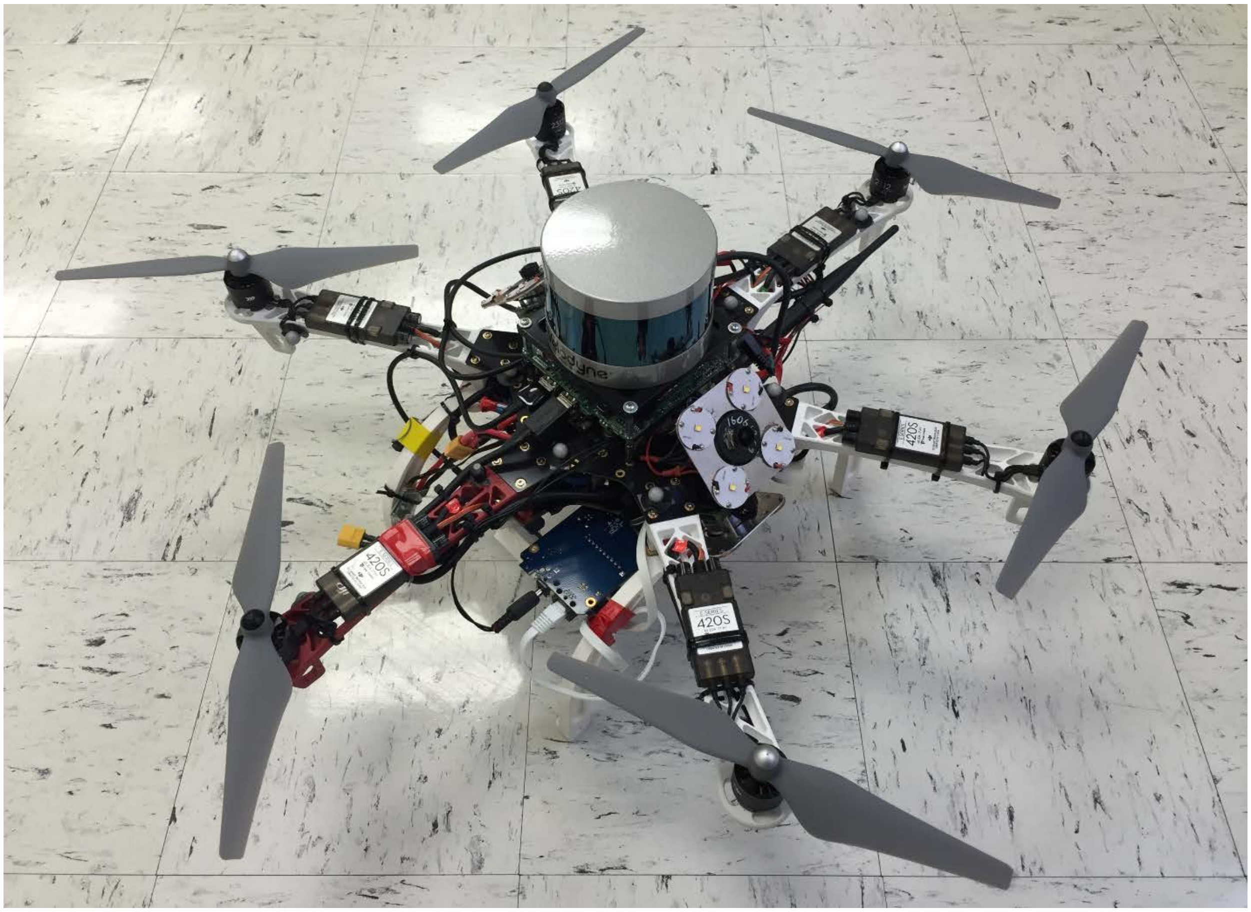

Figure 6. Tunnel Inspection UAS Version 3

Figure 7. Tunnel Inspection UAS Version 4

Figure 8. Tunnel Inspection UAS Version 5

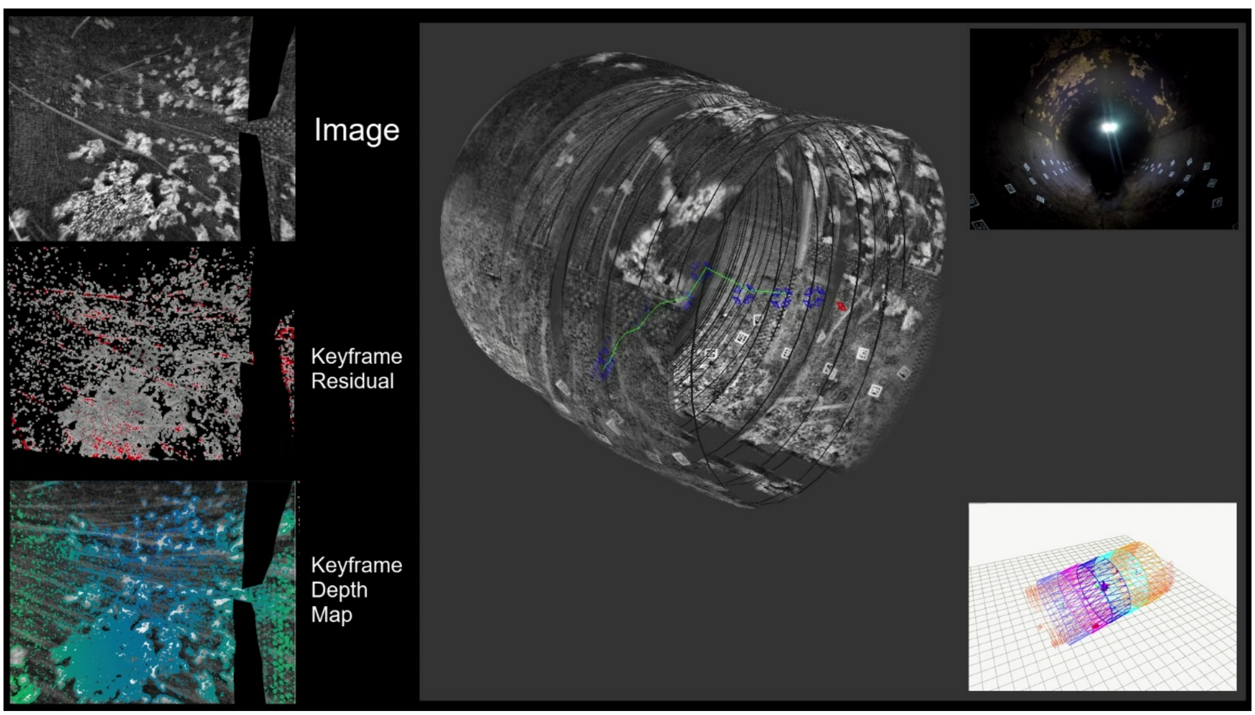

Figure 9. Example of image stitching to fit the tunnel circumference

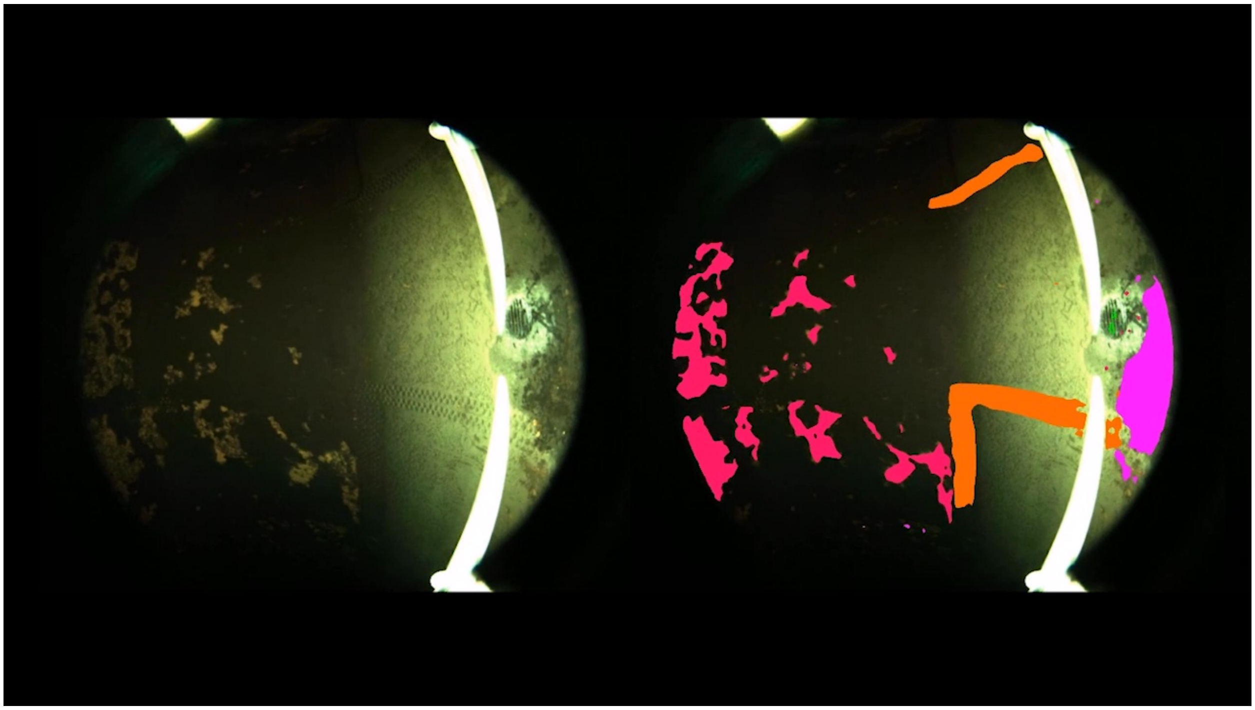

Figure 10. Automatic detection of features including rivets (orange) and corrosion (pink)

Appendix B – Tables

Table 1. Summary of Inaccessible Penstock Related Collaboration Activities

Date	Location	Purpose	Personnel
July 20-24, 2015	Glen Canyon Dam, Page, Arizona	UAS Penstock Testing and Demonstration	Matthew Klein, BOR Bobbi Jo Merten, BOR Tom Hood, USACE Cole Hood, USACE visitor Heath Harwood, USCACE UPenn Researchers
July 11-14, 2016	Center Hill Dam, Smithville, Tennessee	UAS Penstock Testing and Demonstration	Matthew Klein, BOR Heath Harwood, USACE Jennifer Wozencraft, USACE Tom Hood, USACE retired UPenn Researchers
December 8, 2016	TSC, Denver, Colorado	2016 USACE-USBR Research Team annual meeting	Matthew Klein, BOR Heath Harwood, USACE Jennifer Wozencraft, USACE
February 7, 2018	ERDC, Vicksburg, Mississippi	2017 USACE-USBR Research Team annual meeting	Matthew Klein, BOR Heath Harwood, USACE Jennifer Wozencraft, USACE
November 28, 2018	TSC, Denver, Colorado	2018 USACE-USBR Research Team annual meeting	Matthew Klein, BOR Heath Harwood, USACE Jennifer Wozencraft, USACE
May 28, 2019	TSC, Denver, Colorado	S&T UAS Research Training Workshop	Matthew Klein, BOR Jim Keller, UPenn

Table 2. Summary of Penstock/Tunnel Demonstrations

Test	Date	Location	Purpose
1	July 20-24, 2015	Glen Canyon Dam, Page, Arizona	Sensor calibrations and manual operation with position lock
2	July 11-14, 2016	Center Hill Dam, Smithville, Tennessee	Manual flight with optimization and camera improvements
3	October 25-27, 2016	Center Hill Dam, Smithville, Tennessee	Calibrate LIDAR and gate estimation for stopping
4	November 29-30, 2016	Center Hill Dam, Smithville, Tennessee	LIDAR positioning test to maintain offset
5	February 6-9, 2017	Center Hill Dam, Smithville, Tennessee	Semi-autonomous flight within entire penstock with new user interface
6	May 2-4, 2017	Center Hill Dam, Smithville, Tennessee	Added forward view camera and tested collision avoidance
7	October 10-11, 2017	Francis E. Walter Dam, Bear Creek Township, Pennsylvania	Small diameter test
8	April 10-12, 2018	Center Hill Dam, Smithville, Tennessee	New camera and LED test
9	August 1-2, 2018	Center Hill Dam, Smithville, Tennessee	Test precision of location estimator and camera sync/calibration