DamBot™: An Unmanned Amphibious Vehicle for Earth Dam Outlet Inspection

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ABSTRACT

The US Army Corps of Engineers (USACE) owns, maintains and operates several hundred locks and dams across the United States. A large portion of these structures have met or exceeded their design life, therefore the need to perform detailed inspections regularly has become increasingly important. Some of the challenges for inspection personnel are the hazardous conditions associated with entering dam outlet works, and the need to conduct the inspection within a short time frame so that the dam can resume normal operations and maintain downstream water levels.

These subterranean conduits are classified as confined spaces and can be several hundred meters long, have flowing water, and in some instances have toxic gases present. The USACE Engineer Research and Development Center (ERDC) has developed an unmanned amphibious vehicle, called DamBot™, to enter these outlet works with a sensor suite and perform first-look inspections of the conduit and closure gates. In order to carry out these inspections, DamBot™ is equipped with cameras and LiDARs to capture 360 degrees situational awareness around the platform, and a five-meter robotic arm with nine degrees of freedom to perform up close inspection of closure gates, which can be over six meters tall.

Additionally, the DamBot™ is able to capture data of the entire conduit during inspections, collecting a dataset that provides a comprehensive picture of the infrastructure. DamBot™ uses techniques such as simultaneous localization and mapping (SLAM) to assure positional accuracy of data collection in these GPS denied environments. These datasets can be post-processed into 3D models and can be used for structural health monitoring by way of change detection when compared with previous inspections.

DamBot™ has been successfully demonstrated at several active USACE projects, and this paper will detail the specifications of the system and discuss the results of field demonstrations, lessons learned, and future improvements to the system.

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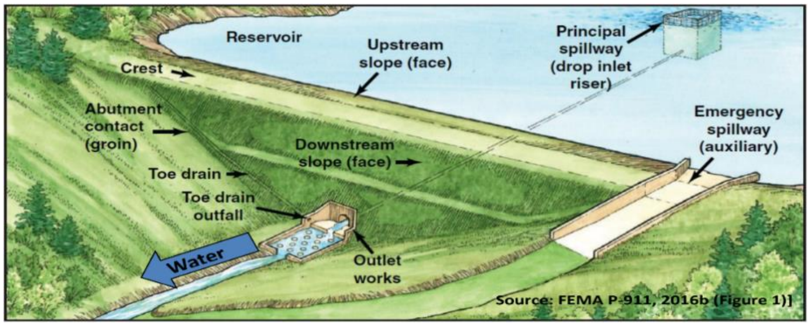

Figure 1. Earth Dam Overview [1]

BACKGROUND

As part of the USACE mission to maintain the Nation's water resources, the operation and maintenance of earth dams is critical to flood risk management. The US has a total of over ninety thousand dams including Federal, State, Local, and privately owned structures. Several hundred critical dam structures are directly in USACE's portfolio, each requiring regular inspection to prevent loss of life and property and ensure operational capability. Over half of these dams have currently exceeded the original lifespan assumed in the design process.

For earthen dams, the outlet works are an important inspection point. The dam's outlet works controls the water level of the reservoir pool by discharging water downstream and is controlled via closure gates, usually located at the upstream end of the conduit located on the bottom of the lake (Figure 1). These subterranean conduits can be several hundred meters long and are classified as confined spaces, including risk factors such as single entry/exit, flowing water, and in some instances, toxic gases. This environment presents inspection personnel with a variety of risks, including slips, ctrips, falls, low light, engulfment, low oxygen, and toxic gas. Additionally, the flowing water can be challenging to traverse upstream, and the structure size can be too narrow and too long for effective use of the current generation of commercially available unmanned aerial vehicles (UAVs). For these reasons, in order to reduce risk to human personnel, ERDC has developed an unmanned amphibious vehicle, DamBot™, to establish a first look at the conduit and closure gates and provide situational awareness of the infrastructure.

In order to carry out these inspections, DamBot™ is equipped with a combination of seven cameras (five RGB and two LWIR) and five LiDARs (three of the common spinning beam lidar and two long-range, directional lidar). The platform also includes a five-meter robotic arm with nine degrees of freedom to perform up close inspection of the closure gates, which can be over six meters tall.

Additionally, the DamBot™ is able to store hours of image and lidar data onboard the platform, ensuring the entire conduit can be captured during a single inspection, collecting a dataset that provides a comprehensive picture of the infrastructure. DamBot™ also uses techniques such as simultaneous localization and mapping (SLAM) to ensure positional accuracy of data collection in these GPS-denied environments and provides autonomous exit capabilities in case of a loss of communication. These datasets are post-processed into 3D models and used for structural health monitoring by way of change detection when compared with previous inspections.

DamBot™ SYSTEM DESIGN

Figure 2. Site Variation across Outlet Works

One of the primary challenges with designing an infrastructure inspection tool for USACE dams is the variation in design across the country. The first task in creating the DamBot™ was to perform site surveys at several dams in many different locations from the Southeast to the Northwest to assess the feasibility of different commercially available off the shelf (COTS) amphibious platforms. Each dam is built in unique environments with unique design considerations by different contractors, resulting in differences in shape, size, and capacity, as well as the construction methods and materials (Figure 2) [2]. These variations in the dams themselves coupled with the differing construction techniques for the tailwaters, require a robust system that can navigate to, enter, and inspect large subset of these structures.

Hardware

The DamBot™ is built on top of the COTS Argo J8 platform with a preinstalled teleoperation kit from Provectus. The J8 was chosen due to its amphibious capabilities, easy-to-configure deck, large payload, and maneuverability both on land and in the water as well as a proven track record (it is based on a system initially designed in the early 1960s [3]. While running the ERDC-developed computational and sensor stack, the J8 can provide up to seven hours of battery life between charges.

The main computational stack consists of a thirty-two-core AMD Ryzen Threadripper 3970X with 128Gbytes of RAM and a NVIDIA RTX 2080Ti, both of which are water-cooled with external radiator to allow for operation in a sealed case in outdoor environments. A 10GbE network switch handles communication and data transfer between the primarily ethernet based onboard sensors and computers.

The sensor/perception stack is built with five 7.1 megapixel cameras arranged for 360° viewing around the platform. These cameras are also used for color projection on points collected by the five LiDAR systems on board. A fiber-optic gyroscope and an inertial measurement unit are also installed to aid in localization. All of these sensors are sampled at 10Hz, resulting in approximately 20GB of data recorded every minute.

Figure 3. Operator View

The panoptic RGB camera array includes a horizontal ring of four cameras and a single upward facing camera to achieve a hemispherical field of view (FOV) of the conduit, shown in **Error! Reference source not found.**. Two additional LWIR cameras are arranged to achieve a 180° forward arc. The two long-range directional lidars (front and rear) provide long-range localization in a long dam conduit, while the three spinning lidars provide coverage for mapping. These sensors are weather-hardened to operate in high temperatures and with water spray.

Robotic Arm

The inspection of dam closure gates is of utmost importance to ensure the safety and reliability of dams. One of the main challenges in inspecting these gates is their size and occasionally complex geometry, which can make it difficult for inspectors to obtain accurate and detailed data. To address this need, a five-meter robotic arm with nine degrees of freedom has been added to the robotic platform (Figure 4). With its long reach and flexible movement, this robotic arm can access even the most hard-to-reach areas of the closure gate, allowing for a comprehensive and detailed inspection. The high-resolution scans produced by the arm can capture detailed surface data, including any

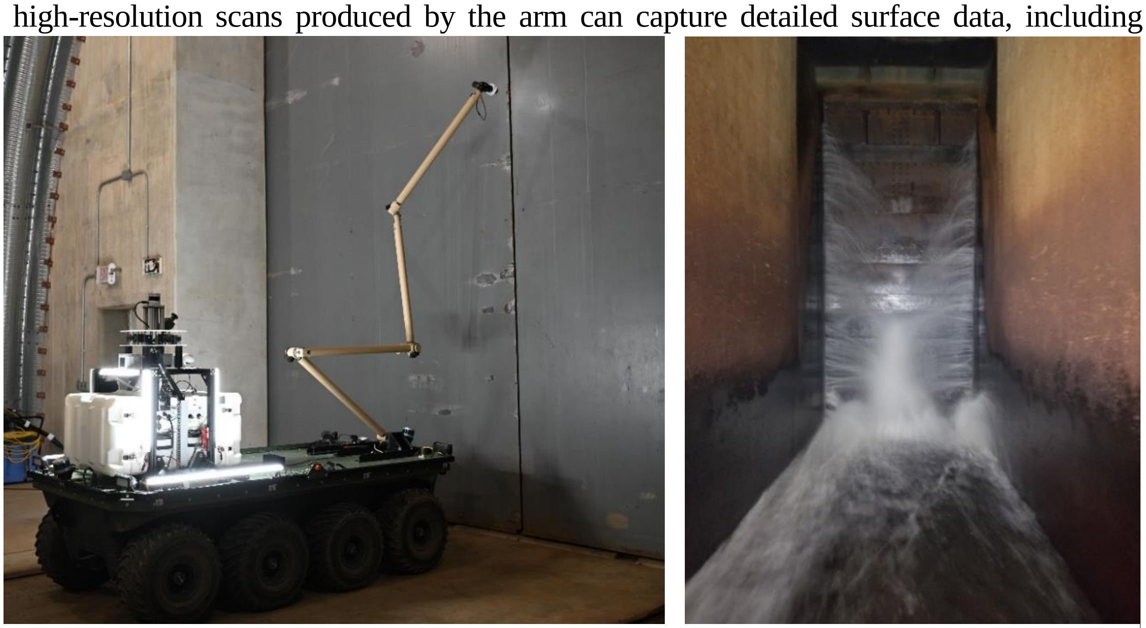

Figure 4. a.) Dambot™ tests the new robotic arm before deployment b.) Example of closure gate geometry

cracks, deformations, or other potential issues that could compromise the gate's safety. Additionally, the nine degrees of freedom enable the end effector to maneuver around the complex geometry of the gate, providing a level of precision and accuracy that is difficult to achieve with traditional inspection methods. This arm has been successfully tested in the lab and field in early 2023.

Software

Onboard, the DamBot™ must be more than a data logger. The conduit of the outlet works is deep underground and rebar reinforced. This can interfere with magnetometers and prevents the effective use of GPS and standard radio communication methods. The operator must currently rely on high power military radios to communicate with the platform during operation. The bandwidth of these radios are limited and connection can be intermittent during operation. Although future work will use additional platforms to daisy chain multiple radios into a mesh down the conduit, the DamBot™ must ensure continuous operation when communication fails, requiring all processes to be run onboard.

To achieve this mission, our team chose the Robotic Operation System (ROS) as the main software framework for the DamBot which enables real-time data collection, processing, and teleoperation. To reduce bandwith over the network, the operator uses a remote desktop application to view RVIS (and other ROS GUI’s), to display live sensor feeds during operation and control the robot.

The software stack used in the DamBot™ includes techniques such as simultaneous localization and mapping (SLAM) through RTABmap [4] to ensure positional accuracy during data collection in GPS dead zones like that of the conduits in outlet works. If the connection to the operator is lost, the platform can use this map to autonomously and safely retreat to the gate entrance for retrieval.

Once the data is collected, the DamBot™ software processes it into a comprehensive dataset that provides a detailed picture of the infrastructure (Figure 5). This dataset can be used for structural health monitoring, as change detection techniques can be applied to compare the current inspection with previous inspections. This analysis can identify any changes or damage that have occurred, allowing for maintenance and repairs to be performed as necessary. Additionally, the 3D models generated from the data can be used for visualization and analysis, providing a powerful tool for engineers and maintenance personnel to understand the condition of the dam conduit. In summary, the software used in the DamBot™ is essential for enabling accurate data collection, mapping, and

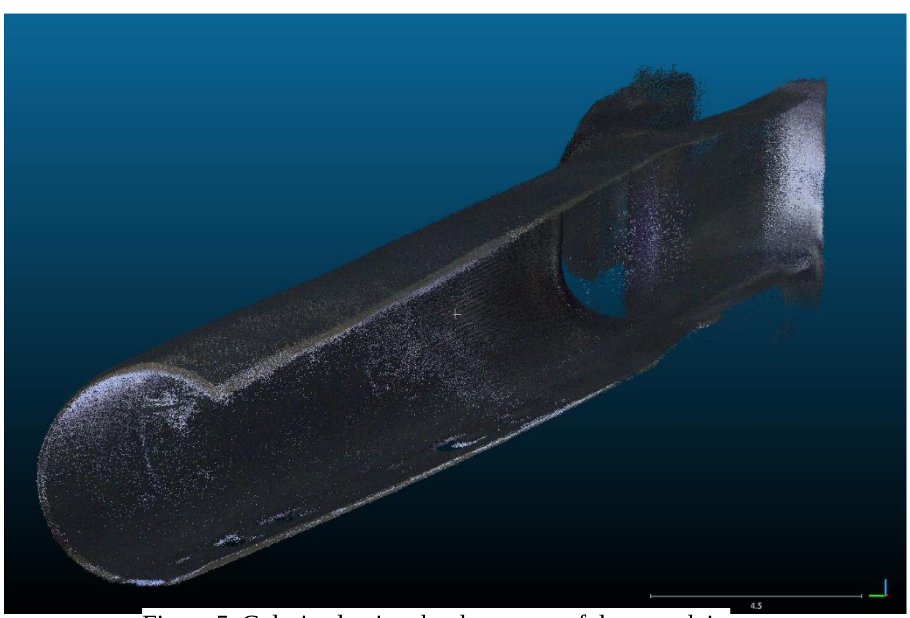

Figure 5. Colorized point cloud segment of dam conduit

analysis of the dam conduit, ultimately contributing to the safety and reliability of the dam infrastructure.

FIELD DEMONSTRATIONS

The DamBot™ platform has gone through several design iterations that were tested and evaluated at active dams across the United States, primarily in the Southeast. While some development is being performed in modeling and simulation, these field demonstrations are opportunities to provide meaningful data to project operators and also to identify ways to improve the system.

The first demonstration was in late 2020 and primarily focused on collecting imagery from a conduit and generating point clouds. In this test, the robot was driven by an operator who entered the conduit and remained within sight of the platform at all times. Results from this test showed the need for additional lighting systems to capture more evenly lit images (Figure 6). A year later, the same conduit was inspected in a fully teleoperated mode, from a command trailer stationed 100m from the entrance to the outlet works. While the teleoperation was successful over the 400+ m long conduit, additional imaging issues presented themselves in the form of motion blur, an issue that was addressed for subsequent deployments.

The second demonstration site was evaluated in late 2022. This project presented new challenges, such as a long swim in the tailwater (800m) to reach the outlet, and a dark biogrowth on the conduit walls, prompting the installation of even more lighting.

The third and most recent deployment was in early 2023. This deployment was the first test of the robotic arm in a relevant operational environment. The platform was successfully operated from 100m outside of the 200m conduit, including operation of the arm (Figure 7). The arm remained approximately 10m from the closure gates, since the platform could not approach the gates due to narrowing of the conduit where it divides for the three gates. An Oak-Pro D stereocamera was mounted to the end effector, allowing for low-light image capture as well as an autofocus feature to support the movement of the arm.

Data from this deployment is still undergoing post-processing. All systems functioned as designed, apart from a burnout on the lighting controller. Given this failure, the lighting output was reduced from approximately 500W to 100W only. Even with this limited lighting, features can be identified in the conduit.

Figure 6. Comparison of Lighting System Improvement

Figure 7. Robotic arm deployed and view from the end effector

Additionally, the onboard SLAM had challenges due to the approximately 50m at the beginning of the conduit when the platform was swimming, i.e., wheel odometry was not accurate. Without the accurate wheel odometry, localizing through the length of the conduit is extremely difficult. The projected GPS coordinates for poses relies heavily on this odometry and cannot be trusted for reconstruction purposes. Adoption of a purely visual/LiDAR based odometry will be necessary to infer positioning.

During these evaluations, the DamBot™ demonstrated its ability to produce high-resolution 3D scans of the dam conduits and ground-level views of the closure gates. The 3D scans produced by the DamBot™ provide a comprehensive picture of the infrastructure, enabling engineers and maintenance personnel to easily identify any damage or changes in the dam's structure.

FUTURE WORK

As we continue to push the boundaries of robotics in the field of dam inspection and maintenance, we are constantly seeking to enhance the capabilities of the DamBot™ platform. To this end, we are currently exploring additional features and functionalities that will enable the platform to operate autonomously in a wider range of environments and situations.

One of the developments in this regard is the ongoing work to develop a 3D frontier exploration approach for the DamBot™'s robotic arm. This capability will allow the platform to scan unknown 3D surfaces, such as the closure gates, autonomously and with precision localization. By using advanced algorithms and sensing technologies, the DamBot™ will be able to explore and map these surfaces in real-time, providing a high-resolution 3D model that can be used for further analysis and monitoring.

Additional work is underway to miniaturize the robotic platform. While the Argo J8 base for an inspection vehicle is suitable for many dams, there are also dams that are too narrow to comfortably fit the J8 while operating remotely. We are currently working on the development of a miniaturized version of the robotic platform to expand its usability for dam inspections. Our team is exploring options for a more compact design that will allow for efficient and effective inspections in all types of dam structures. Additionally, imaging systems developed in partnership with the University of California, San Diego [5] will be integrated and tested on these smaller robotic platforms.

A few other small improvements include more robust lighting controller to control individual light strips, increasing camera resolution to 20megapixels each, as well as the addition of short-wave infrared cameras.

This technology represents a significant advancement in the application of robotics to inspection, with far-reaching implications for the inspection and maintenance of critical infrastructure such as dams. With enhanced autonomous capabilities, the DamBot™ will be able to operate in more challenging and complex environments, providing accurate and reliable data for engineers and maintenance personnel.

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