RECLAMATION

Managing Water in the West

Viability of Computer/Robotic Controlled Penstock Coating Removal and Application

Research and Development Office

Science and Technology Program

(Final Report) ST-2016-4047-1

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

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Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

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.

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14. ABSTRACT *(Maximum 200 words)*

This scoping (literature search) proposal investigates whether technology has advanced to the point where robots can remove and apply coatings within hydro-dam penstocks. It was noted during a Value Study that 30 to 40 percent of the costs for a related project were associated with entry, access, and reducing risk associated with the work due to human activities. Using robots would significantly reduce costs and increase safety. The result of this research is; while there is no single robot that can perform all needed tasks (remove existing coating, inspect surface, and apply new coating), there are existing robots that could perform each individual task. Numerous applications for the use of the technology exist within the public and private sectors. CEATI is an international Research and Development (R&D) organization of which Reclamation is a member. Reclamation should consider developing and partially fund a proposal through CEATI to prove and expand the existing technology for use in penstocks in the aging hydro-electric dams throughout Reclamation's inventory.

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(Signature)

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Executive Summary

This scoping proposal is for a literature search. The intent of this proposal is to answer the following questions;

- Has technology advanced to the point where robots are a viable alternative to human labor to remove and apply coatings to the interior surface of hydro-dam penstocks?
- Which private and public sector entities would benefit from development of the technology?
- Would those that benefit from the development of the technology be interested in a partnering opportunity to develop or prove out the technology?
- What would be the logical path and likely economic level of support for such a partnership?

The inception of this scoping proposal was from a Value Study conducted at Grand Coulee Dam (*Grand Coulee G1 to G18 Penstock Coating Repair*, April, 2015). During the study, a functional diagram of the cost was developed to enhance the study team members' understanding of the project. It was noted by the team that 30 to 40 percent of the costs involved were to allow human entry, to build scaffolding for human access, and to reduce health and safety risks associated with human work activity. Therefore, if the human element of this work could be significantly reduced so would the cost of the work.

The Bureau of Reclamation's (Reclamation's) aging infrastructure includes numerous sites where the interior lining of steel pipe or conduit requires maintenance. These spaces are considered confined spaces because, during normal operations or maintenance, human occupation would be hazardous to health and life. Significantly removing the human element would correspondingly reduce the safety risk of human exposure for the work.

British Columbia Hydro (BC Hydro) is a similar governmental entity to Reclamation in Canada. BC Hydro also has an interest in the viability of robots for use in penstocks. They recently commissioned a report from a Consultant, Traxx Automation, Ltd (*State of Technology Report: The Use of Robotic Technology for Penstock Recoating*, July 2015). BC Hydro also received a report from their subsidiary, Powertech Labs (Penstock Coatings System and Applications Memo) which included a discussion of the automation opportunities for penstock coating. Traxx and Powertech evaluated three tasks for the robots; coating removal, optical inspection, and coating application. The results of their study are that, while there is no single robot that can perform all of the tasks, there are existing robots that can do each of the individual tasks. However, they still recommend human inspection over that of the robotic technology.

The Center for Energy Advancement through Technological Innovations (CEATI), Int is a multi-national Research and Development (R&D) organization. It currently has over 120 member organizations, private and public. CEATI boasts a library of over 2,000 published reports and is currently managing over 150 on-going projects in all areas related to the power grid. Member agencies and corporations in the United States include; US Army Corps of Engineers, US

Department of Energy, Tennessee Valley Authority, PG&E, New York Power Authority, Southern California Edison, and the Bureau of Reclamation.

Accepting funds from other entities, especially from the private sector, has been problematic for governments. Therefore, the logical path for an internal investigation of the technology would be to manage a development project in the private sector. However, it would be a daunting task to set up an inter-agency Memorandum of Understanding so that funds could be obligated to share the costs for the project between agencies. Including private sector entities would be nearly impossible to achieve under a governmental umbrella.

As Reclamation is already a member of CEATI, achieving the intended results would be as simple as putting forth a proposal and obligating funds for a project. Using the CEATI organization to develop or prove out technology would provide a large pool of private and public cooperation of partners. No additional memorandums or inter-agency agreements would need to be drafted. Public and private partners could easily financially support the project without governmental red tape.

The next step for development of the technology is to assemble a team to manage a project. The team shall consider; what parts of the project can be completed with CEATI support or should be fully completed internal to Reclamation; what test sites are available; and, what monetary support would be required depending upon the recommended course of action.

Background

This scoping proposal had its inception during a Value Study of the *Grand Coulee Left and Right Powerplants, Coatings Repairs for Units G1 through G18 Penstocks* Project (April, 2015). During the study the team developed functions for the project to enhance their understanding and look at the project in a logical fashion. After constructing the Functional Analysis systems Technique (FAST) Diagram, the team assigned costs to the functions (Figure 1). It was noted that 30 to 40 percent of the cost of the project was to allow for human entry, to access the workspace for human application of the coating, and to reduce the safety risk of human occupation. Table 1 provides the team's understanding of the tasks associated with the highlighted costs.

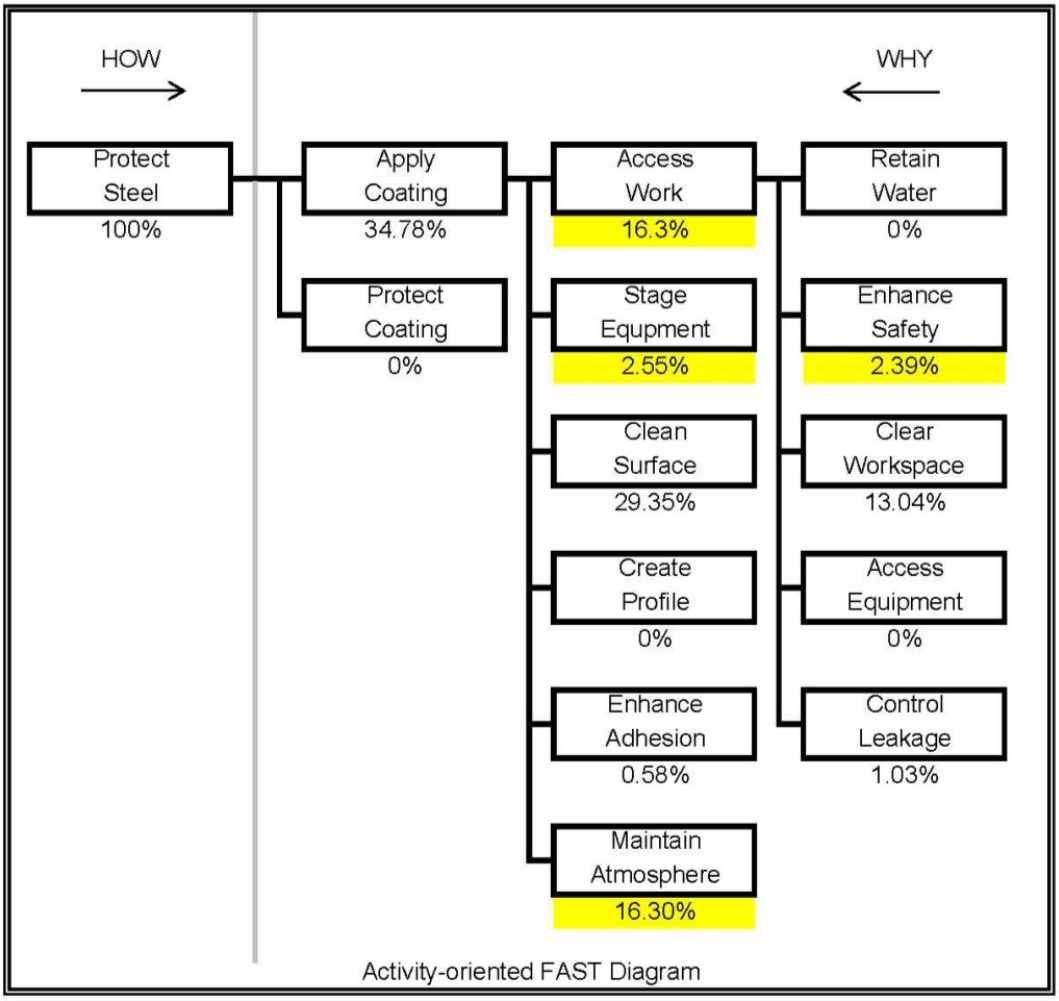

Figure 1. Functional Analysis System Technique (FAST) Diagram with Costs

It is important to note that adding the percentages equates to more than 100 percent. This is because some of the costs perform multiple functions. However, the team used this activity to enhance their understanding and note where function cost-mismatches occurred. While there is

some overlap in the costs (116%), the exercise is valid at the appraisal level of the estimate for the studied project. Additionally, it is a fair and reasonable assessment of the costs for each function.

Table 1. Description of Functions with Related Costs

Function	Description	% Cost
Access Work	Design and mobilize scaffolding and additional support functions	16.3
Stage Equipment	Move scaffolding to each penstock as work progresses	2.6
Maintain Atmosphere	Ventilation for temperature, health and humidity control	16.3
Enhance Safety	Industrial Hygienist and other related controls	2.4
		37.6

Further, it is important to note that not all of the identified functions or their associated costs would be eliminated by using robots in lieu of humans to complete the studied work. However, if even 15 to 20 percent of a project such as Grand Coulee's penstock recoating could be saved, then for this project it would equate to $1.5 - 2 million in savings. Given, Reclamation's aging hydro-power infrastructure and the large number of facilities, the consideration to employ robotic technology represents an opportunity to Reclamation and the American Taxpayer that should not be ignored.

Yet, the cost benefits from investigating and developing robotic technology for this application is only a minor piece of the puzzle. Reclamation is very proud and protective of our "Safety First" philosophy and the work in penstocks is extremely hazardous because of the confined space in which it occurs. On October, 2007, a chemical fire inside a penstock at Xcel Energy's Cabin Creek, hydroelectric plant in Georgetown, Colorado resulted in five lost lives and three injuries. This example of tragic loss of life could be avoided with the development of robotic technology for this application.

Literature Review

British Columbia Hydro (BC Hydro) is a government agency in British Columbia, Canada operating 31 hydroelectric facilities and two geothermal plants. It might be considered a cousin agency to Reclamation. BC Hydro demonstrated their interest in this technology by hiring a consultant, TRAXX Automated Ltd. (TRAXX) to provide a *State of the Technology Report: The Use of Robotic Technology for Internal Penstock Recoating*, July 2015. A copy of the report was provided to Powertech Labs, Inc., a BC Hydro subsidiary, for further review and discussion within their memo, Penstock Coating Systems and Application Memo.

The technology and service providers investigated by TRAXX came from two sources; a market sounding request for information (RFI) issued by BC Hydro and independent research performed by TRAXX. A total of 33 technology and service providers were identified; 19 robotic systems for penstock cleaning, 12 for inspection and quality assurance, and 7 for coating application.

Robotic Platforms

TRAXX identified four predominate types of robotic platforms. A robotic platform is defined as the portion of the robot responsible for delivering and manipulating its payload tools. The robotic platforms have been defined as; *cart crawlers*, a platform that is supported underneath by a set of wheels or tracks; *vacuum crawlers*, a platform that uses vacuum to adhere to a surface thereby allowing it to climb vertical walls and even ceilings of any material; *magnetic crawlers*, a platform that uses magnetic wheels, tracks or belts to adhere to a ferrous surface thereby allowing it to climb steel walls and ceilings; and, *pipe crawlers*, a platform that use multiple sets of wheels or tracks to brace against opposing sides of the pipe.

Cart Crawlers

Cart Crawlers are the most versatile of the platforms. They range from simplistic (providing only power for moving forward) to advanced systems (providing autonomous navigation, programmability, remote control and automatic adjustment to changing pipe geometry). Many cart crawlers use the pipe geometry to keep them on course; which may result in problems at sharp horizontal bends. Additionally, because the pipe crawler uses only its weight and friction at the bottom of the wheel/track to move, it is limited in its ability to climb steep or slippery slopes without additional winching equipment.

Figure 2. Inuktun cart crawler

Vacuum Crawlers

Vacuum crawlers use locomotion provided by powered wheels, tracks or multiple vacuum seals that allow the robot to step or slide incrementally. The vacuum crawlers have difficulty maneuvering on slippery or highly curved surfaces as their wheels or tracks must overcome the force of the vacuum seal. These platforms were originally developed to clean the exterior of ship' hulls which have a relatively large radius of curvature and very uniform surfaces.

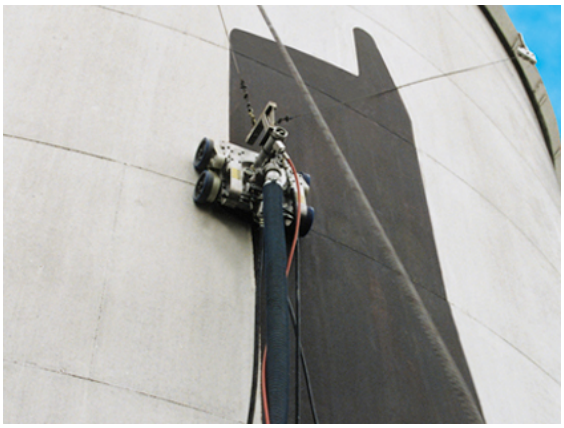

Figure 3. Flow corp vacuum crawler

Magnetic Crawlers

Magnetic crawlers are typically smaller and lighter in order to avoid overcoming the magnetic force that supports the crawler and its equipment. They can only be used on ferrous surfaces. They are often compared to and have similar advantages and disadvantages to the vacuum crawler.

Figure 4: VertiDrive M3 magnetic crawler

Pipe Crawlers

Pipe crawlers systems can increase the track or wheel reaction forces to gain greater traction, allowing them to travel on larger inclines and pull their umbilical farther than the other crawlers. However, due to their size, they require larger opening to access the pipe interior and may require some assembly once inside. Additionally, while more stable than cart crawlers, they have difficulty with changes in pipe diameter or sharp turns without additional structural complexity.

Figure 5: Stock photo of a robotic pipe crawler

Cleaning/Surface Preparation

Among the four robotic platforms, two main methods of cleaning and surface preparations are available; ultra-high pressure water jetting (UHP WJ) and abrasive blasting (AB).

UHP WJ is the most common method developed for the robotic platforms. UHP WJ is defined by the Society for Protective Coatings (SSPC) as water jetting performed at pressures greater than 30,000 psi (210 MPa). UHP WJ is an effective method for cleaning steel, but may not be able to create the desired surface profile for coatings.

High velocity blasting employs propelling a solid media at a surface to clean and create the desired surface profile. Historically, AB is done using human workers, not robotic equipment. Only some AB methods are reliable and effective in creating the SSPC SP10 profile required for immersion service coatings (i.e. penstock interiors).

Comparisons

TRAXX compared the systems and services to achieve three general tasks; remove the existing lining, inspect the resulting surface for an acceptable profile; and, apply new lining in penstock.

An objective rating system was devised to assess the systems or service to achieve relevant tasks. For evaluation, criteria were developed for common requirements (24), cleaning (5), inspection (6), and coating application (10). The criteria were weighted from 1 to 4 (optional = 1, desired = 2, recommended = 3, required = 4) depending upon the perceived criticality for the project. Each system or service was scored regarding how well it achieved the common and task specific requirements. Scores were given as 1, 0.5, or 0, depending upon how well it met the requirement. If no information was provided to allow a scoring, the criterion was left blank.

A weighted score was calculated for each requirement by multiplying the criteria weight with the raw score to achieve the criteria. Further, two evaluation scores were calculated from all of the weighted scores. The Requirement Compliance Score (RCS) is a percentage of the total calculated weighted score divided by the maximum achievable score.

$$RCS\ (\%)\ = \frac{\sum weighted\ requirement\ scores}{Maximum\ possible\ requirement\ score}$$

The Information Availability Score (IAS) is a percentage of the number of requirements rated divided by the total number of requirements.

$$IAS\ (\%)\ = \frac{Number\ of\ available\ requirement\ scores}{Total\ number\ of\ Requirements}$$

Given the raw score and these percentages (RCS and IAS), a complete picture is provided of the system or service for; how well it achieved the rated requirements for the intended tasks, how well it scored within the requirements that could be scored, and how many of the total requirements had adequate information for which it was scored. A system or service having a high raw score might have a poor final result due to low RCS and IAS percentages. A system with a lower raw score but higher percentages would be preferable because the system or service demonstrated a larger number of achieved requirements and, therefore, less risk of the unknown.

State of the Technology

TRAXX Automation developed a comprehensive *State of the Technology Report; The Use of Robotic Technology for Internal Penstock Recoating(July, 2015)* for Powertech Labs and BC Hydro to explore the current robotic capabilities in achieving internal penstock cleaning, inspection, and recoating. They reviewed and filtered submissions to include 33 systems or suppliers. They developed a rating system to provide three relevant scores to compare the available systems; raw score, RCS, and IAS. A system with a high raw score, but without comparable RCS and IAS scores is *not* a viable system.

The report concludes that there is no single robotic technology that is capable of completing all three tasks on the market today. However, there are a small number of robotic systems that could meet some (not all) of the requirements and a large number of robotic systems that could be adapted to penstocks with some development.

Additional research and development is required to achieve the required tasks. Additionally, strong specifications and contracts need to be developed. It may also be necessary to reduce the quality or safety requirements developed for the comparison. Given the current state of the technology for each task, it appears that:

- It will likely be necessary for personnel to enter the penstock to set-up the system, and/or manually clean or coat difficult internal features.
- Personnel may be required to enter the penstock to operate and/or confirm correct operation, as most currently available systems rely on operators to be within the line of sight.
- For the cleaning and coating tasks, more access points to the interior of the penstock would be needed to allow short distance work (less than 1000 feet). This constraint is directly related to the umbilical cord required to import material for the work.
- Some development may be required to add sensors for coating defect detection, surface preparation profile, and dry/wet film thickness measurements onto the robotic systems.
- Additional effort may be required for conduits with riveted or bolted construction. The robotic surface preparation and coating application equipment may not coat these features adequately.

The rated information for the most promising systems and services were received from Abhe & Svoboda (RCS, 86; IAS, 100; Minnesota), Aqua Drill International (RCS, 83; IAS, 100; Sweden), and PRD Company (RCS, 81; IAS, 95; California). These ratings were assigned by TRAXX at the time of the reporting (July, 2015). It is likely there are undiscovered companies that have or could develop the capabilities after the research was completed. Additionally, there may be developments within the industry that could change the ratings assigned to the companies if the research is duplicated.

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Partnership Opportunity

There is likely to be objections to Reclamation (and the US tax payer) paying to solely develop and prove systems that will be used by multiple other agencies, corporations, and governments. Reclamation is the single largest wholesaler of water in the United States. However, hydro-power generation is a secondary consideration to our mission. On the other hand, there is also likely to be objections from other public agencies and private corporations paying for improvements to a site for which they will see no benefits or profit. Therefore, this scoping proposal also develops an available partnership opportunity.

The Center for Energy Advancement through Technological Innovations (CEATI), International is a research and development organization. With over 120 members, CEATI is represented in public agencies and private corporations across the globe. CEATI boasts a library of over 2,000 published reports and is currently managing over 150 on-going projects in all areas related to the power grid. Member agencies and corporations within the United States include, to name a few; US Army Corps of Engineers (USACE), US Department of Energy(DOE) , Tennessee Valley Authority (TVA), Pacific Gas and Electric (PG&E), New York Power Authority, Southern California Edison, and the US Bureau of Reclamation (Reclamation). A number of Canadian Hydro Electric Utilities, including BC Hydro, are members of CEATI. Developing a proposal for CEATI development, provides Reclamation with the opportunity to leverage worldwide support and brings any developed and proven product to the market sooner.

The next step for developing a proposal with CEATI is to define the problem, project and assemble a project team needs to identify:

- What parts of the project can and should be completed with support from CEATI and what parts need to be wholly internal to Reclamation?
- What viable test sites are available without impact power generation or reservoir operations?
- What monetary support can Reclamation offer to back the CEATI proposal?

Once a request for studies or research (referred to as project) is presented to the CEATI organization, and interest from multiple member agencies is, proposals from consultants or organizations that can complete the project would be solicited. The CEATI members that have interest in sponsoring the project will assist with the proposal evaluation and selection. The CEATI members that sponsor the project would split the cost of completing the work and provide representatives to review and accept the deliverables. Member organizations that provide monetary support for the project obtain copies of the results so they can apply the results and technology to their facilities.

The alternative to using the CEATI organization is to develop an internal program through which Reclamation can prove out the technology for our use. Individual Memorandums of Understanding (MOU's) would be required to leverage support of other US agencies. Corporate involvement in the project would require purchasing R&D services similar to the programs run by the Department of Defense (DOD). Some advantages of an internal or multi-agency program

over that of developing a CEATI proposal are that Reclamation (and participating agencies) would have full control over the desired outcome and could move the project forward at our pace. Some disadvantages are Reclamation (participating agencies, and the American tax payer) would pay for the development of a system that would be used the world over. Reclamation would not be in full control of the desired outcome, and the project would move at the pace of the support garnered from the CEATI membership.

Conclusion

No single robot can achieve all three key tasks (i.e. surface preparation, coating application, and quality assurance/control inspection). However, there are robots that can achieve each individual task with varying degrees of success and numerous limitations. None of the available technology appears to meet all of the desired capabilities and some of the technology is considered to be immature as it has not be reliably proven on penstock recoating projects. Most of the available technology was developed for applications other than hydro-power penstocks (ship hulls, municipal pipelines, water storage tanks, etc.). Therefore, the technology needs to be developed and proven for use in hydro-power penstocks before the potential benefits can be realized (i.e cost reduction and reduced worker safety risks during recoating projects). Issues related to the current technology include: range limitations, size of available openings vs size of equipment vs size of penstock, need for workers to enter to assemble and monitor automated equipment performance, lack of availability to monitor or measure work that can be done by traditional means (i.e. workers inside the penstock) due to lack of integration of required sensors in the equipment that is currently available.

Recommendations

Given the potential benefits for cost savings and reduced safety risks for penstock recoating projects, it is recommended that technology research and development into automation of penstock recoating tasks be completed.

Reclamation should use the CEATI organization to foster collaboration between organizations. Such collaboration would allow the organization that would directly benefit to contribute to the development of the technology.

Once the research and development is started, the following items would need to be completed: commit funding to support the relevant CEATI projects, select a test site to prove the technology, and Reclamation staff would need to contribute time to support the project.

Abbreviations and Acronyms

AB	abrasive blasting
BC Hydro	British Columbia Hydro
CEATI	Center for Energy Advancement through Technological Innovations
DOD	US Department of Defense
DOE	US Department of Energy
FAST	Functional Analysis System Technique
IAS	Information Availability Score
MOU	Memorandum of Understanding
PG&E	Pacific Gas and Electric
R&D	Research and Development
RCS	Requirement Compliance Score
Reclamation	US Bureau of Reclamation
RFI	Request for Information
TRAXX	TRAXX Automation Ltd.
TVA	Tennessee Valley Authority
SSPC	Society for Protective Coatings
UHP WJ	Ultra-high Pressure Water Jet
USACE	US Army Corps of Engineers

References

State of Technology Report: The Use of Robotic Technology for Penstock Recoating; Traxx Automation, Ltd. (July 2015)

Penstock Coating Systems and Application Memo; Powertech Labs (July, 2015)

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