Underwater Remotely Operated Vehicle (ROV) Data Collection at Reclamation Sites

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This report outlines a basic introduction to remotely operated vehicles or ROVs and their operation within Reclamation in 2022 and prior. The report also provides a summary of the current state-of-the-art of ROV technology with recommendations to how Reclamation could improve its deployment of ROVs with respect to data collection.

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Cover Photo: A Deep Trekker ROV in operation as part of a demonstration

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Acronyms and Abbreviations

2D	2-Dimensional
3D	3-Dimensional
ACFM	Alternating Current Field Measurement
ASDSO	Association of State Dam Safety Officials
ART	Acoustic Resonance Technology
AUV	Autonomous Underwater Vehicle
CPN	Columbia-Pacific Northwest
DFT	Dry Film Thickness
DVL	Doppler Velocity Log
EIS	Electrochemical Impedance Spectroscopy
F	Fahrenheit
GCPO	Grand Coulee Power Office
GPS	Global Positioning System
H	Height
IMCA	International Maritime Contractors Association
IMU	Inertial Measurement Unit
L	Length
LBL	Long Baseline
LCB	Lower Colorado Basin
LiDAR	Light Detection and Ranging
MFL	Magnetic Flux Leakage
NDT	Non-Destructive Testing
PA	Phased Array
PAUT	Phased Array Ultrasonic Testing
PECA	Pulsed Eddy Current Array
pH	Potential of Hydrogen
Reclamation	Bureau of Reclamation
ROV	Remotely Operated Vehicle
TSC	Technical Service Center
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
USBL	Ultra-Short Baseline
USV	Unmanned Surface Vessel
UUV	Unmanned Underwater Vehicle
UT	Ultrasonic Thickness
W	Width
WT	Water Tracer

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Executive Summary

An ROV, or remotely operated vehicle, refers to a type of robot that is typically operated underwater. The main components of an ROV include the vehicle, controller, and tether to send controls and receive telemetry and video feedback. There are several classes of ROVs mostly categorized by weight and function, the smallest ROVs carrying only a camera and lighting and weighing about 10 pounds out of water, and the largest ROVs carrying specialized equipment and weighing several tons. Other types of ROVs include AUVs, or autonomous underwater vehicles, towed vehicles, remotely operated waterproof crawlers, and USVs, which are unmanned surface vessels.

While the first recorded use of ROVs at the Bureau of Reclamation was not uncovered in this research, ROVs have been used for at least 25 years. In 1998, an ROV was used at Anderson Ranch Dam to inspect the intake structure fixed wheel gate. ROVs have either been contracted or traditionally operated by members of Reclamation's dive team out of Boise, Idaho (Columbia-Pacific Northwest (CPN) Region) or Boulder City, Nevada (Lower Colorado Basin (LCB) Region). However, ROVs have also been owned and operated by some facilities like Shasta Dam and Grand Coulee Power Office (GCPO).

This research focused mainly on identifying the current equipment and applications of ROVs within Reclamation and researching the current ROV technology both in the operation of the ROV and sensors that can be placed on the vehicle for data collection. Finally, the research sought to identify gaps in Reclamation's current use of ROVs and the state-of-the-art in order to make recommendations for future upgrades and capability.

The findings in the research point to three recommendations (listed below) based on consideration of issues related to ROV piloting expertise, comparison to unmanned aerial system (UAS) technology, and costs. Operating an ROV is more challenging than other types of remotely operated equipment in that the vehicle is influenced by the water movement and oftentimes must be operated in low visibility environments, unlike the aerial counterpart which can rely on the global positioning system (GPS) for stability and has nearly unlimited visibility. For these reasons, it is recommended to utilize divers as ROV pilots. Finally, ROVs and underwater sensors are much more expensive making it difficult to obtain and upgrade to the highest quality. The three recommendations for acquisition of ROV equipment are:

1. Replacement of older, less powered, lower resolution ROVs with higher and more modular capabilities.
2. High-resolution sonar for inspection and mapping.
3. Autonomously controlled USV for hydrographic and bathymetric surveys with the ability to merge underwater data with shoreline data.

Introduction

ROV is an acronym that stands for Remotely Operated Vehicle. An ROV is defined in the Bureau of Reclamation's (Reclamation) Diving Safe Practices Manual – Underwater Inspection Program as "an unmanned vehicle used to perform underwater tasks or observations. ROV's can be simple camera platforms or complex units with robotic arms to perform specific tasks." [1].

The typical components in an ROV (refer to the ROV categories section below) include the frame, float and ballast, onboard navigation processor, thrusters, camera, lights, tether, controller and monitor, and power source. The frame is the structure to which all other components are attached. The float and ballast are used to provide gravitational stability to the frame and accommodate the mass of all the other components. The float and/or ballast are usually adjustable to adapt to different internal and external characteristics. The onboard navigation processor consists of accelerometers or gyroscopes, compass, depth meter, and other similar positioning sensors to provide information on the movement of the ROV and interpret the inputs from the operator to ensure that the ROV can be directed accordingly. Thrusters are used to position the unit, and they are oriented differently based on purpose of the ROV. Depending on the water clarity, the camera can be used for navigation or just for inspection. In some cases, more than one camera may be used. Lighting attached to the ROV is essential for the camera in most cases and is oriented to illuminate the cameras field of view. Most ROVs provide control and feedback through a neutrally buoyant tether. A controller is typically connected to one or more monitors for video and telemetry feedback to guide the ROV to its subject area. The ROV can be powered with batteries to save weight on the tether. For long-range continuous operations, power can be provided via the tether through land- or watercraft-based power generators. ROVs can carry a multitude of payloads, though some of the most common are sonar and grabber arms. Sonar is used to aid navigation in both high and low visibility conditions. Grabber arms are typically used to capture water and soil samples or to grasp items.

ROV Categories

The definition of "ROV" is so broad that it is useful to further separate the role of the ROV into different categories. In an article published on the LinkedIn website, the International Maritime Contractors Association (IMCA) is reported to have developed a code that defines ROV classifications [2]. They are:

Class I: Pure observation level ROV; which is a system that features an on-board camera and real-time video feed to the operator. These are typically the least expensive ROV types and can often be found commercially off-the-shelf and ready to operate without extensive set-up. Since this is usually smaller and lighter, it can be deployed from the shore as well as from a boat.

Class II, A: Observation ROV with configurable load options; this system also features an on-board camera with real-time video feed to the operator but can also be outfitted with other cameras, sensors, and data/sample collection apparatuses. Class II, A ROVs are also typically lightweight and can be deployed from the shore or a boat.

Class II, B: Observation ROV with mild investigation and intervention ability; this system has the same features as the Class II, A classification and features a light manipulator to perform underwater tasks and object retrieval. Another distinctive feature about a Class II, B ROV is that, due to its weight, it usually requires a winch and gantry to deploy and recover the machine. This means it is better deployed from a boat, ship, or barge.

Class III, A: Standard working ROV, with a total weight of about 2,000 pounds and a capacity for both payloads and sample collection of about 400 pounds. The applications for this type of system includes investigations, measurements, and construction. Because of its weight, the ROV requires a dedicated launch and recovery setup on a water vessel.

Class III, B: Enhanced working ROV, with a total weight of over 6,000 pounds and a load capacity greater than 400 pounds. This type of ROV is typically used in offshore oil and gas construction and maintenance and therefore usually has special equipment onboard related to that purpose.

Class IV, A: Towed vehicle mainly for laying cables. Class IV, A ROVs have skis or sleds and are used to lay cable across a seabed.

Class IV, B: Tracked cable laying vehicle. This ROV is tracked and is used to lay cable more accurately and can navigate rocky seabed better than a Class IV, A ROV.

Class V: Prototype or custom ROV. This ROV is special built for a specific purpose, usually as a one-time use.

Class VI, A: AUV weighing less than about 200 pounds. An AUV is an autonomous underwater vehicle. A Class IV, A ROV or AUV is currently used for data collection and some miliary uses.

Class VI, B: AUV weighing greater than about 200 pounds. This type of AUV can handle larger payloads for data collection, can be programmed for specific autonomous tasks. They often have military uses.

Another category of ROVs not mentioned above but of interest in Reclamation are unmanned surface vessels, or USVs. Most USVs are the size of a small ROV but can also be as large as a boat or ship. USVs can be remotely operated or programmed to operate autonomously. While there are many applications for USVs, including military and inspections, one of the main applications with respect to Reclamation is mapping and surveying of reservoirs [3].

Most of the ROVs used in Reclamation – both internally and contracted – typically fall into the Class II category, though there are some Class I deployments. There is also significant interest in Class VI AUVs. A full survey of the ROVs operated by Reclamation is shown in the next section.

Current Applications and Equipment

ROVs have been used within Reclamation over the last 20 years or so, though there are some indications that they may have been used even earlier. The most significant application for Reclamation's ROVs is underwater inspections, though they have also been used for mapping, photogrammetric data collection, and limited underwater repairs.

In 2010, an ROV was used to inspect the Nimbus Dam Gate 15 Bulkhead Gate to find the cause of leakage in the gate using a VideoRay Pro 3 [4]. From the travel report, it isn't clear whether the ROV was operated by a contractor or by Reclamation. While the VideoRay Pro 3 is no longer manufactured, some of the specifications include a depth rating of 500 feet, weight of about 10.5 pounds and size of 14.5 inches long, 9 inches wide, and 8.5 inches tall, with a maximum forward speed of 4.1 knots. The Pro 3 ROV was powered over the 130-foot-long tether and was controlled with a case system featuring the controls and monitor [5].

In 2014, a newly acquired VideoRay Pro 4 was used by the CPN dive team's Ryan Hedrick to reattach the stop log pressurizing valve lever arm control cable to allow crews to remove the stop log gate. The operations were conducted successfully in 175-foot-deep waters [6].

In the fall of 2015, Reclamation contracted an ROV inspection company to collect inspection video, underwater laser, and photogrammetric data in the intake structure of Trinity Dam. The ROV was operated via a tether to inspect the 1,700-foot-long underwater tunnel that was about 14 feet in diameter [7]. The following features were inspected during the 5-day dive: trash racks, bulkhead seal, interior and exterior of the vertical portion of the intake structure, elbow transition to the horizontal tunnel, horizontal section, and the fixed wheel gate upstream face, seals, and guides. The inspection company used a Sub-Atlantic Mojave ROV, though the type of laser scanner is unknown. The Mojave ROV is a larger Class II, B ROV weighing 187 pounds, and 39.4 inches long, 23.6 inches wide, and 19.7 inches tall without payloads. Its maximum forward speed is 3.5 knots and has a depth rating of nearly 1,000 feet [8]. The Mojave ROV was powered, monitored, and controlled with a control center setup in an enclosed trailer mobilized on the dam crest nearest the intake structure.

Anderson Ranch Dam has been deploying ROVs for at least 20 years for the inspection of the intake structure fixed wheel gate. The first time the gate is reported to be inspected by ROV was in 1998, with one of the most recent inspections occurring in 2018. In 2018, the ROV was operated by the CPN dive team led by Ryan Hedrick. The type of ROV used in the inspection is not given in the report [9].

Officially, Reclamation's ROV operations are part of its Underwater Inspections Dive Team. Currently, the Lower Colorado Basin (LCB) Region and the Columbia-Pacific Northwest (CPN) Region dive teams offer advanced ROV operations. Despite the technology packed into an ROV, there is a considerable amount of expertise required to operate the ROV successfully. Being on a dive team provides experience that can be translated for ROV operations, including navigation and familiarity with underwater environments. However, many regional offices, area offices, and facilities have also acquired ROVs for limited applications and use. The following table shows all the known ROVs throughout Reclamation and their locations:

Table 1.—List of ROVs in use in Reclamation

	ROV Make and Model	Location	Class
1	Chasing Innovation M2	Montana Area Office	II, A
2	Chasing Innovation M2	Montana Area Office	II, A
3	Chasing Innovation M2	Dakota Area Office	II, A
4	Deep Trekker DTG3	Grand Coulee Power Office	II, A
5	Deep Ocean Engineering Triggerfish Model 508	Grand Coulee Power Office	II, B
6	Deep Ocean Engineering Phantom T5	Grand Coulee Power Office	II, B
7	Inuktun Scallop	Grand Coulee Power Office	I
8	OpenROV v2.6	Technical Service Center	I
9	Teledyne Seabotix LBV150	LCB Dive Team	II, A
10	Teledyne Seabotix vLBV300	LCB Dive Team	II, A
11	VideoRay Pro 4	CPN Dive Team	II, A
12	VideoRay Pro 4	Shasta Dam	II, A
13	VideoRay Pro 5	Folsom Dam	II, A

As can be seen in Table 1, the majority of ROVs in operation support portable observation and inspection applications. A more detailed description of each of the models represented is shown in the table below. As can be seen, most of the ROVs weigh less than 40 pounds, and none have a depth rating of greater than 1,000 feet. All of the dive team ROVs have tethers up to 1,000 feet long and receive their power for operation over the tether. While a camera and video feed are important for inspection and observation, navigation of the ROV relies heavily on sonar and other positioning sensors to provide heading and depth. However, high-resolution sonar can assist with underwater inspections in low visibility water. For additional information about Reclamation's ROV services and capability, contact Ryan Hedrick (CPN Dive Team) or Caireen Ulepic (LCB Dive Team).

Table 2.—Reclamation owned ROV specifications (note that many of the specifications are found on the company website and actual specifications may vary).

ROV	Dimensions, L x W x H[1] (inches)	Weight (pounds)	Power	Control	Speed (knots)	Tether length (feet)	Depth Rating (feet)	Sonar option	Manipulator option
Chasing Innovation M2 [10]	14.9x10.5x6.5	10	Battery, 3 hours	Hand controller	3	Up to 650	330	No	Yes
Deep Trekker DTG3 [11]	11.0x12.8x10.2	18	Battery, 8 hours	Hand controller	2	650	650	Yes	Yes
Deep Ocean Engineering Triggerfish Model 508 [12]	- Legacy -	-	-	-	-	-	-	-	-
Deep Ocean Engineering Phantom T5 [13]	35x22x23	145	Over tether	Console, power supply	4	1,000+	Up to 1,600	Yes	Yes
Inuktun Scallop [14], [15]	14x9x8.5	9	Over tether	Control station case	-	125	100	No	Yes
OpenROV v2.6 [16]	11.8x7.9x5.9	6	Battery, 1-1.5 hours	Hand controller, laptop	2	330	330	No	No
Teledyne Seabotix LBV150 [17]	21x9.65x10	24	Over tether	controller, monitor, power supply	3	500	500	No	Yes
Teledyne Seabotix vLBV300 [18]	24.6x15.4x15.4	40	Over tether	Controller, monitor, power supply	3	800	1,000	Yes	Yes
VideoRay Pro 4 [19]	14.8x11.4x8.8	14	Over tether	Controller, laptop, power supply	4.2	-	1,000	Yes	Yes
VideoRay Pro 5 [20]	19.6x14.7x8.8	22	Over tether	Controller, monitor, power supply	4.4	328	1,000	Yes	Yes

[1] L: length, W: width, H: height

Currently, Reclamation does not operate a high-resolution sonar on a ROV. However, the Hydraulic Investigations & Lab Services group at the Technical Services Center (TSC) has a stationary sonar system, the Kongsberg 1071-series sonar head paired with the MS1000 processor, that can be lowered into the water either from a vessel or structure to a depth of nearly 10,000 feet. In addition to the sonar capability, the Hydraulic Investigations & Lab Services group also has an underwater laser scanner system, the 2G Robotics ULS 200 (now the Voyis Insight Pro) for high-accuracy, mid-range underwater scanning, which is deployed similarly to the stationary sonar system. For more information about underwater scanning at Reclamation, contact Jacob Carter-Gibb (TSC).

United States Army Corps of Engineers (USACE) Applications and Equipment

As part of the research for this report, Reclamation contacted the Technical Director for Navigation at the USACE regarding underwater ROV use within their organization. Reclamation was then put into contact with the Dive Coordinator for the Portland District. The Dive Coordinator indicated that many segments of the USACE utilize underwater ROVs and provided a briefing presentation of the Portland District's particular ROV capabilities [21]. The Dive Coordinator indicated that the Portland District's ROV equipment and applications were likely representative of the USACE as a whole.

The Portland District currently possesses a fleet of the ROVs described in Table 3. These ROVs can be deployed from a small trailer which includes the necessary computer hardware and generators for powering the ROV system. In addition, the ROVs have been deployed from watercraft.

Table 3.—Underwater ROV's in the USACE Portland District's fleet.

ROV	Dimensions L x W x H (inches)	Weight (pounds)	Description
Deep Ocean Engineering Phantom T5 [13]	35x22x16	87	Reclamation also owns an ROV of this model; USACE describes this ROV as a "top-end observation class ROV."
Deep Ocean Engineering Phantom XTL [22]	Unknown	Unknown	Legacy model no longer in production. Designed for use in hot water (up to 176°F).
VideoRay Pro 3 GTO [5]	14.5x9x8.5	10.5	Reclamation utilized the same model ROV in 2010 to survey the Nimbus Dam Gate 15 Bulkhead Gate; the USACE describes this ROV as a "micro ROV" with a "very high thrust-to-weight ratio."

The Portland District has utilized their ROVs for inspections of stilling basins, fish-ways, locks, penstocks, piers, and other underwater structures. In addition, the ROVs are used for marine life surveys and sediment sampling.

They also have the capability to utilize several payloads aboard their ROVs. Within their fleet, the Portland District has attachments for ultrasonic thickness testing (UT, discussed later in this report), grabbing and cutting implements for retrieval of objects, a laser scaler for determining object size, and several sonar units.

Sonar units have been used by the Portland District to perform underwater surveys of structures, as a means of underwater navigation, and for identifying submersed objects for recovery. Sonar has the benefit of increased range when compared to the ROV's onboard cameras, with USACE reporting sonar ranges upward of 150 feet. Figure 1 is an image created by one of the Portland District's ROVs, showing a dam intake structure.

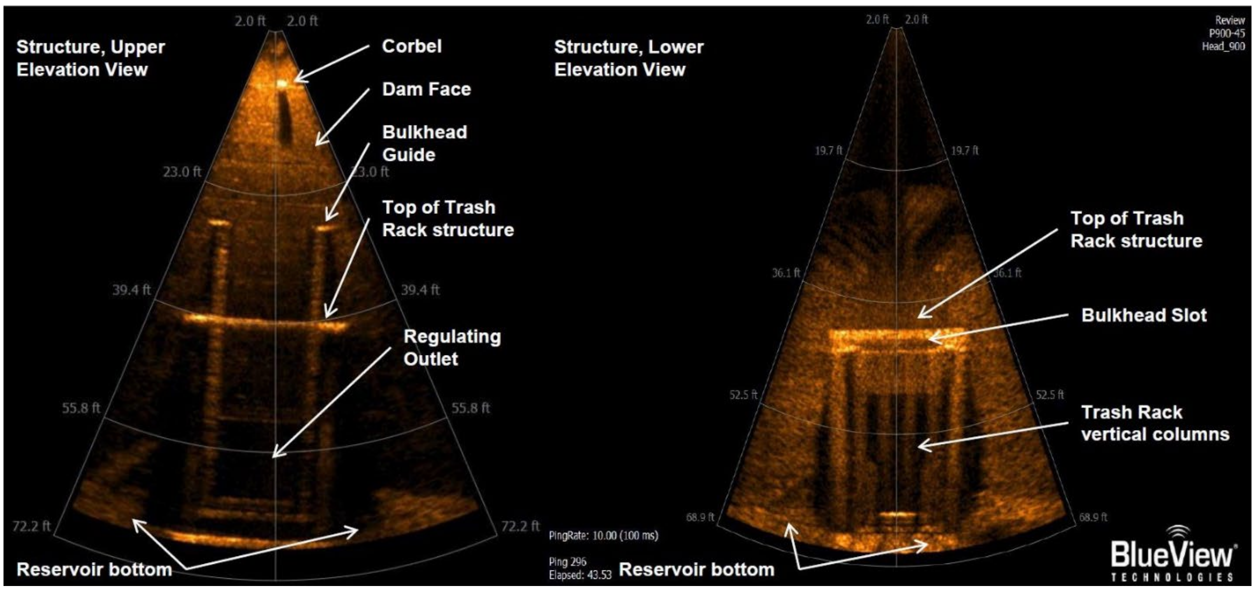

Figure 1.—Sonar image of a dam intake structure (USACE).

In addition to the above-noted payloads, the Portland District's ROVs have USBL for navigation (discussed later in this report), along with a digital compass for measuring heading. The Portland District also has access to HYPACK Survey, a software package that processes and plots hydrographic survey data from ROVs.

Industry State-of-the-Art

The following is a list of industry state-of-the-art technologies that are applicable to Reclamation. Each technology is defined, and a description of the technology is given. Some of the features aren't available commercially yet but are worth mentioning and monitoring in the event that they do become available.

Tetherless Operations

Conventionally, underwater ROVs have relied on the use of tethers for power, control, and feedback. In a tethered connection, a cable connects the ROV to a ground control station either on a water vessel or the shore. This cable is used to transmit control inputs from the operator and provide a video feed of the ROV's camera [23]. Depending on the ROV system, power can be provided over the tether or via batteries onboard the ROV [24].

In some battery powered ROVs, the control tether is connected to a floating module or buoy at the surface of the water that transmits the video and control signals wirelessly to the controller [25]. This type of system is called a hybrid connection. The tether and float system are necessary for radio control because radio waves dissipate over a very short distance in water.

Fully wireless control systems are also in development that allow for tetherless control of battery powered ROVs, eliminating the need for cables. These technologies rely on acoustic signals to transmit control inputs, in conjunction with pulses of light that can relay a video feed [26]. However, the reliance on pulses of light for video transmission means that these ROVs cannot operate in murky water, where light transmission is low. In addition, even in the best conditions, prototype wireless ROVs are only capable of being operated at a range of around 150 feet. No fully tetherless underwater ROVs are currently available commercially [27].

Autonomous Underwater Vehicles

Underwater ROVs are directly controlled by an operator. As mentioned earlier, there is a level of expertise required to operate ROVs, especially in the challenging environments around Reclamation's infrastructure. In less visible water, the operator must rely on sonar for spatial awareness, and interpreting a sonar screen is not always intuitive.

Autonomous Underwater Vehicles (AUVs) can perform navigation and surveying tasks without direct control by an operator, and some do not need to be tethered. AUVs can travel between preplanned surveying waypoints and return to their original position upon completion of the route, when the battery level is low, or when it encounters an issue [28].

Navigation Technologies

ROVs and AUVs can determine their position and speed through several technologies. These include long baseline (LBL) acoustic systems, ultra-short baseline (USBL) acoustic systems, doppler velocity log (DVL) systems, inertial measurement units (IMUs), depth sensors, or a combination of the above. While some of these systems have been in operation on ROVs for some time, the discussion of them is essential to understanding how future ROVs can leverage the systems for autonomous operations.

LBL systems rely on a set of acoustic transducers located at fixed points around the ROV's area of operation. The ROV sends out short acoustic signals or "pings", which are received by the transducers. The velocity of acoustic wave transmission in the body of water can be calculated via a calibration process, and this information can be used to estimate the location of the ROV via triangulation [29].

USBL systems rely on an array of transducers located on the ROV and a transceiver located at a base point (typically mounted within the body of water below a stationary ship). The transceiver emits a ping, which is received by the transducer array aboard the ROV. A computer utilizes differences in phase of the acoustic signal received by each transducer in the array to estimate the ROV's angle relative to the stationary transceiver. In addition, the time delay between the transceiver's ping and when it is received at the ROV transducer array can be used to calculate the ROV's distance from the transceiver based on a known acoustic wave propagation velocity in water. Thus, the angle and distance of the ROV from the transceiver can be determined, and the ROV can be located [29].

DVL systems estimate velocity of the ROV relative to the bottom of a waterway. A DVL unit includes an antenna that emits an acoustic signal, which reflects off the bottom of the waterway and is then received again by the antenna. Differences in the received signal as the ROV travels can be used to estimate its velocity, in a manner similar to echolocation [29].

IMUs consist of an array of accelerometers and gyroscopes that can be used to measure the acceleration of an ROV in all six degrees of freedom. This allows for calculation of the ROV's position based on its acceleration time history [30].

Finally, depth sensors can utilize one of several different available technologies to estimate the depth of the ROV in the body of water based on either buoyancy or measurement of the pressure exerted by the surrounding water [31].

All of the above-noted systems for measuring the location, orientation, and/or speed of an ROV can develop error. The magnitude of this error tends to increase as the ROV is operated and moves away from its starting point. As such, modern ROVs tend to rely on several different locating systems that are used in conjunction with one another to decrease error and provide redundancy [32].

In addition to the above navigation systems, a limited number of underwater ROVs are available with GPS units that are capable of positioning to a degree of accuracy suitable to surveying, with the additional ability to geotag photos and videos created by the ROV [33]. Geotagging is the process by which a GPS unit is used to record the global position at which a photo or video was taken within the file's metadata. These devices utilize a GPS unit within the ROVs control module (which the operator uses to operate the drone), in addition to a floating USBL module in line with the control tether. The USBL module can reference the drone's location back to the GPS location of the controller in order to determine the GPS coordinates of the ROV itself.

Internet-Integrated ROVs

One manufacturer has recently released a commercial ROV that is capable of being controlled over an internet connection. This ROV is tethered to a 4G or 5G cellular internet modem, allowing video feeds and control inputs to be transferred over the internet, and the ROV to be operated by a user in a remote location [34]. This technology could also be used to allow video feeds from the ROV to be viewed by a remote worker (such as an engineer in an office), while a field operator pilots the ROV. However, it appears that this technology is in its infancy at this time and is not widely available.

Portability

Early underwater ROVs were large, had high power demands, and required tethered connections for power, control, and video. This required large external power supplies, in addition to heavy voltage converters on the ROV itself. These voltage converters increased the ROV's weight and limited its portability [35]. In addition, the weight of the tether cables required the use of winches and cranes, limiting the feasibility of operating an ROV in situations with difficult access [26]. These limitations of the technology meant that underwater ROVs were primarily used aboard large seafaring ships and offshore oil drilling platforms.

Today, underwater ROVs are available in a wide variety of sizes and for varying applications. Large ROVs are still used aboard ships and oil platforms, but smaller ROVs are also available that can be more easily deployed in the field.

Some ROVs can be powered via gasoline generators, requiring a two-to-three-person team for mobilization of a field operation. In addition, many new ROVs are battery-powered and can be carried and deployed by a single operator. In such systems, tethers provide only communication and video feed connections. This means that some modern tethered ROVs only require a relatively lightweight communication cable, which can be transported on a compact spool [36].

Battery Power vs. Power over Tether

As mentioned in previous sections, some modern ROVs are capable of being powered by rechargeable batteries, similar to a modern consumer-grade unmanned aerial vehicle (UAV). Battery technology has the advantage of decreasing the weight of the ROV system as a whole and the diameter/weight of the tether cable, since power does not have to be supplied via the tether. In addition, batteries can eliminate the need to mobilize gasoline generators to the site to provide power. As such, these ROVs can be deployed by a single operator in many cases.

However, battery power has its limitations. The ROVs listed later in this report have a manufacturer claimed battery life ranging between 1 and 8 hours. However, prior Reclamation experience suggests that some of these battery life claims may be overestimated for the agency's typical use case. In addition, batteries increase the weight of the ROV.

ROVs that utilize external power, on the other hand, have been successfully operated on Reclamation projects that required long survey times or range. Pipelines, penstocks, and other similar structures, which can be thousands of feet long, have been surveyed over a period of several days with externally-powered ROVs; this would not have been possible with battery-powered units. In addition, the external power supply scheme allows operators to leave the ROV in a difficult-to-access location overnight at the end of a shift and continue work the following day, cutting down on mobilization times [7].

In summary, battery-powered ROVs can be useful where light weight and ease of mobilization are desired, and where short travel distances and battery life are acceptable. ROVs that utilize power over tether require additional mobilization time and effort but can facilitate more involved studies that require long travel distances and complicated navigation.

Control Stations

Conventionally, underwater ROVs have utilized relatively large and complex control stations. These control stations provide the benefit of uninterrupted power via external power supplies (such as gas generators), as noted in the previous section of this report. They also have the benefit of allowing for larger or multiple monitors for simultaneous viewing of video feeds by multiple personnel and for displaying more information during the dive.

With the advent of more compact computer and controller technology, some underwater ROV manufacturers are moving over to handheld controllers that are battery powered, some of which integrate with phones or tablets to provide a display [37]. In addition, some handheld control units are water resistant and can be used underwater by a diver [38]. These control units are useful for quick mobilization, but they may not allow for multiple individuals to comfortably view a video feed. If a video signal is to be sent out to an external display for better viewing in the field, then an external power supply would likely still be required, negating the mobilization efficiences of a small tablet-oriented unit.

As such, it is important to evaluate the intended use of an ROV when it comes to its control module and video feed technology. ROVs with compact, tablet-based control units are appealing due to their size and weight, but they may not be the most appropriate choice in every field operation.

Payloads

Many underwater ROV manufacturers offer off-the-shelf attachments (or payloads) that can be used for a variety of purposes.

Grabber arms come in a variety of designs and can be used to retrieve objects from a body of water or carry an object or device into the water. These typically consist of two or three claws, which may interlock with one another to form a closed loop. Some claws are capable of cutting cables, collecting deposited sediment, or sampling water [39].

Several measurement devices and sensors are also available from various manufacturers, including:

- Calipers for measuring thickness [40].
- Water quality analysis devices for measuring temperature, pH, conductivity, or turbidity. In addition, various devices can be used to measure dissolved oxygen, chlorophyll A, ammonium, nitrate, chloride, or rhodamine WT content [41].
- CP (Cathodic Protection) probes for measuring voltage potential within cathodically protected components [42].
- Hydrophones for monitoring underwater sounds [43].
- Other non-destructive testing and field assessment technologies described below.

Non-Destructive Testing and Field Assessment Technologies

A variety of non-destructive testing (NDT) and field assessment technologies are available which could potentially be performed underwater by an ROV equipped with either off-the-shelf or custom-fabricated NDT payloads. The following sections describe several technologies that could be adapted by Reclamation for ROV use.

Visual Assessment

Underwater ROVs are readily capable off-the-shelf of performing visual condition assessments of submerged structures and mechanical components. The cameras aboard ROVs could be used to perform crack mapping, identify extents of deterioration/corrosion, and assess the operating condition of moving componentry, among other uses. Photographs and videos captured during these investigations could be used for reporting purposes. The usefulness of ROVs for visual assessment is limited primarily by the viewing range of the camera, which can be prohibitively short ranged in turbid water [44].

Cameras

Underwater ROVs are available with a variety of camera technologies. Video resolution of integrated, proprietary cameras in commercial ROVs typically ranges between 1080p and 4k. However, the image quality of underwater cameras is usually limited by turbidity and low light conditions, such that a 4k or 8k camera may not offer a significant improvement in overall image quality. As a corollary, the best cameras for underwater ROV use are generally those that offer good low light performance (i.e., capable of a high ISO setting) [45].

Rather than utilize a proprietary camera, some ROVs are designed to encapsulate a separate camera body and lens [46]. This allows the user to select a camera with resolution and other specifications that meet their needs.

Many ROVs utilize wide angle lenses, which allow for a wider field of view at the cost of distortion of the image. This wider view helps with navigation and capturing complete views of close objects, but the distortion can make it more difficult to visually discern scale.

In addition to conventional cameras, prototype underwater ROVs have been developed which utilize a 360-degree camera that captures a panoramic image [47]. However, it does not appear that any commercial ROVs are available with this technology.

Underwater Photogrammetry

Photogrammetry is a process by which a series of consecutively positioned photographs are taken of an object or structure and then used to develop a 3D point cloud representation. This is done by computer software that assesses differences in perspective between adjacent photographs, similar to the way that human eyes judge depth using stereoscopic vision. Photogrammetry is widely used to map topography and create 3D models of structures in unmanned aerial system (UAS) applications [48].

Underwater ROVs can perform a similar function as a UAS, taking progressive photographs to perform photogrammetry underwater [49]. It is even possible to utilize a UAS for conventional photogrammetry and an ROV for underwater photogrammetry of the same structure, then marry the two sets of data into a continuous model that shows both the above-water and below-water structure.

Reclamation currently possesses photogrammetry processing capabilities within the TSC that have been utilized for underwater 3D modeling, including processing frames of images taken from the video inspection at Trinity Dam to recreate the condition of the upstream face of the fixed wheel gate for visual inspection of areas of corrosion [7].

Underwater Laser Scanning (LiDAR)

Laser scanning (also known as Light Detection and Ranging or LiDAR) is a technology in which pulses of light are emitted from a laser at an object or structure. The light reflects off the object and is detected by a scanner. The amount of time that elapses between the emission of the light and when it is received at the scanner can be used to calculate the distance to the object. This method can be used to generate a three-dimensional point cloud of an object or structure, which can be used to efficiently gather dimensional data [50].

LiDAR units have typically been mounted on skids or booms off a fixed surface in the body of water (referred to as stationary scanning). Several manufacturers now offer compact LiDAR units that can be attached to an ROV. In addition, it is possible with the use of the positioning systems mentioned previously in this report for some LiDAR/ROV systems to operate while moving (dynamic scanning) [51].

Like visual assessments and photogrammetry, the primary limitation of LiDAR in underwater applications is the light transmission level of the water. Previous Reclamation research suggests that LiDAR range may be less than 5 feet in turbid water [52].

Sonar

Sonar, which is a portmanteau of "sound navigation and ranging," is an acoustic method in which sound waves (a ping) are emitted by a projector aboard a vessel, which reflect off hard boundaries. This creates an echo that can be monitored by a transducer. By knowing the time between the emission of the ping and the measurement of an echo, and assuming a known speed of sound in water, a distance to a hard target can be measured. These distances can then be mapped to create 2D or 3D images of stationary objects within a body of water [53].

Several different sonar methods currently exist. Multibeam sonar, which is primarily used to map seabed, utilizes a vertically oriented fan-shaped beam form that can simultaneously collect a continuous line of depth measurements for each ping. As the vessel travels horizontally, the distance between the sonar projector and hard boundaries below can be measured and mapped [54].

A system using side-scan sonar emits a series of discrete pings following either a conical or fan-shaped sweep that is oriented either in front of or behind the vessel, with some degree of downward angle from horizontal. Like multibeam sonar, the distance to hard surfaces is mapped as the vessel travels [55].

Rotating head sonar utilizes a projector that rotates a full 360 degrees, allowing for collection of distance measurements in front of, behind, and on either side of the ROV as the vessel travels forward [56].

At least one system is commercially available that allows for information from sonar, LiDAR, and video cameras to be combined to create a 3D representation of underwater objects. Specifically, images captured by the camera are mapped onto a 3D model created via a combination of sonar and LiDAR. Reportedly, this processing can be performed in real-time, allowing for a streaming 3D image to be produced. This technology could potentially be used as a means of rapidly collecting dimensional data, in addition to allowing the ROV to gauge its distance to objects and perform tasks underwater [57].

For Reclamation's purposes, sonar could be used by underwater ROVs to create 2D or 3D representations of the submerged portions of structures, allowing for collection of dimensions and geometries to be used for assessment, repair, and/or design purposes.

Acoustic Resonance Technology

Acoustic Resonance Technology (ART) is an NDT method in which an acoustic waveform is emitted by a transducer (essentially a speaker) toward the wall of a metal pipe or tank structure filled with either a liquid or gaseous medium. The ART unit monitors the standing compression waves that are generated in the fluid when the pipe or tank wall is excited by the acoustic wave. This data can be used to determine the resonant frequencies of the pipe or tank wall, which are a function of the wall thickness. This technology can be useful in estimating the remaining wall thickness of a corroded metal pipe or tank [58].

Alternating Current Field Measurement

Alternating Current Field Measurement (ACFM) is a test method in which an electrical probe induces an alternating current at the surface of a metal component. The probe monitors the magnetic field. Non-uniformity of the magnetic field indicates that the current is traveling around a crack or other discontinuity; the measured non-uniformity in the magnetic field can be mathematically related to crack width. This test method is useful for identifying cracks within welds and is applicable to both ferrous and non-ferrous metals [59]. The test method also has the advantage of being able to be performed through coatings.

Magnetic Flux Leakage

Magnetic Flux Leakage (MFL) involves a strong magnet, which is used to create a magnetic field in a thin-walled ferrous metal component. As the magnet passes over the metal component, changes in flux are measured via sensors placed between the poles of the magnet. These changes in flux can be indicative of internal flaws or corrosion [44].

MFL is suitable for use on underwater ROVs as it can be performed in both dry and wet environments. It also does not require direct contact with the component being tested. However, the method does require a relatively clean surface free of deposits; as such, ROVs equipped for MFL may require an additional surface cleaning apparatus [44].

Pulsed Eddy Current Array

Pulsed Eddy Current Array (PECA) is an NDT method used on thin-walled metal components, such as pipes and tanks. In this method, eddy currents are magnetically induced in the component with a probe, and the decay of these eddy currents is measured and monitored. Decay can be directly related to the thickness of the wall, as eddy currents tend to take longer to decay when the wall is thicker. For Reclamation purposes, this test method is useful in assessing the remaining thickness of a thin-walled metal component that has experienced corrosion. It is also advantageous in that it can be used through painted, fireproofed, or insulated surfaces [60].

Ultrasonic Thickness

Ultrasonic Thickness (UT) is a test method involving a piezoelectric transducer in contact with a thin-walled metal component. The transducer emits ultrasonic waves, which reflect off the backside of the component, in addition to cracks or other anomalies. The measured response of the reflected ultrasonic waves within the metal component can be used to map the presence of cracks, variations in material properties, variations in thickness caused by corrosion, and variations in coating thickness [44].

Phased Array Ultrasonic Testing (PAUT) is a related method that involves an array of piezoelectric transducers. The transducers intermittently emit and receive ultrasonic waves, sweeping along the length of the array. The PAUT method allows for a linear cross-section of a metal component to be tested at one time, as opposed to a discrete UT transducer that provides a test result at a single point [61].

UT in a dry environment require the use of an ultrasonic coupling gel that must be manually applied to the transducer and/or the surface of the metal. However, in underwater applications, the surrounding water can serve as a suitable ultrasonic couplant. This means that underwater UT could feasibly be performed remotely by an ROV without needing to devise a way to apply couplant.

Coating Thickness

A variety of test methods that are used to evaluate the dry film thickness (DFT) of coatings could potentially be adapted to use aboard underwater ROVs [44]:

- The UT method, discussed previously in this report, can be used in a pulse-echo mode to assess the thickness of coatings.
- The thickness of coatings on ferrous metals can be estimated via a method similar to MFL. A magnet is passed along a surface while in contact with the coating, and changes in the measured flux are indicative of variations in the coating thickness.
- With non-ferrous substrates, eddy current techniques can be utilized. In these methods, eddy currents are induced in the substrate, and the measured magnitude of the eddy currents at the surface is proportional to the coating thickness.

These test methods have the same limitations as UT. That is, it is necessary to keep the instrument in contact with the surface of the component, which may be difficult in flowing water. These methods also require a clean testing surface.

Electrochemical Impedance Spectroscopy

Electrochemical Impedance Spectroscopy (EIS) is a method used to determine the extent to which a coating applied to a steel component is able to act as a barrier to water and ions, thereby limiting corrosion. In this method, an electrode is placed in contact with the surface of the coating, and another electrode is placed in contact with the steel component. The impedance between the two electrodes is measured, and a higher impedance corresponds to a greater degree of corrosion protection [44].

This test method has not been adapted for underwater use at this time. In underwater applications, it would be necessary to electrically isolate the electrodes from the surrounding water to ensure that current flows through the coating/steel component and not the surrounding water [44].

Unmanned Aerial Vehicle (UAV)/ROV combinations

Several devices are in development that can operate as both a UAV (in the air) and as an underwater ROV. One device by Rutgers University is capable of landing in water, then immediately diving directly underneath the water [62]. Another unit developed by a joint effort between three firms in Asia consists of a UAV that can land on the surface of the water, then deploy a tethered underwater ROV from the bottom of the UAV [63]. Currently, no robust UAV/ROV combination devices are available commercially.

Demonstrations

As part of the research, the team observed several vendor demonstrations. However, about half of the demonstrations were virtual due to the COVID-19 pandemic. While the pandemic prevented travel for the first part of the research, virtual demonstrations represented a cost savings to the project, allowing for more demonstrations than if the team had to travel. However, the disadvantage to a virtual demonstration was that the team was not able to get hands-on feedback from each of the systems and had to rely on the vendor to put the equipment through the paces.

A total of 11 demonstrations were conducted. The first five demonstrations were conducted virtually. Three of the demonstrations were conducted at the Downings Reservoir on the Denver Federal Center campus. One of the demonstrations was conducted in Reclamation's hydraulics laboratory sump pools. One of the demonstrations was conducted jointly with Grand Coulee Dam and on location. The last demonstration was conducted at one of the vendors offices in San Diego, California. In addition to the demonstrations, the team also attended a training event sponsored by the Association of State Dam Safety Officials (ASDSO). Finally, one team member was able to attend the HydroVision Conference. A description of each activity is given below.

Demonstration 1: Seaview Systems BlueROV2

Seaview Systems markets itself as a company that manufactures marine technology as well as provides underwater ROV, inspection, analysis, and consulting services [64]. Seaview Systems uses the Blue Robotics BlueROV2 as its only ROV platform. Seaview Systems and the BlueROV2 are unique in that the control system is open source, and the ROV is modular, which allows for endless customization and integration of different sensors including those that could be used for autonomous navigation. The ROV is also able to be fitted with data collection payloads such as an ultrasonic thickness gage for measuring steel thickness. The ROV is battery powered with optional topside power solutions and can be controlled using a handheld tablet for portability. Battery life is expected up to 4 hours. The size of the BlueROV2 is about 18 inches long, 13.3 inches wide, and 10 inches tall with a dry weight between 20 and 22 pounds. The maximum forward speed is 3 knots. Seaview offers 2 variations of the BlueROV2: 1) a copper tether system with a depth rating of about 330 feet and tether length up to 980 feet and 2) a fiber optic system with a depth rating of about 1,310 feet and tether length of up to 16,400 feet [65].

The demonstration was given virtually on August 3, 2021. During the demonstration, Seaview Systems focused mainly on a live demonstration of the BlueROV2 in a tank (see Figure 2 below). Seaview Systems was able to provide both a live stream from the ROV as well as a view of the ROV in the tank. Because of the limited space in the tank, Seaview Systems was unable to demonstrate any sonar, autonomous navigation, or other advanced sensors and payloads.

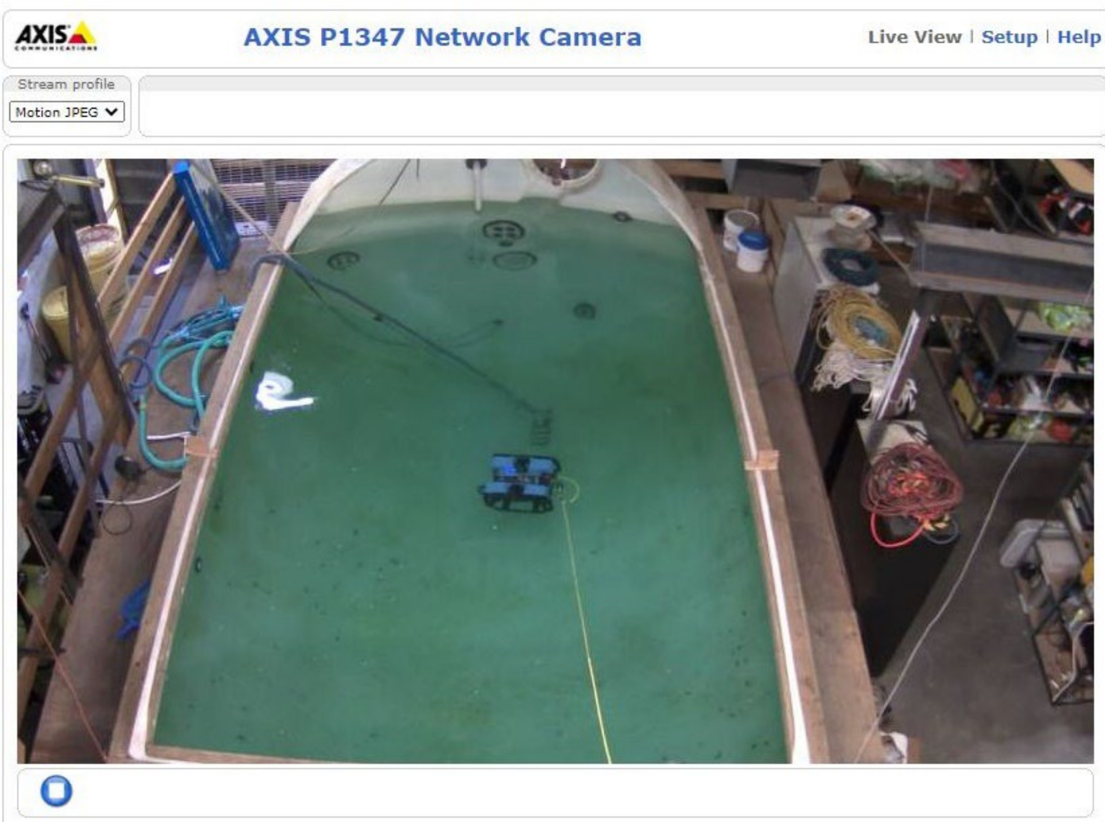

Figure 2.—Seaview Systems live view of the Blue Robotics BlueROV2 in a tank as part of the virtual demonstration.

Demonstration 2: Strategic Robotic Systems (SRS) Fusion

In contrast to the highly modular Blue Robotics BlueROV2, the SRS Fusion ROV or unmanned underwater vehicle (UUV) is considered a professional grade integrated system that is intended to be intuitive and highly portable [66]. The Fusion UUV can be controlled in three different ways: 1) autonomously where the mission points are preprogrammed, 2) remotely by an operator stationed on a vessel or onshore, or 3) by a diver. Optional payloads include sonar (forward looking and side scan), grabbers, and a magnetometer. Like the Blue Robotics BlueROV2, the Fusion ROV is battery powered and can be controlled using a handheld tablet for portability. Battery life is estimated between 3 to 4 hours. The size of the Fusion ROV is about 27 inches long, 18.8 inches wide, and 10.8 inches tall with a dry weight of 60 pounds. The maximum forward speed is 3 knots. The SRS Fusion ROV depth is rated to 1,000 feet with fiber optic tether options between 1,650 and 6,560 feet.

The demonstration of the SRS Fusion ROV was given on August 4, 2021. For their demonstration, SRS presented a slide show featuring the company profile and mission, detailed specifications of the Fusion ROV, and examples showing results from the sensors as well as autonomous mission editing and execution. A live demonstration of the ROV was not conducted during the meeting.

Demonstration 3: Teledyne Marine (Seabotix and Oceanscience)

Teledyne Marine provided the next demonstration as one of the largest and well-known subsea technology companies represented. Teledyne Marine has collaborated to bring acoustic and underwater imaging, instrument, interconnect, seismic, and vehicle services together in one company [67]. In 2014, Teledyne Marine acquired the ROV manufacturer Seabotix and currently features two ROV models: 1) the vLBV300[2] and 2) the vLBV950. In the same year, Teledyne Marine also acquired Oceanscience's offerings for remotely controlled and autonomous surface vessels also consisting of two models (with variations): 1) the Q-/Z-Boat 1800RP/T and 2) the Q-/Z-Boat 1250. Like the Blue Robotics BlueROV2, the vLBV300 and vLBV950 are intended to be modular and customizable based on the environment and project needs. The main difference between the -300 and the -950 is that the -950 is rated for deeper water. The vLBV300 is rated for 1,000 feet, and the vLBV950 is rated for 3,120 feet of depth. Both systems require power over the tether with the topside controller, monitor, and power supply built together. They are the same size with a length of 24.6 inches, width and height of 15.4 inches, and a dry weight of about 40 pounds. The reported maximum forward speed is 3 knots. The vLBV300 has a tether length of about 850 feet, while the vLBV950 tether varies between 2,460 and 6,560 feet. There is a variation of the vLBV300 that features a 6,000-foot tether length as well. Both ROVs can be configured with a variety of sensors and tools, including grabber and robotic arms, cameras, acoustic sensors like sonar, sensor tools like ultrasonic thickness and cathodic protection probes, as well as various tools like cleaning brushes, pressure washers, and extra lights [68].

The USVs mentioned above are intended to collect acoustic Doppler current profile data (Q-Boats) and high-resolution shallow-water hydrographic survey and shoreline LiDAR data (Z-Boats). The

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[2] Recall that Reclamation's LCB region currently operates two Seabotix models (see Table 1 above): 1) the LBV150 and 2) vLBV300.

third variation is of the Z-Boat with Trimble high-resolution positioning and geotagging to about 3/4 of an inch in the z-direction. The 1800RP/T vessels are single hull and heavier at about 150 pounds, with between 8 and 10 knots velocity and battery life of about 4 hours. The 1800RP/T dimensions are about 71 inches long, 40 inches wide, and 13 inches tall. The 1250 vessel features trimaran hulls with adjustable crossbars for portability and can weigh less than 50 pounds. Its dimensions are about 50 inches long, 37 inches wide, and 12.5 inches tall without instruments attached. Speeds of the 1250 boats are between 2 and 3 knots, with battery life between an hour and 4 hours [69].

The demonstration of some of the relevant equipment and sensors provided by Teledyne Marine was given on August 9, 2021. Like SRS, Teledyne Marine relied solely on a presentation to showcase their company and equipment. The presentation covered a description of the company, with a major emphasis on their ROVs and especially the vLBV300, including features, specifications, payloads, applications, and some examples of sensors that might be relevant to Reclamation. The specific sensors that Teledyne Marine highlighted included the Teledyne BlueView BV5000-1350 and -2250 3D Mechanical Scanning Sonar and a Cygnun Instruments Mini ROV Multiple Echo Ultrasonic Digital Thickness Gauge. Teledyne Marine concluded the presentation with a discussion of their surface vessels.

Demonstration 4: Deep Trekker Pivot

Deep Trekker has been in business since 2010 and specializes in designing and manufacturing underwater and confined space remotely operated vehicles, including ROVs, pipe crawlers, magnetic utility crawlers, and underwater cameras [70]. The company offers three ROVs, but the one highlighted on this demonstration was the Pivot ROV. The Pivot ROV is described as a versatile inspection ROV with optional lighting, grabber arm, enhanced positioning, and sonar. Like the Seaview Systems BlueROV2 and SRS Fusion, the Pivot is battery powered with an estimated battery life of up to 3 hours and a maximum forward speed of 2.5 knots. The ROV is controlled with a custom portable handheld controller, including outputs to connect external monitors and tether lengths between 325 and 985 feet. The size of the Pivot ROV is 22.7 inches long, 14.2 inches wide, and 12.2 inches tall, weighing about 38 pounds, with a depth rating of 1,000 feet [71].

The virtual demonstration of the Deep Trekker Pivot was given on August 20, 2021.

Demonstration 5: VideoRay Pro 5 and Defender

VideoRay was founded in 1999 and began manufacturing ROVs shortly afterwards, beginning with the VideoRay Pro [72]. The company offers two ROVs and welcomes custom requests: 1) Pro 5 and 2) Defender. The basic difference is that the Pro 5 is small and fast, while the Defender is designed for heavier payloads. The Pro 5 is the fifth generation of VideoRay's first ROV and is powered through the tether like the Seabotix ROVs. It is controlled through a console that consists of a monitor, processor, power supply, custom hand controller, and 328-foot-long tether. The size of the Pro 5 is 19.6 inches long, 14.7 inches wide, and 8.8 inches tall with a dry weight of about 22 pounds and a depth rating of 1,000 feet. The maximum speed of the Pro 5 is given as 4.4 knots. While the

Pro 5 is not highly configurable, it can be outfitted with forward looking sonar and a manipulator arm [20].

By contrast, the Defender is modular and has been configured in over 500 variations including sonar, positioning and navigation sensors, data collection sensors including ultrasonic thickness and cathodic protection measurements, and grabber arm options. Like the Seabotix ROVs and the VideoRay Pro 5, the Defender is powered through its 1,310- to 6,560-foot-long tether and controlled via the same console system including monitor, processor, power supply, and custom hand controller. The size of the Defender without any payloads is 29.6 inches long, 15.5 inches wide, and 10.5 inches tall, and it weighs 38 pounds in the air. The depth rating is up to 1,000 feet, and the manufacturer claims a maximum speed of 4 knots [73].

VideoRay's virtual demonstration was given on August 26, 2021. The virtual demonstration featured a live demonstration of both the Pro 5 and Defender ROVs, including the topside control console setup with a live view from the ROV. The live demonstration was conducted in VideoRay's test pool in Pottstown, Pennsylvania.

Demonstration 6: Seafloor Systems Echoboat 160

Seafloor Systems, Inc. is a company of hydrographers that designs and builds equipment for hydrographers, including surveying equipment and vehicles like USVs and ROVs. The USVs are remotely controlled but can also be operated autonomously [74]. The USVs are available in different hull configurations and with different capabilities, but the one that was demonstrated was the Echoboat 160. The Echoboat 160 can conduct hydrographic surveys and can be outfitted with GPS, sonar, LiDAR, and velocity profilers. Its remote-control range is up to 6,560 feet with a handheld controller with sensor setup through a wi-fi-connected computer. The dimensions of the vessel are 66.9 inches long, 31.5 inches wide, and 31.9 inches tall. The 100-pound empty hull can accommodate up to 65 pounds of payload equipment, including batteries that can last for up to 8 hours. The maximum speed is up to 5 knots [75].

The demonstration of the Seafloor Systems Echoboat 160 was conducted on September 22, 2021, at the Downings Reservoir on the Denver Federal Center campus (see Figure 3). Reclamation coordinated with USGS, who had previous approval from GSA to conduct the demonstration. The USV was operated remotely during the demonstration. The vendor also demonstrated the wi-fi connection to the Echoboat 160 instruments. The autonomous features were not demonstrated.

Figure 3.—Seafloor Systems Echoboat 160 demonstration at the Downings Reservoir at the Denver Federal Center.

Demonstration 7: General Electric (GE) Renewable Power Hydro Solutions Underwater Hydropower Turbine Inspection Robot

GE is a well-known conglomerate that provides innovations in several different areas, including a segment dedicated to Renewable Energy [76]. Recently, GE's Renewable Power Hydro Solutions developed a remotely operated system that can be used to inspect hydropower turbines without dewatering the penstock. The system consists of an ROV and underwater spherical camera with lighting to collect 360-degree optical imagery of the turbine for post-processing and analysis.

A demonstration of the technology was conducted at Grand Coulee's Nathaniel "Nat" Washington Power Plant between December 13, and 16, 2021. For the demonstration, the ROV had to be lowered into the water about 50 feet from the top of the draft tube bulkhead installation slot outside of the power plant. From there, the ROV was manually controlled to navigate up the 40-foot diameter draft tube to the underside of the turbine. Due to the large size of the draft tube and the low visibility, it was difficult to maintain orientation up the draft tube, and the batteries were depleted enough to require a change mid-survey. On the last day of data collection, after all the data had been collected, the spherical camera probe float became stuck in one of the turbine blades and had to be retrieved through a hatch in the draft tube.

The ROV used was the Deep Trekker Revolution (see Demonstration 10 below). The ROV is equipped with a camera that can tilt 260 degrees, with lighting tracking the camera tilt. The underwater spherical camera connected to the ROV was the Kandao QooCam 8k, which was built into a custom designed waterproof housing with its own lighting and cage to prevent damage to the housing [77]. The spherical camera assembly is attached to the ROV on a short tether with a couple of floats connected to the top of the assembly to allow it to “dangle” over the top of the ROV and be floated in between each of the turbine blades (see Figure 4 and Figure 5 below). The tiltable ROV camera video feed is used to position the spherical camera assembly within the turbine blades. The spherical camera is also connected to the ROV, controller, and monitor for a live view of the video. Data is collected and post-processed to identify potential issues with the turbine including erosion, cavitation, corrosion, impacts, and foreign objects.

Figure 4.—The GE Renewable Power Hydro Solutions Underwater Hydropower Turbine Inspection Robot; note the spherical camera assembly and floats connected to the tether to the left.

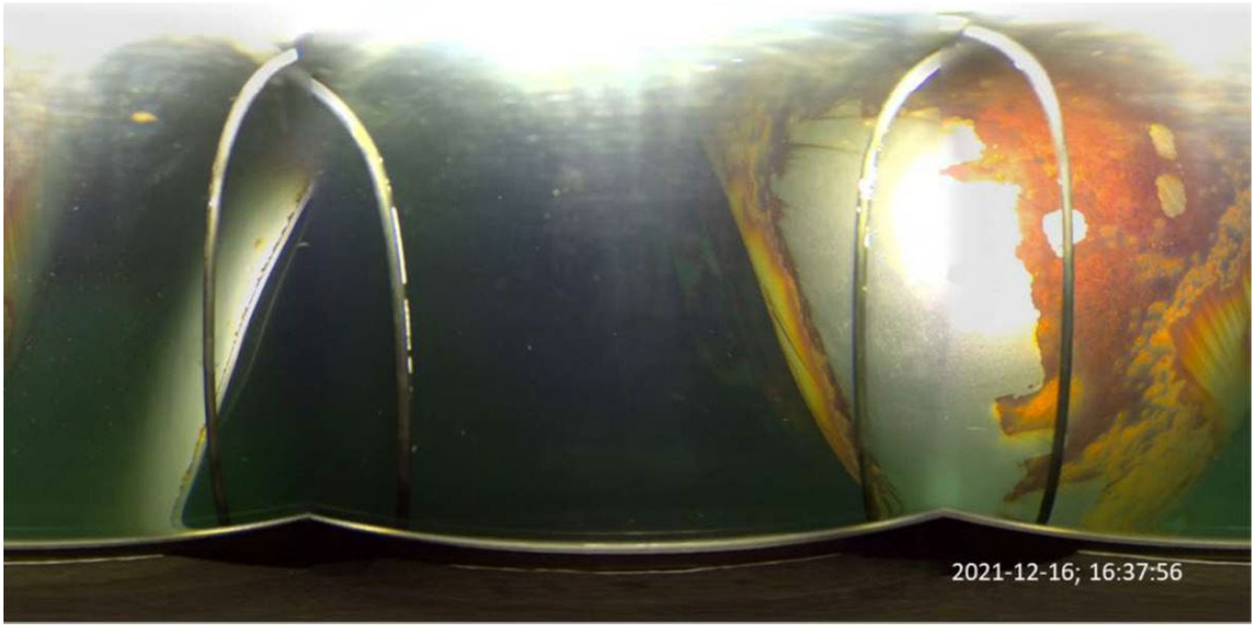

Figure 5.—Example of the data collected by the underwater spherical camera in the cavity in between two turbine blades.

Demonstration 8: Uncharted Research and Development Incorporated (UNRD) Prosecutor Gen 2

UNRD assembles custom built ROVs exclusively for government agencies, with one of their main applications being boat and ship inspections using a top mounted fisheye camera to be able to observe the underside of the hull [78]. The company also claims to have one of the most responsive ROV customer service experiences in the industry to help prevent field downtime in the event of issues with the ROV. During a virtual presentation, the following details were shared with the team: the UNRD Prosecutor Gen 2 ROV measures 18 inches long, 20 inches wide, and 18 inches tall with a dry weight of 45 pounds and a depth rating of up to 1,200 feet. Like many other portable ROVs, the Prosecutor Gen 2 is battery powered with a battery life of between 1 and 3 hours and has a maximum forward speed of 3 knots. The ROV feedback and control is through laptop connected to a tether and a handheld controller. The laptop provides telemetry, live video from the camera, and a display of the sonar map. Tether lengths can vary from 300 to 1,000 feet.

UNRD hosted the virtual presentation on November 20, 2021 and offered to loan Reclamation one of their ROVs for evaluation and demonstration. After signing a liability agreement, the ROV arrived at Reclamation's Hydraulic Investigations & Lab Services group in February of 2022. The research team assembled at the Hydraulics Lab sump pool on February 22, 2022, to observe and operate the ROV. The demonstration ROV was outfitted with a forward-looking sonar, lighting, and a grabber arm (see Figure 6 below).

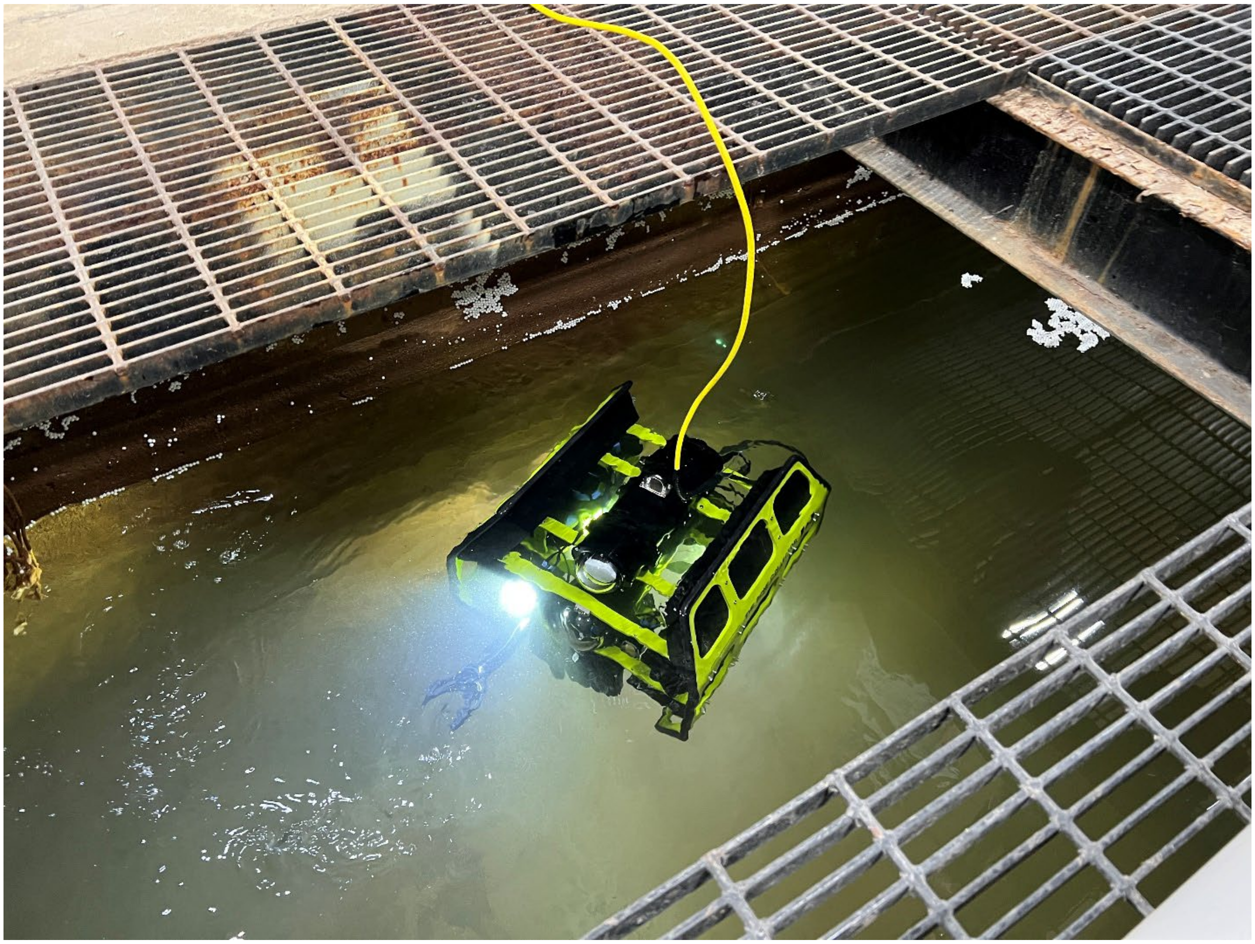

Figure 6.—Operation of the UNRD Prosecutor Gen 2 ROV at the Hydraulics Lab sump pool.

Demonstration 9: VideoRay Defender and Sound Metrics Aris Explorer 3000

While VideoRay had provided a virtual demonstration of their ROVs before, a real-world demonstration of the Defender ROV with a custom mounted Sound Metrics Aris Explorer 3000 sonar was conducted in the Downings Reservoir on the Denver Federal Center on July 12, 2022 (see Demonstration 5 above). While the Defender ROV had a Blueprint Subsea Oculus forward looking multibeam sonar, the Aris Explorer 3000 sonar is described as being able to collect "more data than any other imaging sonar in its class" [79]. To further enhance its capability, the sonar is mounted on a rotating platform as a modular attachment under the VideoRay Defender ROV (a detailed description of the Defender is given above). Since the sonar beam extends from the unit in a 30-degree by 15-degree fan, rotating the sonar allows the operator different views and can help provide better interpretation of the environment around the ROV.

Downings Reservoir features a small intake structure with concrete walls and steel trash racks. It also has some buoys further out in the water. Both features were investigated and observed visually and using the sonar. The water clarity in the reservoir gave a visibility of about 2 to 3 feet, but the sonar allowed the operator better navigational confidence and provided high resolution scans of the structural elements. The ROV and sonar are shown in Figure 7 below.

Figure 7.—VideoRay Defender ROV and the custom attachment for the rotating Aris Explorer 3000 sonar in the lower right.

Demonstration 10: Deep Trekker Pivot and Revolution

The Deep Trekker Revolution ROV seems a bit more streamlined than the Pivot but can be integrated with other sensors, including sonar, grabber arms, and sensors. (For details on the Deep Trekker Pivot, refer to Demonstration 4 above.) One of the most unique features of the Revolution is that the manipulator arm rotates with the main camera. The dimensions of the Revolution ROV are 28.2 inches long, 17.3 inches wide, and 9.3 inches tall. The ROV is battery powered with a battery life of about 3 to 6 hours and is controlled by a hand-held controller through a 980-foot tether. It is rated for 1,000-foot depths and has a maximum forward speed of 3 knots. While the Revolution is sleeker than the Pivot, it is heavier at 57 pounds in air [80].

For Demonstration 4 (which was virtual), Deep Trekker focused on their Pivot ROV, but during this live demonstration, both the Pivot and Revolution ROV were operated in Downings Reservoir at the Denver Federal Center on July 15, 2022 (see Figure 8). (Note that the Deep Trekker Revolution was operated by GE for the demonstration of their turbine inspection system.) Similar to the VideoRay Defender demonstration, both the Deep Trekker ROVs were operated in the open water and near the intake structure. However, only the Revolution ROV had a Blueprint Subsea Oculus forward looking multibeam sonar which allowed for more "visibility" in the turbid reservoir water than the optical cameras.

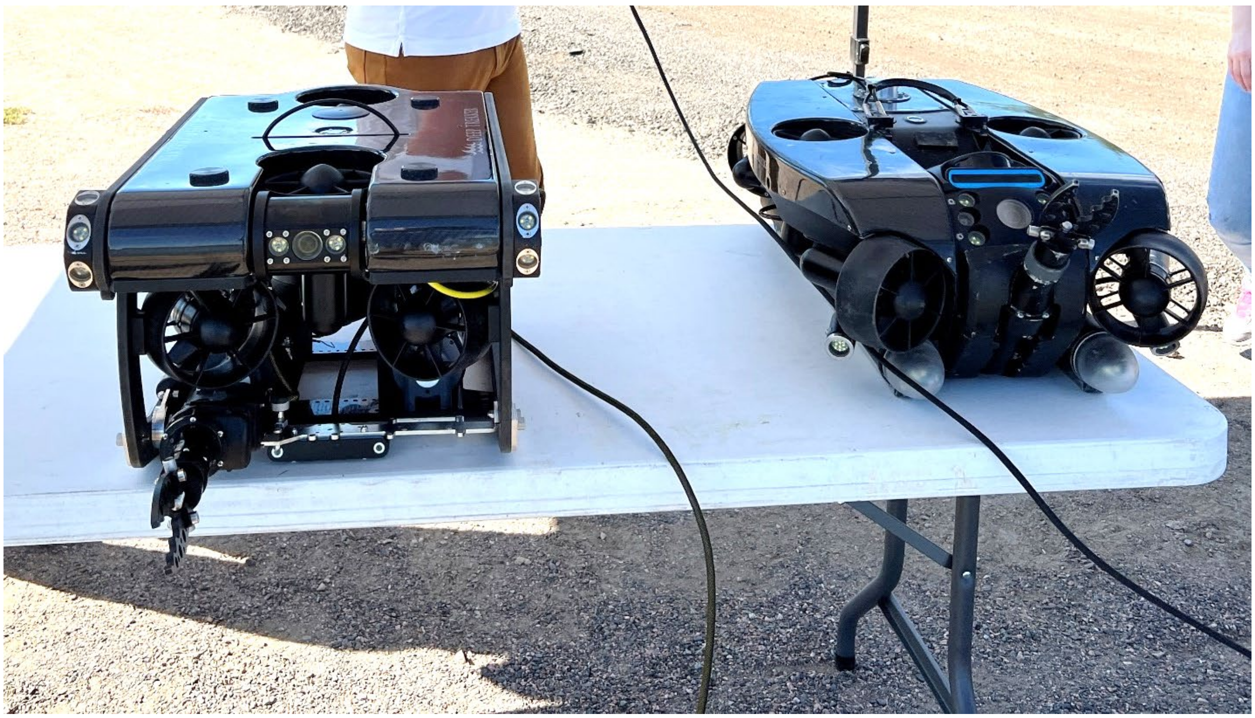

Figure 8.—The Deep Trekker Pivot (left) and the Deep Trekker Revolution (right).

Demonstration 11: VideoRay Pro5 and Defender

Because some of the research team were unable to attend Demonstration 9: VideoRay Defender, they opted to arrange a second live demonstration at a VideoRay office in San Diego, California on September 23, 2022. During this demonstration, team members were able to operate the ROVs in the North San Diego Bay, as the VideoRay office was located near the bay.

A side-by-side demonstration between the Pro 5 and Defender was completed. The main difference between the 2 vehicles was the Defender was equipped with DVL, which allowed the vehicle to hold position – even in current. The DVL on the Defender also allowed the vehicle to operate in very precise movements backwards, forwards, up, down, right, and left. The movements increments could be set. This feature would be an excellent tool for inspecting structures.

During the demonstration, team members operated the VideoRay splash proof handheld controller (see Figure 9 below). A few benefits of the handheld controller were the large display screen, ability to connect to a second screen if needed, and the option to mount in a control box. A few disadvantages of the handheld controller were the weight that could be fatiguing over a long day of ROV operations and the smaller screen than the control box screen.

Figure 9.—The VideoRay handheld controller.

ASDSO Training Event: Use of Underwater Remote Systems in Dam Safety

Some of the research team members were able to attend a webinar hosted by the Association of State Dam Safety Officials (ASDSO) on July 13, 2021 [81]. The webinar was titled "Use of Underwater Remote Systems in Dam Safety" and was presented by experts in the fields of ROV operations, underwater inspections, hydrographic monitoring and surveys, and acoustic images, as well as visualization of large survey datasets. The webinar included a discussion on types of underwater equipment and sensors, equipment specifications, advantages and disadvantages of different equipment for different applications, data collection methodologies and post-processing, and how to set expectations for data collection and what that data means.

HydroVision 2022 International Conference

Team members also attended the exhibit hall of the HydroVision 2022 International Conference, which was held in Denver, Colorado on July 12 to 14, 2022. During the exhibit hall visit, the opportunity to have discussions with vendors about the current and future underwater ROV and sensor technology was made possible. The vendors visited are listed below with descriptions of the company and potential options for Reclamation:

Niricson: Since 2020, Niricson has been processing optical and other types of data using artificial intelligence and machine learning for the purpose of identifying surface and subsurface defects on concrete civil infrastructure like dams. This technology can be used to monitor the defects over a period of time to show changes in deterioration [82]. The system is tuned to process data collected from unmanned aerial systems (UAS) but can process data collected in other ways as well. Niricson was also highlighted in another Reclamation research paper focusing on machine learning for crack detection [83].

VideoRay: VideoRay has already been mentioned in Demonstration 5, 9, and 11 above. VideoRay ROVs are used by CPN, Folsom Dam, and Shasta Dam (see Table 1 above).

Underwater Acoustics International: Underwater Acoustics International, or UAI, is a company that performs underwater structural inspections of penstocks, tunnels, intake gates, and trash racks. They also provide hydrographic services, 3D laser scanning and LiDAR data collection, and data processing [84]. The company can apply their data collection to monitor changes over time. The company can deploy several types of instruments to collect data, including ROVs, USVs, remotely operated crawlers, UAS, LiDAR, and sonar.

Deep Trekker: Deep Trekker also is mentioned above in Demonstration 4 and 10. A Deep Trekker ROV is used at Grand Coulee Power Office (see Table 1 above).

Deep Ocean Engineering: Deep Ocean Engineering is a company that has designed and built their own ROV and USV platforms for a variety of applications for over 30 years [85]. The company offers Class I, II, and III type ROVs, and both catamaran and single-hull style USVs. Deep Ocean Engineering claims that many of their early platforms are still in operation due to their lifetime customer service and support. Grand Coulee Power Office owns two Deep Ocean Engineering ROVs (see Table 1 above). In addition, the USACE operates two Deep Ocean Engineering units (see Table 3 above).

Seamor Marine/Imagenex: Seamor Marine has been advancing ROV technology for more than 30 years. Seamor Marine designed and produces three Class II ROVs: Steelhead, Chinook, and Mako [86]. The systems are customizable with a variety of accessories and upgrades, including Imagenex sonar equipment [87].

Oceanbotics™: Oceanbotics™ is a division of RJE International, Inc since 2017. The company currently offers one ROV platform and is described as being intuitive to operate with extreme maneuverability and precise control [88].

Gaps and Recommendations

This research was intended to find the current equipment and applications for ROV operations in Reclamation and compare them to the current state-of-the-art to identify potential gaps or missed opportunities for more efficient, higher quality, or greater data collection. The research uncovered many more ROVs in operation than previously thought; it also identified some areas for growth that Reclamation can take advantage of.

Reclamation has traditionally embedded its ROV expertise within its dive team. There are some advantages to, this including giving ROV operators hands-on experience with the underwater environment. In addition, many times, ROV operations are in support of diving operations, and when ROV operators understand the dive atmosphere, there is greater communication and understanding. The dive team operators highly recommend that ROV operations continue to function within this setting for efficiency. It is also noted that there are occasions where facilities might need to take a first look at an underwater issue prior to determining if greater expertise is required. For such routine inspections, it is reasonable to have ROVs operating at facilities and area/regional offices with no dive team presence. As ROVs and ROV applications become more prevalent in the coming years, Reclamation's dive team and other operators may consider a dedicated sub-team to address custom innovation, maintenance, operations, data collection, and processing.

When reviewing the current underwater technologies for ROVs compared to the UAS revolution of the last decade, there are not as significant upgrades. The biggest challenges for ROVs compared to UAS are water visibility and underwater positioning. Because of poor water visibility at many of Reclamations facilities, operating cameras alone underwater sometimes is not able to provide the same quality and quantity of information that aerial cameras are able to. As such, underwater inspection applications will need to consider other types of data collection, including high-resolution sonar and laser scanning. The large success of UAS is mostly due to the integration of GPS into the flight controller to provide stable and reliable navigation, as well as the ability to geotag data products. Underwater positioning and data geotagging is more complicated and not readily available, but they could provide significant value to ROV operations and applications. Many of the currently available underwater positioning and geotagging alternatives are prone to error caused by sensor drift and are large approximations of the actual data locations. In informal discussions with many ROV vendors, there seems to be an acknowledgement of this deficiency and plans to address it with new technology and methods within the next 5 to 10 years.

One of the greatest opportunities highlighted by this research would be the application of USVs for hydrographic and bathymetric data collection. USVs are not limited by positioning the way underwater ROVs are and can take advantage of GPS for autonomous subsurface data collection by positioning the GPS sensors above the water and the profiling and modeling sensors underwater. USVs can operate on battery for significant amounts of time because of the ability to carry large batteries in the vehicle, which promotes stability. Reclamation currently does not have any USV capability and relies solely on manned operations for similar data collection.

In consideration of the current state-of-the-art, the research team proposes the following three acquisition recommendations:

1. Replacement of older, less powered, lower resolution ROVs with higher and more modular capabilities.
2. High-resolution sonar for inspection and mapping.
3. Autonomously controlled USV for hydrographic and bathymetric surveys, with the ability to merge underwater data with shoreline data.

One last consideration in the world of ROVs, USVs, and underwater sensors is that of the cost. Prices have been lowering over the last few years as less expensive but higher quality technology is available, but the acquisitions still represent a significant investment that makes it difficult to update. However, while no formal return-on-investment studies have been conducted, it is estimated that Reclamation can stand to benefit from developing better marine technologies and applications. Reclamation should develop plans and partnerships across programs to help reduce the costs and help realize a more robust underwater data collection system.

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