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Demonstration of Remotely Operated Vehicles to Aid Underwater Inspection of Corps of Engineers Navigation Structures

Winfield Locks and Dam 13–17 August 2007

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Abstract: We organized a demonstration of remotely operated vehicles (ROVs) at Winfield Locks and Dam to assess their merits to aid underwater inspections at U.S. Army Corps of Engineers navigation facilities. The demo was informative, not competitive, with tasks varying according to concurrent diver-based inspections. The demo illustrated that commercially available ROVs can significantly aid divers, not replace them, in conducting underwater inspections. ROVs increase safety whenever their use precludes the need for divers and through pre-dive reconnaissance when dives are unavoidable. They also offer shorter mobilization, easier access to confined areas, and permanent visual inspections records. When gates are closed, ROVs can work safely within the turbulent leakage flow in stilling basins and could in principle be used to investigate leaky valves and gates with no risks to divers. Learning curves for the systems demonstrated were shortened by the divers' exceptional knowledge of the underwater terrain and components to be inspected. Sonar was essential to navigate the ROVs in the low-visibility conditions, and the imaging sonar's quasi-3D images made precision navigation easier. The costs of ROV systems are modest in relation to capital equipment common at locks and dams, and pale in comparison to the expense of unplanned maintenance arising from insufficient inspection coverage.

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Preface

This demonstration was made possible by the enthusiastic support of Huntington District personnel and the participating ROV vendors. We thank them all: Domenico Chainesi, Scott Kinzel, Bill McNabb, Cork McAnnis, John Crabtree, Freddy Middleton, Bill O'Dell, Steve Hamm, Chris Gress, Richard White, Grant Fletcher, Mike Gilson, Karl Luttrell, Darrell Martin, Sean Newsome, Eben Franks, Darren Moss, Steve Fondriest, Erick Estrada, Chris Gibson, Tom Glebas, Joe Perreaud, Dan Scoville, and Jim Rall. We also thank our USACE-ERDC program managers Jim Clausner and John Hite for encouraging and supporting this work, and the other USACE participants for their helpful input: Rick Lewis, Vernon Lowrey, Terry Warren, Kate White, and Andy Tuthill. Jeff Byars warrants special recognition and appreciation for lending his experienced hand piloting the ROVs and discussing their potential applications throughout USACE.

COL Gary E. Johnston was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

Unit Conversion Factors

Multiply	By	To Obtain
feet	0.3048	meters
inches	0.0254	meters
pounds (mass)	0.45359237	kilograms

1 Introduction

The U.S. Army Corps of Engineers (USACE) must conduct underwater inspections at its navigation structures to identify and track maintenance concerns. Because more than half of the 240 USACE navigation locks are more than 50 years old, this need will increase to ensure safe, reliable, and cost-effective operations. Historically, human divers conducted these inspections at yearly intervals, with dewatering to inspect facilities more thoroughly at 5- to 10-year intervals. However, costs and safety concerns with divers have reduced the number of USACE dive teams, while increases in unscheduled maintenance at navigation structures indicate that more frequent inspections are already needed.

Commercially available remotely operated vehicles (ROVs) could help to increase underwater inspection rates safely and cost-effectively. ROVs are maneuverable tethered robots that are manually piloted from a surface control unit using video and sonar feedback to navigate. They can be equipped with acoustic and magnetic diagnostic sensors to aid inspections, but highly useful visual inspection and documentation can be achieved simply using the vehicle's camera systems. ROVs are not yet broadly used within the USACE, although their limited experience has shown that these systems can be very cost-effective (Lever et al. 2007).

We organized a demonstration of five commercially available ROVs to assess their merits to aid underwater inspections at USACE navigation facilities. Huntington District hosted the demo at Winfield Locks and Dam during the week of 13–17 August 2007, concurrent with annual diver inspection of the facility. The demo was intentionally noncompetitive and the inspection tasks differed each day according to diver activities. Our aim was to assess the merits of ROVs generally to aid underwater inspections and to obtain feedback from lock personnel and divers responsible for such inspections.

2 ROV Systems

The five ROV vendors who attended the demo were Deep Ocean Engineering, SeaBotix, Teledyne-Benthos, VideoRay, and Hydroacoustics, listed in order of their appearance during the week. In addition, the first four ROVs included imaging sonar by BlueView Technologies, who also sent a representative to participate. Each vendor offers a variety of ROV platforms and optional equipment. We describe here the basic characteristics of their systems as demonstrated; the vendors' Web sites have more information on these systems and their variants. Appendix A provides additional photos of the ROVs and descriptions of daily operations during the demo. Table 1 summarizes the physical parameters and approximate costs of the systems as tested.

Deep Ocean Engineering *Triggerfish*

Figure 1 shows the Deep Ocean Engineering (DOE) *Triggerfish* vehicle. As tested with sonar attached, it weighed about 33 kg and measured $1.09 \times 0.53 \times 0.41$ m. It has a tilting color-zoom video camera, two tilting lights, and a fixed-position BlueView P900E-20 imaging sonar at the front of the vehicle. It uses two longitudinal thrusters for fore/aft propulsion and two diagonal thrusters for vertical/lateral propulsion. Its depth rating is 152 m. Navigation aids include a fluxgate magnetic compass and a depth sensor. The modular topside equipment includes an operator control unit with joystick to drive the vehicle, auto-depth and auto-heading functions, and a video display with data overlay. The tether is 2 cm in diameter. The system cost as tested was about \$57,000 exclusive of the sonar.

SeaBotix *LBV150SE*

Figure 2 shows the SeaBotix *LBV150SE* vehicle. As tested with sonar attached, it weighed about 13 kg and measured about $0.53 \times 0.24 \times 0.35$ m. It has a tilting camera assembly consisting of a fixed-focal-length color video camera, LED lights, and a fixed-focal-length low-light black and white video camera mounted at 70° to the color camera. The BlueView P900E-20 imaging sonar was mounted horizontally on a skid under the

Table 1. Summary of ROV characteristics.

	Deep Ocean Engineering	SeaBotix	Teledyne-Benthos	VideoRay	Hydroacoustics
Model	<i>Triggerfish</i>	<i>LBV150SE</i>	<i>Stingray</i>	<i>Pro 3 XE GTO</i> (two systems)	<i>Proteus 500</i>
Weight (kg)	33	13	34	5–6	43
Dimensions (m)	1.09 x 0.53 x 0.41	0.53 x 0.24 x 0.35	0.99 x 0.46 x 0.46	0.36 x 0.21 x 0.33	0.69 x 0.46 x 0.45
Maximum depth (m)	152	150	350	152	152
Thrusters	Two fore/aft, two lateral-vertical on diagonal	Two fore/aft, one vertical, one lateral	Two fore/aft, one vertical, one lateral	Two fore/aft, one vertical	Two fore/aft, one vertical, one lateral
Tether diameter (cm)	2	0.76	1.7	0.80–1.0	0.35
Navigation	Fluxgate magnetic compass and depth gage	Fluxgate magnetic compass and depth gage	Fluxgate magnetic compass, depth gage, pitch-and-roll sensors, & yaw-rate gyro	Magneto-inductive compass, depth gage	Compass, depth gage
Lights	Two w/tilt	LED w/tilt	Two w/tilt	Two, fixed, LED array for rear camera	Two, fixed
Camera(s)	Color w/tilt and zoom	Color and low-light B&W w/tilt	Color w/tilt and zoom	Color w/tilt, low-light B&W rear facing	Color w/tilt, color fixed
Scanning sonar	NA	NA	NA	Tritech Sea-Sprite	Imagenex 881A
Imaging sonar	Blueview P900E-20	Blueview P900E-20	Blueview P900E-20 w/tilt	Blueview P900E-20, forward or side-looking	NA
Other onboard features	NA	NA	NA	Gripper arm	Onboard battery powered
OCU features	Auto-depth, auto-heading, video w/data overlay	Auto-depth, auto-heading, adjustable thruster gains, video w/data overlay	Auto-depth, auto-heading, video w/data overlay	Auto-depth, video w/data overlay	Auto-depth, auto-heading, water temperature, all control and display via one laptop computer
Approximate cost as tested	\$57,000 w/o sonar	\$26,300 w/o sonar	\$75,000 w/o sonar	\$27,500 w/o sonar or gripper	\$25,000 w/o sonar



Figure 1. Deep Ocean Engineering *Triggerfish* ROV carried by two divers (top). Underside (bottom) shows longitudinal thrusters at bottom, diagonal thrusters in middle, tilting video camera and light in top-center slot, and BlueView imaging sonar in top-right corner.

vehicle. The ROV uses two longitudinal thrusters for fore/aft propulsion, one thruster for vertical propulsion, and one thruster for lateral propulsion. Its depth rating is 150 m. Navigation aids include a fluxgate magnetic compass and a depth sensor. The compact topside system integrates an operator control unit with joystick to drive the vehicle, auto-depth and auto-heading functions, and a video display with data overlay. The tether is 0.76 cm in diameter. The system cost as tested was about \$26,300 exclusive of the sonar.



Figure 2. SeaBotix LBV150SE ROV (left) with color camera, black and white camera, and light mounted on tilt frame behind front cylindrical window, and one-person deployment/recovery (right).

Teledyne-Benthos *Stingray*

Figure 3 shows the Teledyne-Benthos *Stingray* vehicle. As tested with sonar attached, it weighed about 34 kg and measured $0.99 \times 0.46 \times 0.46$ m. Under the front of the vehicle, it has an externally mounted tilt bar with color-zoom video camera, lights, and BlueView P900E-20 imaging sonar attached. The ROV uses two longitudinal thrusters for fore/aft propulsion, one thruster for vertical propulsion, and one thruster for lateral propulsion. Its depth rating is 350 m. Navigation aids include a fluxgate magnetic compass, a depth sensor, pitch-and-roll sensors, and a yaw-rate gyro. The modular topside equipment includes an operator control unit with joystick to drive the vehicle, auto-depth and auto-heading functions, and a video display with data overlay. The tether is 1.7 cm in diameter. The system cost as tested was about \$75,000 exclusive of the sonar.

VideoRay *Pro 3 XE GTO*

VideoRay brought two complete *Pro 3 XE GTO* systems to the demo (Fig. 4). One vehicle had a gripper claw mounted underneath and a Tritech Sea-

Sprite scanning sonar mounted on top. The other had a BlueView P900E-20 imaging sonar mounted underneath. The ROVs with accessories weigh



Figure 3. Teledyne-Benthos *Stingray* shown from above (left) and underneath (right) with longitudinal thrusters at left end, lateral thruster and electronics housing in middle, and tilt bar with camera, lights, and sonar attached at right end.

about 5–6 kg and measure about $0.36 \times 0.21 \times 0.33$ m. These were the smallest and lightest ROVs demonstrated. They each have a fixed-focal-length tilting color video camera facing forward, fixed front lights, and a low-light black and white video camera facing rearward. Each ROV uses two horizontal thrusters for fore/aft propulsion and a smaller vertical thruster; they are rated at 152-m depth. Navigation aids include a compass and a depth sensor. The compact topside systems each integrate an operator control unit with joystick to drive the vehicle, auto-depth function, and a video display with data overlay. The tethers were 0.8–1.0 cm in diameter. The cost for each *Pro 3 XE GTO* system was about \$27,500 exclusive of sonar and gripper.



Figure 4. VideoRay's two *Pro 3 XE GTO* vehicles with scanning sonar (left vehicle) and imaging sonar (right vehicle) and topside control and display equipment for both ROVs.

Hydroacoustics *Proteus 500*

Figure 5 shows the Hydroacoustics *Proteus 500* system. This ROV was powered by on-board batteries (normally Li-Ion but NiMH at the demo) rather than powered via the tether as all other systems demonstrated. Mounted at the front, the vehicle has two fixed-focal-length color video cameras (one tilting, one fixed) and two fixed lights. It also has a vertically mounted Imagenex 881A scanning sonar. With sonar, the ROV weighs about 43 kg and measures about $0.69 \times 0.46 \times 0.45$ m. The ROV uses two longitudinal thrusters for fore/aft propulsion, one thruster for vertical propulsion, and one thruster for lateral propulsion. Its depth rating is 152 m. Navigation aids include a compass and depth sensor. The topside equipment includes a laptop computer-based operator control unit with joystick to drive the vehicle, and auto-depth and auto-heading functions. The laptop screen can display video and sonar simultaneously in separate windows. The tether was the smallest demonstrated at 0.35 cm in diameter. It is slightly negatively buoyant but floats can be added to provide slight positive buoyancy. The system cost as tested was about \$25,000 exclusive of the sonar.



Figure 5. Hydroacoustics *Proteus 500* ROV (left) with vertically mounted Imagenex sonar, tilt color camera, fixed lights, and two longitudinal battery tubes along bottom of vehicle, and (right) laptop-based operator station.

BlueView P900E-20 imaging sonar

The BlueView P900E-20 is a multibeam sonar that creates two-dimensional (2D) images of intensity versus angle and distance across a $45^\circ \times 55$ -m field of view at update rates up to 10 Hz (Fig. 6). The sonar frequency is 900 kHz, and each of the 256 beams measure 1° horizontal \times 20° vertical, with 0.18° horizontal spacing. Its range is 1–55 m with range resolution of 2.5 cm. It provides the sonar equivalent of video images us-

ing illumination from a single source, with coarser resolution and slower update than video but independent of water clarity. Solid walls show as bright lines across the images; bright returns and shadows cast by raised or recessed features provide quasi-three-dimensional (3D) effects within the images. The sonar can be used to navigate the ROV and provide geometric data on the condition of underwater structures over much larger fields of view than are possible with video images in low-visibility water. The sonar weighs 1.9 kg and measures 18 × 10 cm in diameter. It costs about \$25,000–\$35,000 integrated onto an ROV, including sonar hardware and software but requires its own laptop computer to display and record the images.

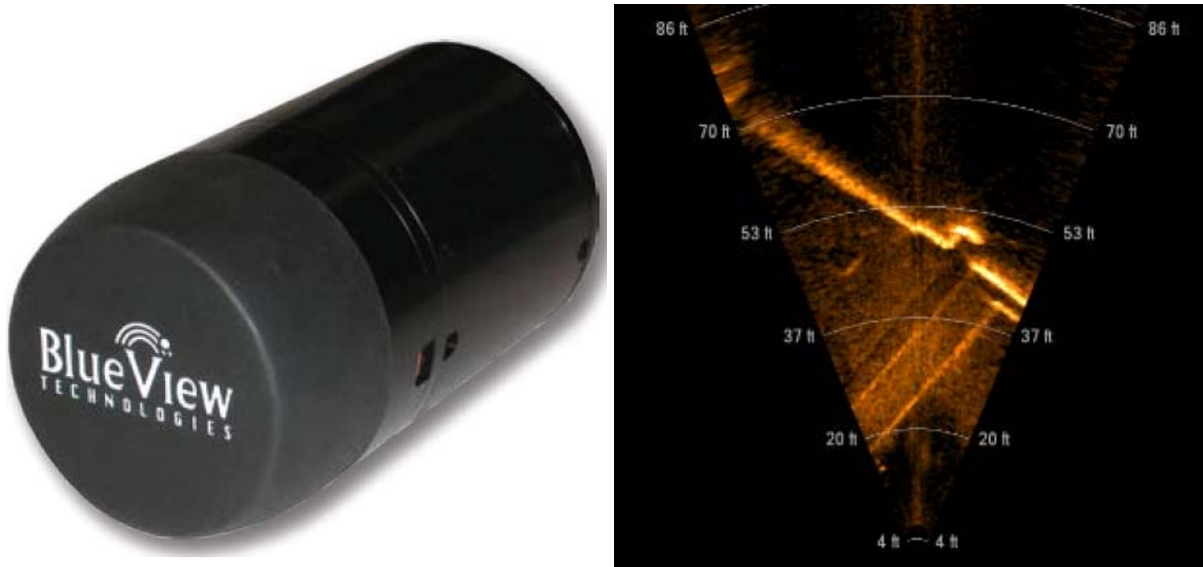


Figure 6. BlueView P900E-20 imaging sonar (left) was mounted on four of the five ROVs. The sonar image taken in the main lock chamber (right) clearly shows the lock wall diagonally from upper left to middle right, the stop-log recess in the wall, the stop-log sill diagonally from lower left, and one of the stop-log alignment blocks near middle left.

3 Demo Operations

Winfield Locks and Dam is located on the Kanawha River downstream from Charleston, WV, and consists of a relatively new 800- x 110-ft lock with miter gates, two smaller auxiliary locks with miter gates, and a dam with roller gates and stilling basin (Fig. 7). The Huntington District Web site (www.lrh.usace.army.mil/projects/locks/win/) has additional information on the facility and its function.

During the week of the ROV demo, 13–17 August 2007, the District's dive team conducted inspections of the facility. Their tasks varied each day, ranging from assessing the condition of the miter-gate seals on the main and auxiliary locks to examining the stilling basin for possible scour of the concrete.

Each morning, the dive team mobilized its equipment on a barge connected to a towboat (Fig. 8). During this time, some of its members, other Winfield staff, the authors, and other USACE personnel attended morning briefings by the vendors regarding the features and use of their ROVs. The vendors then mobilized their ROV equipment according to the day's inspection tasks. For four vendors, we operated the ROVs from the dive team's barge; the VideoRay demo operated from the land-side pier adjacent to the main lock chamber.

We primarily attempted to conduct similar inspections as the divers. Over the first four days, we deployed the ROVs to inspect the miter-gate seals, filling culverts, and culvert valves for an auxiliary lock and for the main lock. On the last day, we deployed the ROV initially to inspect a portion of the stilling basin and then to search for lost floating moorings downstream of the lock and potential debris on the towboat propeller. Besides vendor representatives, Winfield staff and dive-team members also piloted the ROVs. Appendix A provides a summary and some photographs of each day's operations.

Jeff Byars from Mobile District attended the three middle demo days and piloted the SeaBotix, Teledyne-Benthos, and VideoRay ROVs. Byars is a snag boat captain and diver. He custom-built and operated his own ROV for Mobile District and now operates a VideoRay *Pro 3* ROV regularly

within Mobile District and occasionally for other Districts (Lever et al. 2007). We pressed Byars into service as a guest ROV pilot to help us understand how well the systems could conduct the underwater inspections once the pilot gained experience.



Figure 7. Winfield Locks and Dam on the Kanawha River, WV looking downstream. In this photo, the main lock chamber (center right) is filled with eight barges and a towboat. The older auxiliary locks in the center can accept individual barges. Four bays of the dam are visible across the center left.



Figure 8. Dive-team barge and towboat moored at downstream end of 800-ft main lock chamber before inspection of lower miter gates.

4 Demo Outcomes and Desirable ROV Characteristics

The demo was intentionally noncompetitive and the inspection tasks differed each day. We do not seek to recommend that the USACE acquire any particular product based on this demonstration. Rather, our comments here aim to convey the qualitative strengths and weaknesses of the ROVs generally as aids to underwater inspections at USACE navigation structures. Furthermore, it is clear from the demo that ROVs can aid diver-based inspections, not replace them.

All ROVs possessed video cameras and lights that produced high-quality images when the target was within visible range, which was 0.3–0.6 m during the demo. The ROVs can easily provide permanent records of the inspected features provided they are within range and at known locations. An excellent example of this was the long, continuous video record of the miter-gate seals obtained with Byars piloting a *Pro 3 XE GTO* during our demonstration. Comparison of records obtained at regular intervals could help to identify changes in conditions that warrant preventative maintenance. Under the conditions at Winfield during the demonstration, divers also reported needing to get within 0.3–0.6 m of the target feature to conduct a visual inspection, but they were able to inspect some hard-to-access features by touch. Their extensive knowledge of the underwater terrain usually suffices for them to determine their location and maintain orientation. A diver's verbal description of a feature is often sufficient to assess its condition; however, if a visual record is needed the diver must separately use an underwater camera. This is a somewhat awkward task that a well-piloted ROV achieves inherently.

All ROVs were quite intuitive to operate. Divers and lock personnel with no previous experience could pilot them quite proficiently within a few minutes of taking the controls. The key was to move the ROV smoothly to interpret the sonar images while navigating towards the desired feature. Scott Kinzel, a dive-team coordinator and Huntington District engineer showed that slow, deliberate maneuvering coupled with extensive knowledge of the facility could compensate for lack of piloting experience. Impressively, Byars' combination of ROV piloting experience and knowledge of lock terrain resulted in more efficient inspections than were achieved by

experienced vendor pilots operating in a lock or culvert for the first time. These results suggest that ROV learning curves will be short for most divers and lock personnel, and that inspection quality and efficiency will increase quickly with piloting time.

The ROV systems were all well designed, with consideration given to simplicity and ease-of-use. These are commercial off-the-shelf systems and most have many years of proven reliability with many fielded systems. Software and control systems also worked reliably. With some modest training, USACE personnel should easily be able to operate and maintain these systems over many years of inspection duty.

Sonar is essential to navigate an ROV in low-visibility water. The video screen is essentially blank until the ROV is about to bump into something. Even after contact, the ROV location may be unknown if no uniquely identifiable features remain within visible range. The P900E-20 imaging sonar provided long-distance navigation and data collection independent of visibility. Once the system was tuned for local conditions (e.g., sonar downward tilt, image threshold, and brightness) its quasi-3D images readily highlighted known lock features and greatly aided navigation precision. Local knowledge of the underwater terrain speeded this interpretation. Generally, slow movements of the ROV were necessary to interpret the scenes and navigate precisely. Furthermore, multiple reflections or ringing of sonar returns required some experience to interpret. Nevertheless, the system clearly imaged the geometry of key lock features such as culvert ports, culvert walls and floors, miter gates and sills, stop-log sills, and other features. The learning curve to tune and interpret the imaging sonar was steeper than for scanning sonar, and imaging sonar is more expensive. However, imaging sonar produces geometrically correct 2D images updated several times per second, whereas ROV movement distorts the images produced by scanning sonar. In addition, the image sector away from the sweep line can be several seconds out of date for scanning sonar. With Byars' level of experience as an operator, he quickly adapted to the imaging sonar and used it very effectively, preferring it for navigation over the scanning sonar. Depending on the need, the *P900E-20's* combination of fast update and quasi-3D geometrically correct images can certainly justify its extra cost.

Neither sonar systems quite overlapped in range with the underwater video cameras, so the ROVs were usually flying blind for the last meter be-

fore reaching visual range. The pilot would often become disoriented unless a distinguishing feature appeared on the camera. Bumping into a wall often resulted, followed by repeated attempts to reorient the ROV. This problem can be surmounted by working with the vendors to tune the sonar to achieve a minimum range less than 0.3–0.6 m.

Size was perhaps the feature that most significantly distinguished the ROVs. The larger *Triggerfish*, *Stingray*, and *Proteus* ranged 33–43 kg and required two-person transport and deployment/recovery. The *Triggerfish* and *Stingray* also had more topside equipment and consequently required greater mobilization effort than the smaller systems. The *LBV150SE* as tested was 13 kg and was easily transported and deployed/recovered by one person. The *Pro 3 XE GTO* is termed a micro-ROV and each of the two units demonstrated weighed only 5–6 kg. They could be deployed essentially with one hand. The ease of mobilization and deployment/recovery of the smaller ROVs is helpful when numerous inspection tasks are distributed around a facility or when expediency is important. They also lessen the mobilization/demobilization burden for a dive team concurrently using an ROV. Storage space requirements are reduced by ROVs with smaller footprints, and mobilization to alternate locations, including by airline, is easier.

Operationally, the smaller ROVs have the advantage of better access and maneuverability to conduct inspections in tight spaces, for example, to inspect culvert-valve chambers and miter-gate quoins. Cameras needed to be quite close to the target features to obtain useful video images. The larger ROVs took longer to find and inspect some features or were unable to approach closely enough to obtain video images. Conversely, based on the *Proteus* inspection of the stilling basin, the larger ROVs probably have a stability advantage over the smaller ROVs in the presence of large-scale turbulence. They also can accept larger sensor payloads more easily than the smaller units, although the *LBV150SE* and *Pro 3 XE GTO* both successfully integrated the P900E-20 imaging sonar.

In most cases, the divers were much more efficient at conducting the underwater inspections than the ROVs. Nevertheless, ROVs have some key advantages primarily related to the need to assure diver safety. ROVs can be mobilized more quickly than divers to conduct expedient inspections, for example, to determine the reason why a gate, valve, or stop-log does not seat properly. If the cause is debris, Byars' experience is that an ROV

can often place a hook or line on the debris to haul it out without needing to mobilize divers from across the District. The presence of leakage flows in these or other circumstances prevents use of divers altogether. Culvert inspections are also more easily conducted with an ROV owing to additional safety requirements for penetration dives. At Winfield and similar locks, divers do not inspect within the confined spaces of culvert-valve chambers. Diving inspections of stilling basins are also hampered by the highly turbulent flow leaking through imperfectly closed gates and the difficulty of inspecting such large areas in low-visibility conditions. Although not demonstrated here, ROVs should also be able to inspect in-the-wet construction activities during circumstances that would be unsafe for divers. In all these cases, if the ROV-based inspection is not adequate to assess the situation for maintenance or quality-control decisions, they should help divers to focus their attention on key issues and establish any additional safety measures necessary in advance of the dive.

Tethers are essentially a defining characteristic of an ROV, contrasting them with unmanned underwater vehicles (UUVs). ROVs are piloted by a person from the surface rather than programmed to navigate autonomously. Tethers enable high-bandwidth surface-vehicle control and communications, including transmission of real-time, high-quality video and sonar images. This feature is particularly important for inspections: newly discovered anomalies can be closely inspected immediately rather than waiting to recover a UUV to review the inspection record. Tethers simplify power and navigation requirements and thus reduce the cost and complexity of ROVs compared with UUVs. A tether also provides a line to deploy and recover the vehicle. Indeed, they usually are strong enough to allow retrieval of small objects or debris when the ROV is equipped to grip objects. Commercial ROVs generally have tethers that are long enough to serve most USACE inspection needs with length to spare. The possibility of entangling the tether is its only drawback, and this can usually be avoided through careful tether management during operations and the acquired skill of piloting the vehicle back along the tether to withdraw from cramped or cluttered spaces.

The USACE is not currently a significant consumer of ROV systems. Consequently, ROV manufacturers have not tailored their systems to address USACE inspection needs. Some tailoring would be very easily accomplished, such as providing a depth readout in the elevation datum used at navigation structures. Other capabilities that would address USACE needs,

such as incorporating feature-based navigation methods, ROV track overlay on 3-D virtual facility images, and geo-spatially referenced inspection archives, for example, could be developed relatively quickly. Significant demand for such enhancements would readily spur their development by the ROV manufacturers and their accessory suppliers. Development efforts that were significant might require USACE-industry partnerships, but this would ensure products best suited to USACE inspection needs at its many, valuable navigation structures.

5 Conclusions

The week-long demo of commercially available ROVs at Winfield Locks and Dams successfully highlighted how they can aid underwater inspections at USACE navigation facilities. With years of experience on site, the divers were clearly able to conduct inspections of key components more quickly than the ROVs. However, compared with divers, the ROVs offered shorter mobilization, easier access to confined areas such as filling/emptying culverts and culvert-valve chambers, and permanent visual records of inspections. They also worked safely within the large-scale turbulent flow in the stilling basin and could in principle be used to investigate leaky valves and gates and conduct inspections during in-the-wet construction with no risks to divers.

Winfield personnel piloted the ROVs remarkably well, their lack of experience more than compensated by extensive knowledge of underwater lock terrain. Jeff Byars from Mobile District, having used ROVs at USACE navigation structures for many years, conducted several very efficient inspections of filling conduits and miter-gate seals using different ROVs. Sonar was essential to navigate the ROVs in the low-visibility conditions, and the imaging sonar's fast update rate of quasi-3D images made precision navigation easier.

We conclude that commercially available ROVs would significantly aid divers, not replace them, in conducting inspections at USACE navigation facilities. Learning curves for these systems are shortened by the divers' exceptional knowledge of the underwater terrain and components to be inspected. The costs of ROV systems are modest in relation to capital equipment common at locks and dams (trucks, barges, towboats, dive equipment) and of course pale in comparison to the cost of the facility itself and the expense of unplanned maintenance arising from insufficient inspection coverage.

References

Lever, J. H., G. E. Phetteplace, and J. C. Weale. (2007) *Benefits of using remotely operated vehicles to inspect USACE navigation structures*. ERDC/CRREL Technical Report TR-07-4. Hanover, NH: Cold Regions Research and Engineering Laboratory.

Appendix A: Daily Log

13 August 2007

Attendees

USACE: Jim Lever, Gary Phetteplace, Scott Kinzel, Bill McNabb, Cork McAnnis, John Crabtree, Freddy Middleton, Rick Lewis, Bill O'Dell, Steve Hamm, Chris Gress, Richard White.

Deep Ocean Engineering: Mike Gilson, Karl Luttrell, Darrell Martin.

BlueView Technologies: Grant Fletcher.

ROV system

Deep Ocean Engineering *Triggerfish* ROV with BlueView P900E-20 imaging sonar (Fig. A1)

ROV operations

- Approximately 1-h mobilization time onto barge.
- Moored upstream of auxiliary lock (Fig. A2); water depth ~33 ft.
- One-person deployment, two-person recovery of ROV.
- One operator, one person to manage tether.
- Grant Fletcher operated and interpreted BlueView sonar.
- Water visibility only 1–2 ft, but good video images at close range.
- Tilting color camera and light work well together.
- Sonar aids navigation (e.g., clear images of filling-culvert ports, walls gates, etc.), but requires experience to interpret images (e.g., to “filter” secondary returns); image update rate slow, many system reboots—communication problems related to tether.
- Darrel Martin (DOE) pilots ROV with experienced hand, but lack of knowledge of lock terrain slows inspection of miter gate and culvert ports; Martin reluctant to drive into culvert to avoid snagging tether.
- Steve Hamm pilots well for 10 min, lack of experience compensated by extensive knowledge of lock terrain.
- Large-diameter tether requires attentive management.



Figure A1. Deep Ocean Engineering system showing (clockwise from upper left): *Triggerfish* ROV carried by two divers; underside of ROV with longitudinal thrusters at bottom, diagonal thrusters in middle, tilting video camera and light in top-center slot, and BlueView sonar in top-right corner; ROV and topside control/display equipment; ROV and tether in water just upstream of auxiliary lock.



Figure A2. Winfield Locks and Dam twin auxiliary locks (center of photo) are located between the new main lock chamber (right) and dam gates (left). ROV deployments were just upstream of left auxiliary lock to inspect miter-gate seals and filling-culvert ports.

14 August 2007

Attendees

USACE: Jim Lever, Gary Phetteplace, Scott Kinzel, Bill McNabb, Cork McAnnis, John Crabtree, Freddy Middleton, Rick Lewis, Bill O'Dell, Steve Hamm, Chris Gress, Richard White, Domenico Chinesi, John Hite, Jeff Byars.

SeaBotix: Sean Newsome.

BlueView Technologies: Grant Fletcher.

ROV system

SeaBotix *LBV150SE* ROV with BlueView P900E-20 imaging sonar (Fig. A3).

ROV operations

- Approximately 20-min mobilization time onto barge.
- Moored upstream of auxiliary lock (Fig. A2), water depth ~33 ft.
- One-person deployment and recovery of ROV.
- One operator, one person to manage tether.
- Grant Fletcher operated and interpreted BlueView sonar.
- Water visibility only 1–2 ft, but good video images at close range.
- Tilting color camera, black and white camera, and light work well together.
- Sonar aids navigation (e.g., clear images of filling-culvert ports, walls, gates, etc.) but requires experience to interpret images (e.g., to “filter” secondary returns); image update fast and stable on fiber-optic tether; Fletcher has gained experience interpreting lock terrain on sonar.
- Sean Newsome (SeaBotix) pilots ROV with experienced hand, but lack of knowledge of lock terrain slows inspection of miter gate and culvert ports.
- Scott Kinzel pilots well for 15 min, lack of experience compensated by extensive knowledge of lock terrain and patient touch on controls.
- Jeff Byars pilots very well for 40 min, including inspecting miter-gate pintle and entering filling-culvert port, despite having never previously driven a SeaBotix ROV; however, Jeff has extensive experience piloting a VideoRay ROV and thorough knowledge of lock terrain.

- Small-diameter tether requires infrequent management, depending on inspection task.



Figure A3. SeaBotix system showing (clockwise from upper left): LBV150SE ROV with color camera, black and white camera, and light mounted on tilt frame behind front cylindrical window; ROV with underside skid-mounted BlueView sonar, topside control/display unit, and tether reel; Scott Kinzel piloting ROV patiently and well; one-person deployment/recovery.

15 August 2007

Attendees

USACE: Jim Lever, Gary Phetteplace, Scott Kinzel, Bill McNabb, John Crabtree, Freddy Middleton, Rick Lewis, Bill O'Dell, Chris Gress, Richard White, Jeff Byars, Vernon Lowrey, Terry Warren.

Teledyne-Benthos: Eben Franks, Darren Moss, Steve Fondriest.

BlueView Technologies: Grant Fletcher.

ROV system

- Teledyne-Benthos *Stingray* ROV with BlueView P900E-20 imaging sonar (Fig. A4).

ROV operations

- Approximately 1-hr mobilization time onto barge.
- Moored at downstream end of main lock chamber (Fig. A5) to inspect lower miter gates, water depth ~20 ft with gates open.
- One-person deployment, two-person recovery of ROV.
- One operator, one person to manage tether.
- Grant Fletcher operated and interpreted BlueView sonar (afternoon only).
- Water visibility only 1–2 ft, but good video images at close range.
- Tilting color camera and lights work well together; BlueView sonar also mounted on tilt bar.
- Sonar aids navigation (e.g., clear images of filling-culvert ports, walls and stop-log recesses, gates, etc.); image update fast and stable; Fletcher has gained experience interpreting lock terrain on sonar.
- Eben Franks (Teledyne-Benthos) pilots ROV with experienced hand, but lack of knowledge of lock terrain slows inspection somewhat; successful inspection along bottom J-seal.
- Moored near upstream filling-culvert ports of main chamber; water depth ~40 ft.
- Jeff Byars pilots very well for 40 min, including entering filling culvert and piloting downstream to inspect partially open culvert valve, despite having never previously driven a Teledyne-Benthos ROV; however, Jeff has extensive experience piloting a VideoRay ROV and thorough knowledge of lock terrain.
- Nice sonar images looking down culvert and tilting sonar to see walls, ceiling and floor, culvert valve, etc.

- Tether requires attentive management (as expected for operation in filling culvert).



Figure A4. Teledyne-Benthos system showing (clockwise from top left): system components fill pick-up truck; *Stingray* ROV with stainless steel frame and thruster impellers; assembly of topside control and display equipment; underside of ROV with longitudinal thrusters at left end, lateral thruster and electronics housing in middle, and tilt bar with camera, lights, and sonar attached at right end.



Figure A5. Barge and towboat moored at downstream end of 800-ft main lock chamber before inspection of lower miter gates.

16 August 2007

Attendees

USACE: Jim Lever, Gary Phetteplace, Scott Kinzel, Bill McNabb, John Crabtree, Freddy Middleton, Bill O'Dell, Chris Gress, Richard White, Jeff Byars.

VideoRay: Erick Estrada, Chris Gibson, Tom Glebas.

BlueView Technologies: Grant Fletcher.

ROV systems

(1) *VideoRay Pro 3 XE GTO* with *BlueView P900E-20* imaging sonar, and (2) *Pro 3 XE GTO* with *Tritech SeaSprite* scanning sonar and gripper (Fig. A6).

ROV operations

- Approximately 20-min mobilization time onto land-side pier of main chamber (both systems), water depth ~20–50 ft depending on pool elevation.
- Easy one-person deployment and recovery of each ROV.
- One operator, one person to manage tether for each ROV.
- Grant Fletcher operated and interpreted *BlueView* sonar.
- Water visibility only 1–2 ft, but good video images at close range.
- Tilting color camera and fixed but diffuse lights work well together; rear black and white camera helps to find tether when reversing direction.
- Both sonars aid navigation; less learning curve to interpret scanning sonar provided ROV doesn't move quickly and blur lines; imaging sonar produces impressive images of lock features (culvert internal geometry, stop-log sill with protruding guide blocks, etc.) when set at grazing angle; Fletcher now able to tweak sonar very effectively (four days experience at lock); imaging sonar images still require experience to interpret, but lock personnel (Gress, Kinzel, Crabtree) can quickly identify lock features based on their appearance when lock was built or from drawings.
- Chris Gibson and Tom Glebas (*VideoRay*) skillfully drive the ROVs inside the filling culvert valve chamber to inspect the grease lines, valve seals, etc.; the ROVs' small sizes allow easy maneuvering around the various valve struts shaft and lifting cables (tainter gate style); the close quarters allow the pilots to follow grease lines visually and refer to sonar when needed to orient vehicle.
- Jeff Byars pilots one ROV very efficiently, needing only about 30 min to inspect the sills and J-seals of both upper miter gates during essentially one continuous inspection run (very smooth video record of whole run); Jeff has

extensive experience piloting a VideoRay ROV and thorough knowledge of lock terrain; this indicates the proficiency possible with piloting experience combined with lock knowledge.

- ROV's small size and Jeff's experience allows him to inspect miter-gate quoin and pintle efficiently, with camera close enough to reveal details.
- Small-diameter tethers require infrequent management, depending on inspection tasks; careful tether management is needed when inspecting in valve chamber to avoid entanglement.
- VideoRay personnel deployed the DesertStar long-baseline acoustic positioning system in main lock chamber (four transponders placed at known locations on lock walls to triangulate position of ROV); they worked through several problems but were ultimately unable to operate the system successfully.



Figure A6. VideoRay systems showing (clockwise from upper left): two *Pro 3 XE GTO* vehicles with scanning sonar (left vehicle) and imaging sonar (right vehicle); topside control and display equipment for both ROVs; the ROV with imaging sonar being lowered into the land-side filling valve chamber to inspect the grease lines and valve seals; looking down on ROV with scanning sonar approaching the miter gate to inspect the quoin block, sills, and J-seals.

17 August 2007

Attendees

USACE: Jim Lever, Gary Phetteplace, Scott Kinzel, Bill McNabb, Freddy Middleton, Bill O'Dell, Chris Gress, Richard White.

Hydroacoustics: Joe Perreaud, Dan Scoville, Jim Rall.

ROV system

Hydroacoustics *Proteus 500* ROV with Imagenex 881 scanning sonar (Fig. A7). ROV has onboard batteries for power, laptop-based control, and display software.

ROV operations

- Approximately 20-min mobilization time onto barge.
- First dive—moored below gates 1 and 2 in stilling basin (Fig. A8); water depth ~16 ft.
- Two-person deployment and recovery of ROV.
- One operator, one person to manage tether.
- Small tether (3.5-mm diameter) used small floats to achieve slight positive buoyancy.
- Water visibility ~4 ft owing to leakage through gates; good video images at close range but still need sonar to navigate.
- Imagenex sonar updates via sweeps on screen similar to scanning sonar so walls curve when ROV moves just as with scanning sonar.
- Dan Scoville (Hydroacoustics) pilots with experienced hand; very effective piloting despite turbulent flow in stilling basin.
- Jostling by flow, short visible range, and slow sonar sweep rate combine to make it difficult to conduct systematic survey of stilling basin; nevertheless, Scoville identifies location, pilots ROV onto and off dissipater blocks, onto and off rear wall, and successfully navigates to scour hole downstream of wall at location previously identified by echo sounder survey (near centerline of gate 3 and 15 ft downstream of wall).
- Dive coordinator prefers not to use divers to inspect basin downstream of gates 2 and 3 owing to leakage flow.
- Second dive—moored at edge of navigation channel approximately one-half mile downstream of lock to search for chains from lost floating moorings.

- Shallow water and large riprap make it difficult to identify chains within the sonar images; stop searching after ~30 min.
- Third dive (expedient deployment)—moored along river wall of main chamber approach to inspect propeller shaft of our own towboat, *MVPH Worley*, for possible debris.
- ROV tether gets entangled around shaft and rudder; diver cheerfully assists with recovery. Entanglement could have been avoided by removing the tether floats to allow tether to fall below ROV.

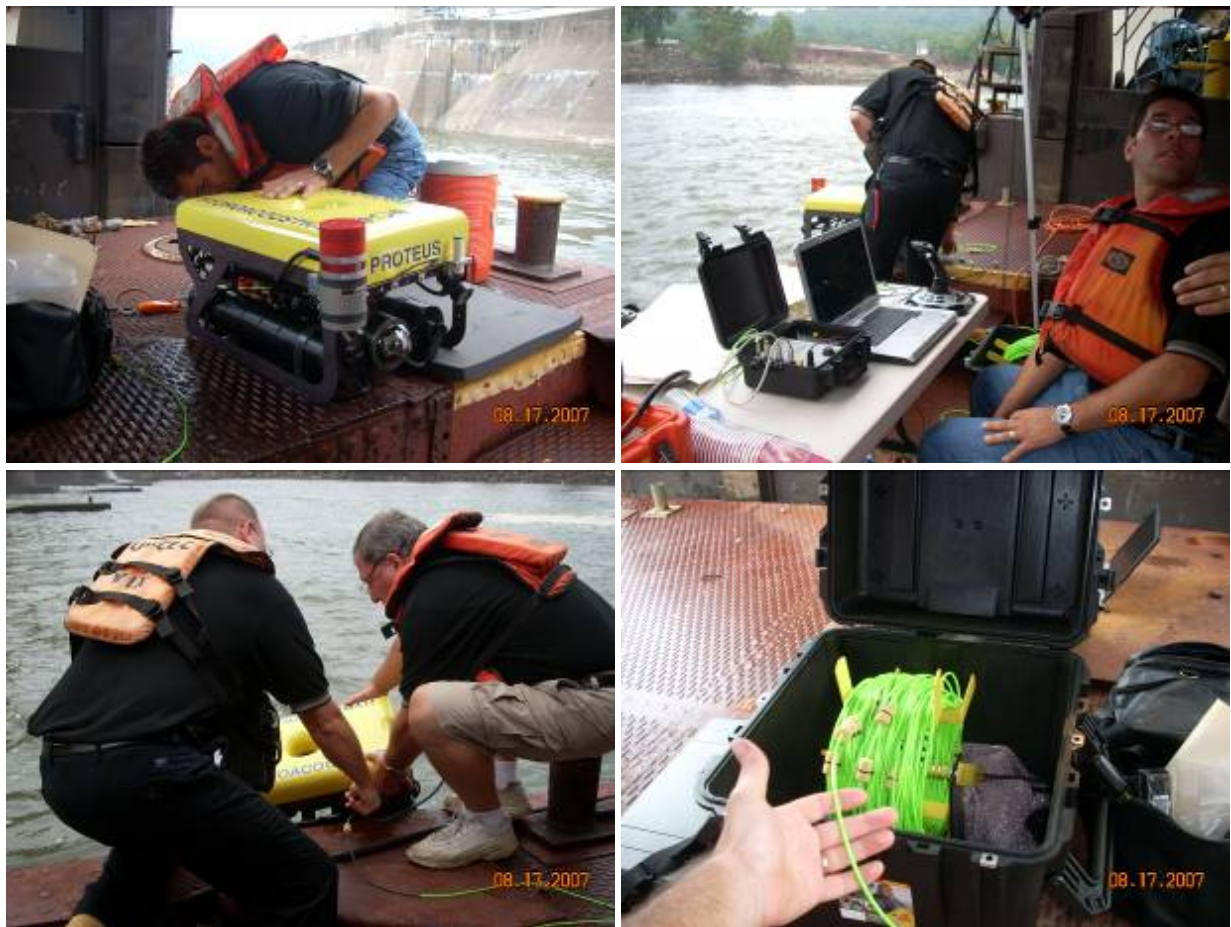


Figure A7. Hydroacoustics system showing (clockwise from upper left): *Proteus 500* ROV with vertically mounted Imagenex sonar (with red cap), tilt color camera, fixed lights, and two longitudinal battery tubes along bottom of vehicle; laptop-based operator station; thin tether with floats; two-person deployment.



Figure A8. View when moored in stilling basin below dam, with gate 2 at left of picture.

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14. ABSTRACT We organized a demonstration of remotely operated vehicles (ROVs) at Winfield Locks and Dam to assess their merits to aid underwater inspections at U.S. Army Corps of Engineers navigation facilities. The demo was informative, not competitive, with tasks varying according to concurrent diver-based inspections. The demo illustrated that commercially available ROVs can significantly aid divers, not replace them, in conducting underwater inspections. ROVs increase safety whenever their use precludes the need for divers and through pre-dive reconnaissance when dives are unavoidable. They also offer shorter mobilization, easier access to confined areas, and permanent visual inspections records. When gates are closed, ROVs can work safely within the turbulent leakage flow in stilling basins and could in principle be used to investigate leaky valves and gates with no risks to divers. Learning curves for the systems demonstrated were shortened by the divers' exceptional knowledge of the underwater terrain and components to be inspected. Sonar was essential to navigate the ROVs in the low-visibility conditions, and the imaging sonar's quasi-3D images made precision navigation easier. The costs of ROV systems are modest in relation to capital equipment common at locks and dams, and pale in comparison to the expense of unplanned maintenance arising from insufficient inspection coverage.						
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