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Augmented Co-Robotics for Remediation of Military Munitions Underwater

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14. ABSTRACT
Marine unexploded ordnance is a significant environmental contaminant, particularly in shallow waters where it may intersect with the public. Effective remediation requires assessment at a minimum, and in many cases either removal or neutralization. In all but the shallowest waters, this requires intervention by divers trained in UXO remediation, a dangerous task requiring specialized training and extraordinary precautions.

Over the preceding half-century, the need to perform inspection and maintenance in the deep ocean, driven largely by the needs of the energy industries, has resulted in sophisticated tele-operated robotic systems designed for operation at pressures inhospitable to human life. Such remotely-operated vehicles (ROVs) frequently feature high-degree-of-freedom arms to perform manipulation tasks under remote control by an operator on the surface. Such technologies originating in subsea intervention could be adapted to perform remote remediation of UXO, reducing the risk to divers. However, despite the critical role such tele-operated manipulators play in maintaining critical deep ocean infrastructure, they are technologically relatively simple, with constrained sensory capabilities and limited manual dexterity. These challenges are highly relevant to teleoperated UXO remediation where precise handling is essential for safe handling of the UXO. However, advances in user-assistive robotic control motivated by the demands of work in the deep ocean can also improve the efficiency and effectiveness of tele-operated manipulation for UXO remediation.

15. SUBJECT TERMS
Maritime unexploded ordnance, robotic remediation, haptic manipulation

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List of Acronyms

HPU	Hydraulic power unit
ROV	Remotely Operated Vehicle
UXO	Unexploded Ordnance
VR	Virtual Reality

Keywords

Maritime unexploded ordnance, robotic remediation, haptic manipulation

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He would also like to thank the program office and program manager for their understanding regarding the closure of the project following the original PI's departure.

Abstract

Introduction and Objectives

Marine unexploded ordnance is a significant environmental contaminant, particularly in shallow waters where it may intersect with the public. Effective remediation requires assessment at a minimum, and in many cases either removal or neutralization. In all but the shallowest waters, this requires intervention by divers trained in UXO remediation, a dangerous task requiring specialized training and extraordinary precautions.

Over the preceding half-century, the need to perform inspection and maintenance in the deep ocean, driven largely by the needs of the energy industries, has resulted in sophisticated tele-operated robotic systems designed for operation at pressures inhospitable to human life. Such remotely-operated vehicles (ROVs) frequently feature high-degree-of-freedom arms to perform manipulation tasks under remote control by an operator on the surface. Such technologies originating in subsea intervention could be adapted to perform remote remediation of UXO, reducing the risk to divers. However, despite the critical role such tele-operated manipulators play in maintaining critical deep ocean infrastructure, they are technologically relatively simple, with constrained sensory capabilities and limited manual dexterity. These challenges are highly relevant to teleoperated UXO remediation where precise handling is essential for safe handling of the UXO. However, advances in user-assistive robotic control motivated by the demands of work in the deep ocean can also improve the efficiency and effectiveness of tele-operated manipulation for UXO remediation.

Technical Approach

This work incorporates three research elements. First is the construction of a testing platform which incorporates a commercial off-the-shelf subsea manipulator, appropriate sensors and a workspace for placing test objects. This test system is scaled to allow operation in the University of Washington School of Oceanography test tank as well as installation on two vessels at UW-APL for testing in local waters. The second element, headed by Olis Robotics, concerns the development of software tools for visualizing and planning grasp maneuvers before execution, allowing delicate grasps to be planned in advance based on observed knowledge of the object in context rather than being planned in real-time by an operator. The third element, driven by the University of Washington School of Electrical and Computer Engineering, concerns the use of virtual reality (VR) in planning and visualizing grasping maneuvers.

Results

The test system was constructed and deployed to the School of Oceanography test tank in the fall of 2018. This allowed completion of a full semi-autonomous grasp cycle, including collection of a 3D point cloud of the UXO in the test workspace using a subsea laser scanner, handoff to of that point cloud to the Olis control software, planning of an ideal grasp, then semi-automated execution of the grasp, allowing a controlled grasp of a UXO stand-in.

Benefits

Once matured, robotic manipulation offers a compelling alternative to human divers for all forms of UXO handling, including removal as well as preparation for destruction-in-place. As shown within this project, integrating robotic perception and control allows more precise, more efficient manipulator control under human operation. It is also a necessary prerequisite for future, more autonomous control in which robotic intelligence might perform elements of UXO remediation under human oversight but without direct human control.

Executive Summary

Introduction

Unexploded Ordnance (UXO) are a significant environmental hazard in marine areas, a legacy of accidents, ill-considered disposal and handling, as well as the explicit use of many maritime areas as target and practice ranges. UXO become a public hazard to boaters, fisherman and divers both through explicit re-opening of former DoD areas to public use, and through transport due to sediment movement and currents. Of particular concern are UXO or munitions fragments which are exposed on the seafloor, as they are a hazardous attractive nuisance for divers, and can easily be caught up by fishing activities.

When necessary, such munitions can be neutralized by trained explosive ordnance demolition (EOD) divers, who use a variety of techniques, including destruction in place, to render the UXO harmless. This interaction is particularly hazardous as any remediation must be performed underwater where the divers' manual dexterity and situational awareness are hindered by diving gear and the vicissitudes of the aquatic environment.

The task of interaction with UXO, whether for retrieval, rendering safe, or for destruction in place, could be accomplished using robotic manipulators. Such manipulators are a mainstay of intervention in the deep ocean, whether to support the energy and telecommunications industries, or for scientific exploration. However, despite the critical importance of manipulation for a broad range of subsea tasks, delicate underwater manipulation remains a challenge. While it is technically possible to utilize an off-the-shelf subsea manipulator for the handling of UXO, the tools for remotely controlling the manipulator are not of sufficient fidelity to enable the delicate operations required for safe UXO manipulation.

Objective

This project supported the development of experimental procedures and algorithmic advances to allow robotic remediation of marine unexploded ordnance. Dexterous robotic manipulators are a common feature in many remotely-operated vehicles (ROVs), unmanned robotic platforms which are used extensively for deep ocean inspection and maintenance in the oil and gas and telecommunications industries, as well as for a diversity of military and scientific purposes. Large ROVs, and particularly ROVs with manipulators suitable for handling the range of typical UXO sizes, are typically not used in the shallow waters where UXO remediation is of greatest concern. Within this program we examine the suitability of robotic manipulators such as those found on large ROVs for handling UXO, and demonstrate tools developed for deep ocean manipulation which allow more precise, more accurate handling of shallow water UXO.

Technical Approach

This program consists of three elements. The first is development of a test apparatus to allow evaluation and testing of UXO manipulation strategies using an off the shelf subsea manipulator. This testing platform allows controlled, repeatable manipulation tasks in a test tank environment. The second research element was undertaken under contract by Olis Robotics, who demonstrated control of the subsea manipulator and developed algorithms for precise control of the manipulator while interacting with UXO-like test objects. Third, the program supported a MS student within the UW School of Electrical and Computer Engineering to develop an interface between the Olis manipulation planning

environment and a commercial virtual reality (VR) headset allowing the visualization and planning of ROV manipulation tasks in VR.

Results and Discussion

The full grasp system was demonstrated in October 2018 in the University of Washington School of Oceanography test tank. A simulated UXO was placed in the testbed environment, where a 3D reconstruction of the UXO and seabed was generated using a 2G Robotic ULS-200 laser scanner. The resulting point cloud was converted to a mesh, including colorization using concurrent camera imagery. This mesh was imported into the Olis Master Controller environment, where a fully virtualized model of the testbed, arm, and UXO could be used to pre-plan retrieval of the object (Figure A). This planning environment allows careful, considered joint-level design of a complex manipulation motion, rather than the realtime control offered by conventional joystick-based manipulator control systems.

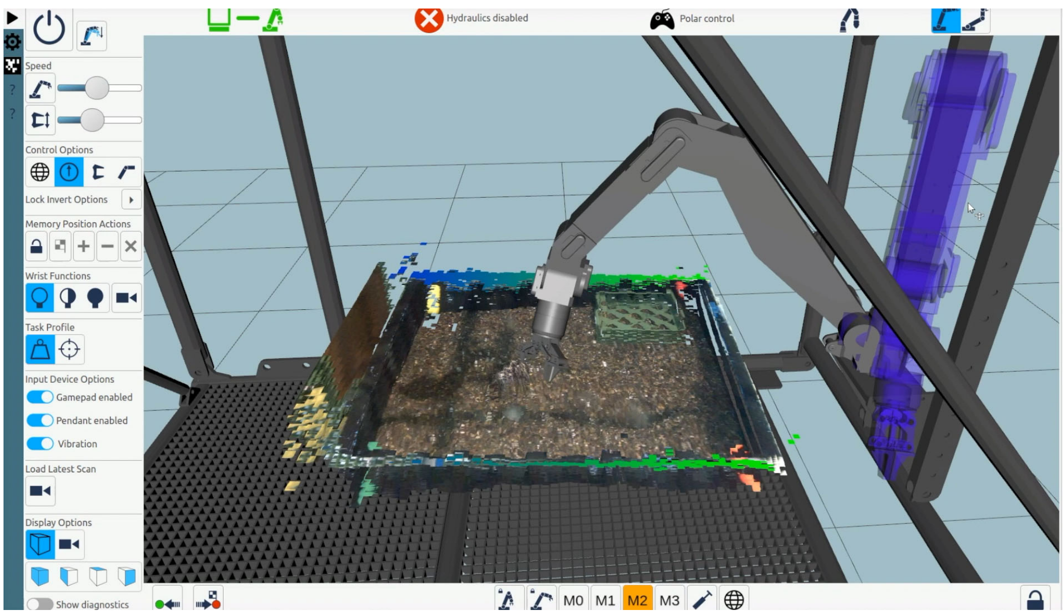

Figure A. Olis manipulator control environment during grasp planning. A 3D reconstruction of the workspace, including the test UXO stand-in, has been placed in the Olis environment (at center). The operator then uses grasp planning tools to describe a desired arm trajectory (grey arm at center) which complies with the constraints of the real arm. The actual position of the physical arm remains at its neutral resting position (in blue at right) during motion planning.

Once satisfied with the planned manipulation, the operator is able to execute the action through the Olis software. In this test, the grasp is not fully autonomous. Instead, the operator provides a simple explicit forward command which progresses the manipulator through the planned operation. The operator can stop or reverse the motion at any point, allowing for dynamic re-planning as required.

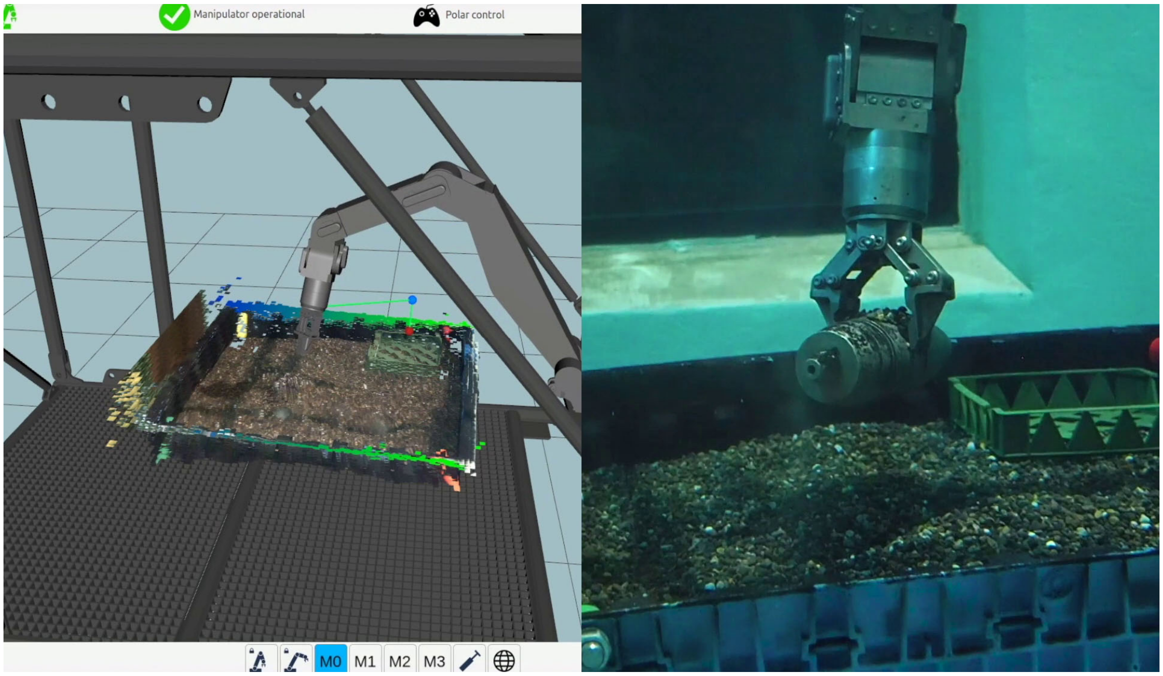

Figure B. Once satisfied with the planned manipulation, the operator can command execution of the planned grasp. In this case the system does not perform fully autonomously, rather than operator remains in the loop, providing a simple "forward" motion command which drives the arm along a complex multi-jointed trajectory. The operator can halt or reverse motion at any point to allow deviation or re-planning of the manipulation.

In this way, retrieval and handling of the UXO was demonstrated at a variety of burial depths and attitudes relative to the sensors and manipulator.

Implications for Future Research and Benefits

This project developed elements required for the advancement of tele-operation for UXO remediation. The developed test facility allows the testing, and demonstration of novel grasping and control strategies. Further, the visualization and manipulation planning elements developed by Olis Robotics provide a foundation for both continued work on automation of remote manipulation and for further manipulation and grasping research at UW-APL.

The system as designed did not address serious questions regarding the suitability of the proposed technical solution for in-the-field UXO remediation. In particular, little consideration was given to the practical collection of the perceptual inputs required to visualize the scene and plan any subsequent actions. The tests shown here use the 2G Robotics ULS-200 underwater laser scanner, which produces data of high accuracy and density, however its slow scan speed and high sensitivity to occlusions in the water, including turbidity, make it of limited use either in dynamic environments (e.g. if the manipulator is mounted on a moving platform like an ROV, rather than on a static platform) and in the shallow waters which motivate the experiment. The former could be ameliorated somewhat through careful design of a concept of operations, for example designing a system which must be firmly seated on the seafloor adjacent to the UXO before starting operations; the latter, however, is a serious impediment to operation in any shallow water scenario.

Ultimately, the prospect of remotely-operated, machine-assisted, or fully autonomous handling of submerged UXO remains a highly desirable outcome, as it would greatly reduce the risks of UXO remediation. While any robotic system is unlikely to be disposable in any sense, the use of robotic analogues may moderate the precaution, and therefore reduce the time and cost, associated with each individual UXO handling event. At the same time, such a robotic system could potentially offer more precise handling than a human diver. However, further research into manipulation strategies must fully account for the actual needs of the UXO remediation community and be based on a realistic understanding of the environmental conditions and appropriate concepts of operations.

Introduction

This project supported the development of experimental procedures and algorithmic advances to allow robotic remediation of marine unexploded ordnance (UXO). Dexterous robotic manipulators are a common feature in many remotely-operated vehicles (ROVs), unmanned robotic platforms which are used extensively for deep ocean inspection and maintenance in the oil and gas and telecommunications industries, as well as for a diversity of military and scientific purposes (Figure 1). Within this program we examine the suitability of robotic manipulators, such as those found on large ROVs, for remotely handling UXO in shallow waters.

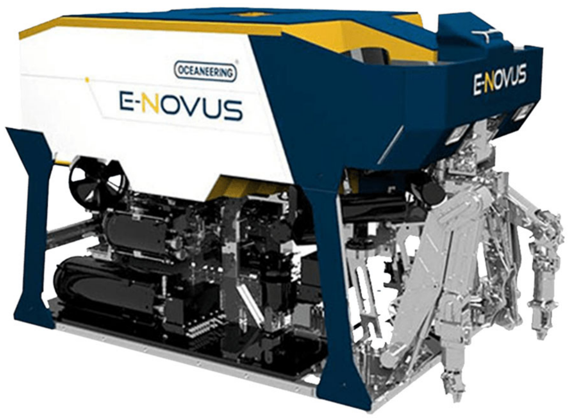

Figure 1. The Oceaneering eNovus ROV is typical of "work class" platforms used in the oil and gas industries. It weighs 3400kg in air and features two hydraulic manipulators. The manipulator used in this project is equivalent to the arm shown in the foreground in this image.

Large ROVs, and particularly ROVs with manipulators suitable for handling the range of UXO sizes, are not typically used in the shallow waters where UXO remediation is of greatest concern. Indeed, the final application of this technology may not be a free-flying ROV at all, but may utilize a fixed platform containing manipulators and sensors which is lowered from a surface ship on a rigid or semi-rigid gantry to sit on the seafloor near the UXO. In very shallow water this significantly reduces the complexity of the subsea element, as all of the positioning and control can be handled by the surface ship.

This project report was written *in absentia* for the original principal investigator who departed UW-APL in June of 2019. The contents of this report are based on interim progress reports and the current PI's limited insight into elements of the described program.

Background

Unexploded Ordnance (UXO) are a significant environmental hazard in marine areas, a legacy of accidents, ill-considered disposal and handling, as well as the explicit use of many maritime areas as target and practice ranges. UXO become a public hazard to boaters, fisherman and divers both through explicit re-introduction of former DoD areas to public use, and through transport due to sediment movement and currents. Of particular concern are UXO or munitions fragments which are exposed on the seafloor, as they are a hazardous attractive nuisance for divers, and can easily be caught in a trawl.

When necessary, such munitions can be neutralized by trained explosive ordnance demolition (EOD) divers, who use a variety of techniques, including destruction in place, to render the UXO harmless. This interaction is particularly hazardous as any remediation must be performed underwater where both manual dexterity and situational awareness are hindered by diving gear and the vicissitudes of the aquatic environment. Interaction with UXO, whether for retrieval, rendering safe, or for destruction in place, could instead be accomplished using remotely-operated robotic manipulators. Such manipulators are a mainstay of intervention in the deep ocean, whether to support the energy and telecommunications industries, or for scientific exploration.

Due to the crushing pressures, human beings are only able to visit the deep ocean in specialized submersibles. Rather than bear the risk and expense of maintaining human safety in such a hazardous environment, early oil and gas industry pioneers developed remotely-operated vehicles (ROVs), robotic platforms which contain thrusters, cameras, sensors, and manipulator arms, which are remotely controlled and powered over an umbilical from a surface ship (Christ 2013). Operators on the ship are able to observe the ocean with the ROV's sensors, maneuver within the extent of the tether, and interact with the natural environment and manmade infrastructure using the ROV's manipulators. Over the decades, ROV technology has become increasingly sophisticated but the fundamental model of teleoperation has remained constant. In particular, the success of ROV operations, including intervention, falls almost exclusively on the human operators. ROV pilots must develop a skill for intuiting situational awareness from the limited sensor inputs available on the vehicle, and must translate complex mission goals into low-level thruster and arm commands. Without a proprioceptive sense of the vehicle's motion, pilots operate extremely conservatively, relying on skill and experience to derive a rich understanding of the ROV's actions from very limited sensory inputs.

The ever-advancing maturity of ROV-derived technologies has made modern subsea manipulators increasingly capable. However, despite the critical importance of manipulation for a broad range of subsea tasks, delicate manipulation remains a challenge. As such, while it is technically possible to utilize an off-the-shelf subsea manipulator for the handling of UXO, the tools for remotely controlling the manipulator are not of sufficient fidelity to allow the delicate operations required for safe UXO manipulation.

This program consists of three elements. The first is development of a test apparatus to allow evaluation and testing of UXO manipulation strategies using an off the shelf subsea manipulator. This testing platform allows controlled, repeatable manipulation tasks in a test tank environment. The second research element was undertaken under contract by Olis Robotics (formerly Bluhaptics), who demonstrated control of the subsea manipulator and developed algorithms for precise control of the manipulator while interacting with UXO-like test objects. Third, the program supported a MS student within the UW School of Electrical and Computer Engineering to develop an interface between the Olis manipulation planning environment and commercial virtual reality (VR) equipment allowing the visualization and planning of ROV manipulation tasks in VR.

Materials and Methods

The primary physical artifact from this project was a portable test frame at 6’ W x 7’ H x 10’ L which allowed mounting various sensors, manipulators and workspaces. This frame is sized to facilitate testing in the University of Washington School of Oceanography test tank (Figure 2), and is also compatible with two research vessels operated by UW APL, providing a path to open water testing. The UW test tank is 10’ W x 24’ L and 13’ deep and is kept at a salinity comparable to local seawater, providing a convenient location for in-water testing. Development of the test frame allows all test systems to be mounted and tested in air in advance of placement in the water. It also allows systems to be tested near the water surface while suspended from the tank hoist (as in Figure 3), rather than being lowered to the tank floor.

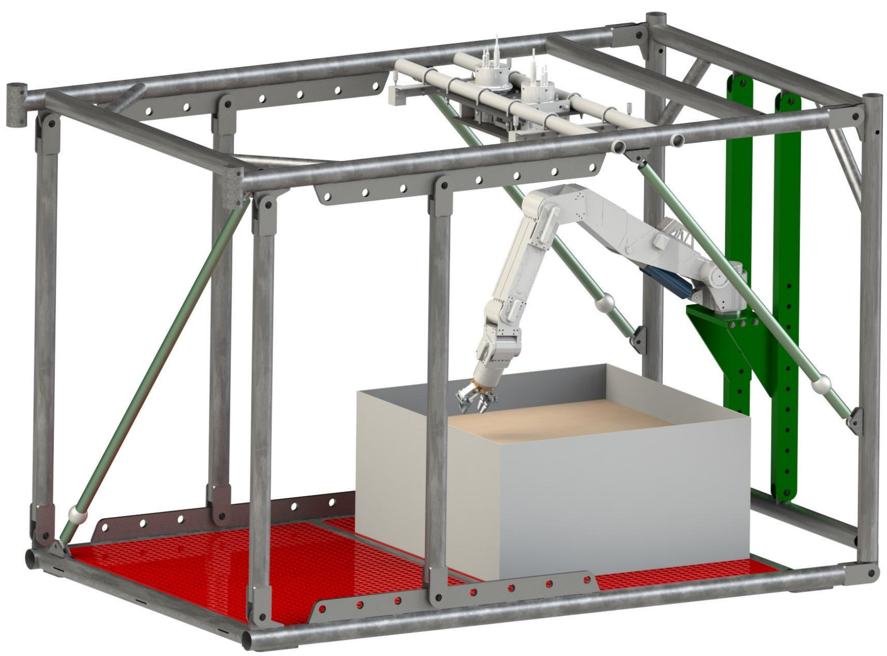

Figure 2. Rendering of test frame showing Schilling arm in position with workspace.

Figure 3. Test frame suspended in University of Washington School of Oceanography test tank. Hydraulic pressure unit (HPU) for operating the Schilling arm is just visible to left.

For UXO testing, this frame was equipped with a Schilling Titan IV manipulator (seen in Figure 2). The Titan IV is an advanced deep-ocean manipulator with seven degrees of freedom (two degrees at the "shoulder," one at the "elbow," one at the "wrist," plus gripper rotation and open/close). It has a reach of 1.9m reach and is capable of lifting 122kg at full extension.

Like many subsea manipulators, the Schilling Titan IV is fully hydraulic in actuation, with an electrical control interface to a hydraulic manifold located within the arm itself. In a typical installation, this hydraulic power is provided either by a hydraulic power unit (HPU) on the ship, and sent to the subsea via the tether (many ROVs utilize hydraulic thrusters as well), or via a specialized subsea HPU embedded within the ROV itself. To accommodate this manipulator for this testing, an independent HPU was constructed which allowed the arm to be engaged while in the test tank.

Control and joint position feedback from the arm are provided via the proprietary Schilling serial protocol. As part of their participation in the project, Olis Robotics developed software modules for interfacing with and controlling the Schilling arm.

For this program, a stand-in seafloor workspace was constructed for the test frame (Figure 4). This consists of a 54" x 54" bulk container containing washed gravel. A false bottom is employed in the container to reduce the total mass of gravel while keeping the top of the gravel near the top of the container, with a total gravel depth of approximately 6 inches. Gravel is used as a seafloor simulacrum as finer particles would be difficult to contain and would inevitably pollute the test tank. As designed, the manipulator is able to reach approximately 80% of the workspace.

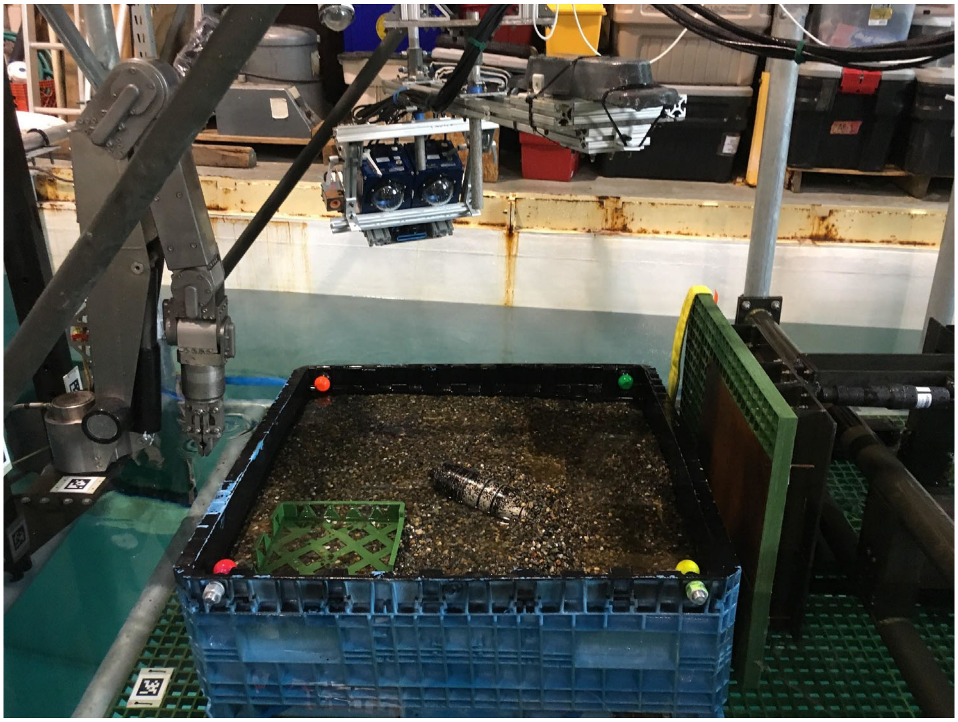

Figure 4. Seafloor workspace installed in test frame, with stand-in UXO at center. Schilling Titan IV arm to left. At center is a sensor package developed under SERDP MR18-1440; these sensors were tested in parallel with the manipulator but were not integral to the program described here. The primary sensors for this program were a subsea laser line scanner and color stereo cameras mounted vertically over the test area.

The ability to capture the workspace in 3D is critical for successful representation of the UXO in the Olis manipulation planning software. Two sensor systems were utilized in this program, a ULS-200 laser scanner from 2G Robotics, and a set of HD color cameras, with the ULS-200 acting as the primary 3D structure sensor. The ULS-200 is a laser line disparity sensor, consisting of a visible blue-green line laser on an offset lever arm from a camera system. This offset creates a parallax where the horizontal position of the laser line in the camera image is proportional to the distance from the sensor to the object struck by the laser. As the laser projects a line, the camera is able to sample a number of points along that line with each image capture, limited only by the vertical resolution of the video sensor. However, to capture a full 3D image of the workspace, the sensor must be mechanically panned across the scene. As the sensor scans across the scene, the horizontal resolution of the point cloud is determined by the update rate of the sensor and the scan speed. In this case, for maximum point cloud quality, the sensor is scanned at 2 deg/second, requiring 45 seconds for a full 90 deg. scan. In this project the scanner was programmed to continuously raster across the scene, producing an updated point cloud with each full scan. While the ULS-200 produces an accurate, high resolution point cloud representing the 3D scene structure, the time for capture is far too long for the capture of a dynamic scene -- operationally it would require a long static scanning period before handling a UXO and after any change in scene geometry.

Multiple HD video cameras were also included on the frame. These cameras were used primarily for human observation of the workspace and to add color to the laser-derived point cloud. While optical sensors can be used to estimate 3D scene geometry, the development of this technology was not part of this program.

Olis Robotics

A critical element in the program development was the involvement of Olis Robotics (operating at the time as Bluhaptics), a developer of tele-operation and autonomy solutions for remote manipulation. The Olis manipulation and control software provides an environment for visualizing, planning, and executing complex manipulation tasks. Olis developed the necessary modules to interface with the Schilling manipulator's electrical control system, developed models for representing the arm in their simulation environment, and control strategies for producing smooth paths with the manipulator.

A key element of the Olis system is a virtual workspace which allows visualization of collected sensor data along with virtual representation of the manipulator. This allows the development and practice of arm motion plans before execution. Olis further supports additional higher-level functionalities within the workspace, for example, machine learning to automatically identify targets in sensor data, and motion compensation algorithms; however, these functionalities were not used within this project.

Virtual Reality for Subsea Teleoperation

Throughout the program, a MS student at the University of Washington College of Electrical and Computer Engineering performed an evaluation of the effectiveness of virtual reality (VR) as a means for visualizing situational awareness and planning grasping maneuvers.

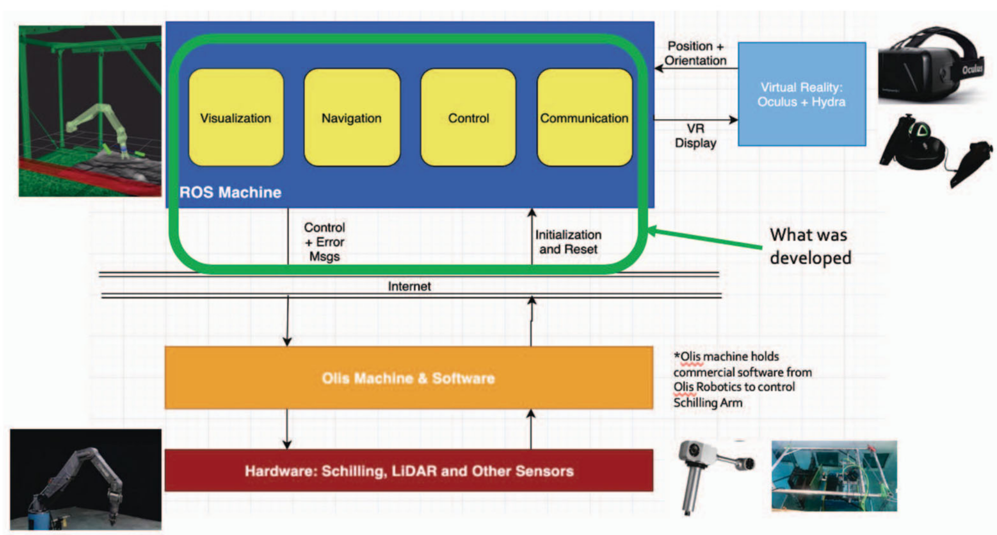

Figure 5. Block diagram of elements in Virtual Reality (VR) environment for visualizing and planning manipulation tasks.

As per Figure 5, the primary development was a visualization engine based on the Robotic Operating System (*ROS*) and its *RViz* visualization engine which communicated with the robotic control system provided by Olis. The student was able to demonstrate visualization of the UXO in the scene as well as the robotic arm in a VR environment. Manipulation goals could be introduced and controlled using the VR hand controllers (Figure 6) (Gharaybehm, 2019)

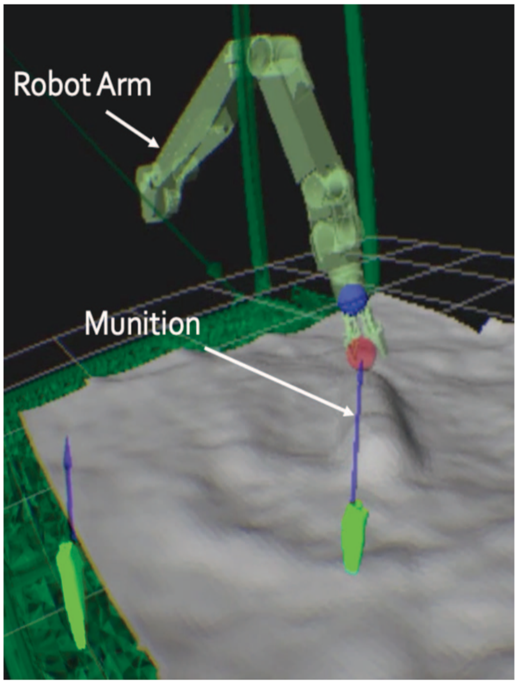

Figure 6. Screen capture from VR visualization environment showing use of VR hand controllers (bright green polygons) to manipulate the position of the robotic arm while planning grasp maneuvers.

Results and Discussion

The described test frame was installed in the University of Washington School of Oceanography test tank in October 2018. This test period included preliminary integration testing of the arm, laser scanner and cameras, as well as demonstration of the UXO manipulation routines developed by Olis.

Each successful grasp required three stages:

1. First, the ULS-200 laser scanner was used to acquire a point cloud of the UXO within the workspace. The resulting point cloud was subsequently smoothed and converted to a triangular mesh (Figure 7). The known alignment between the ULS-200 and the cameras on the test frame allows reprojection of pixel colors from the camera image onto the mesh.

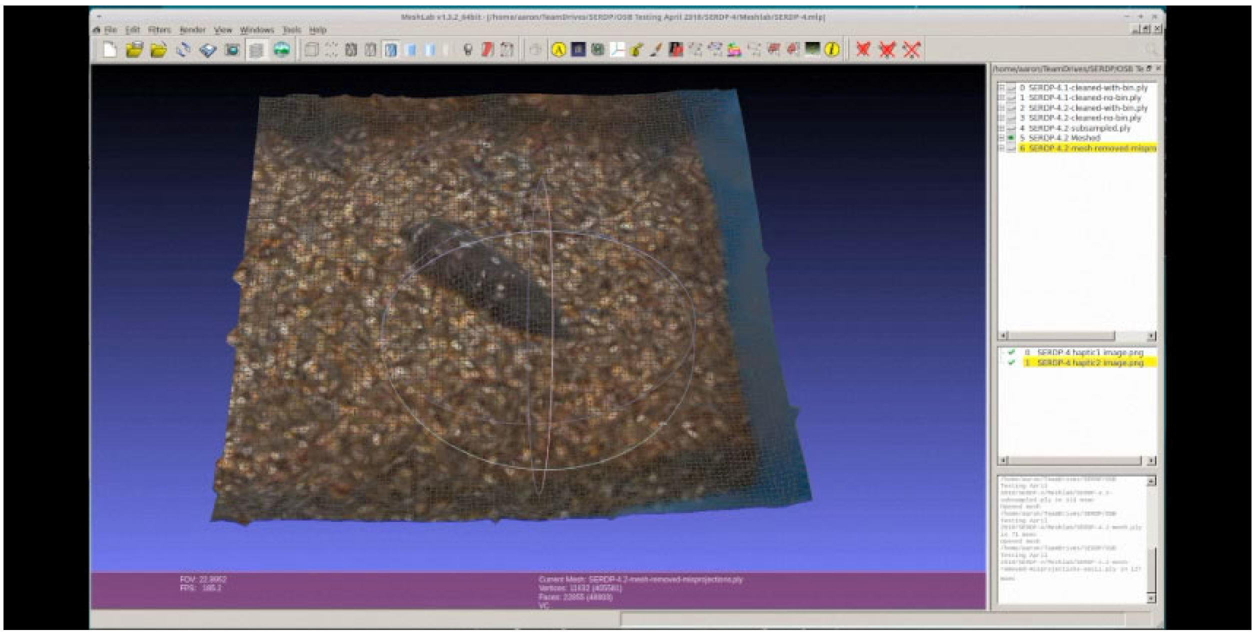

Figure 7. Visualization of the UXO in the testbed. The rendering shows a 3D surface generated from the pointcloud collected by the ULS-200 laser scanner. HD video imagery is overlaid on the mesh to provide color.

2. The mesh was then imported into the Olis Master Controller software. The known location of the ULS-200 within the test frame allows the mesh to be referenced within the virtual representation of the workspace presented by the OMC (figure 8). This simulated environment allows planning and evaluation of potential grasp strategies before actual grasp execution. As shown in Figure 8, an appropriate grasp configuration is planned using the virtual model of the arm -- the purple "ghost" arm in the image is the current position of the real arm based on feedback from position encoders within the arm.

   Once an arm trajectory proposal is generated in the OMC software, it can be simulated and refined within the OMC software.

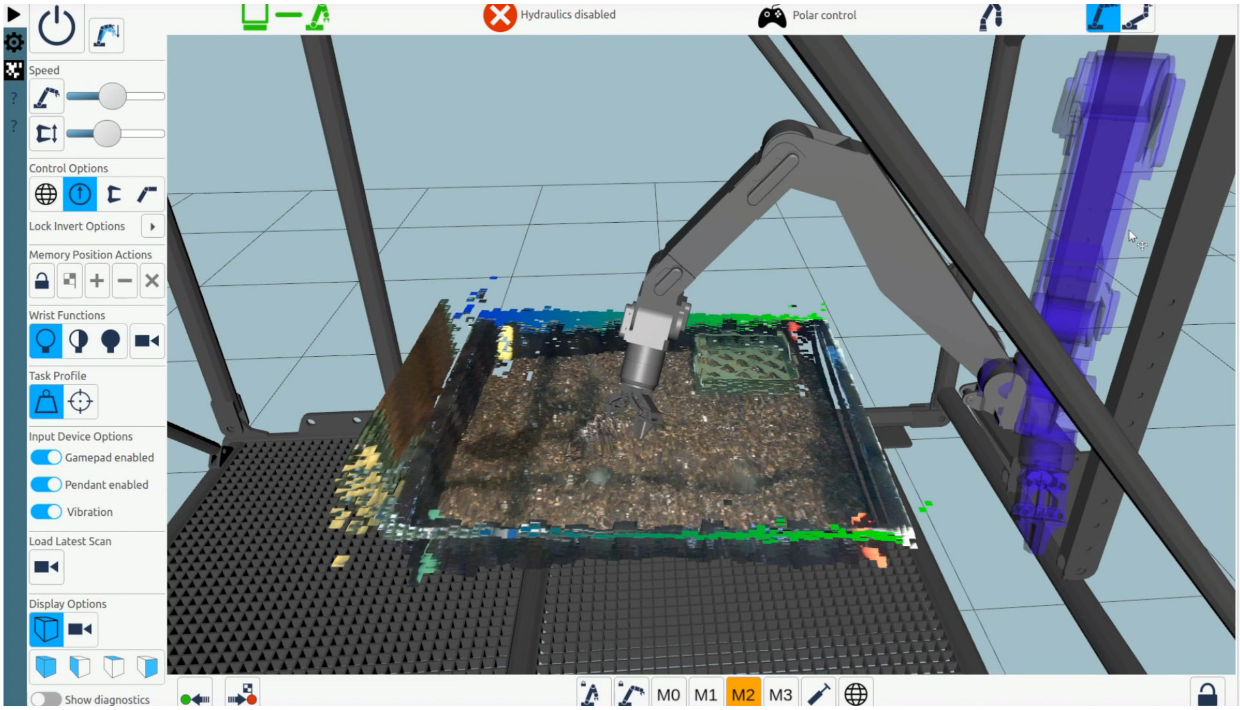

Figure 8. Olis manipulator control environment during grasp planning. The UXO rendering (analogous to Figure 7) has been placed in the Olis environment (at center). The operator then uses grasp planning tools to describe a desired arm trajectory using a simulated stand-in (grey arm at center) which fully describes the motions and constraints of the real arm. The actual position of the physical arm remains at its neutral resting position (in blue at right).

3. Finally, once the trajectory proposal is acceptable, the OMC will command the arm to execute the trajectory (figures 9a and 9b). In this case, the arm does not execute the trajectory in a fully autonomous mode, instead relying on the operator to provide explicit intent, using forward/back commands to guide the arm along the programmed trajectory. At any point during the manipulation, the operator can also break from the programmed trajectory and return to full control of the arm.

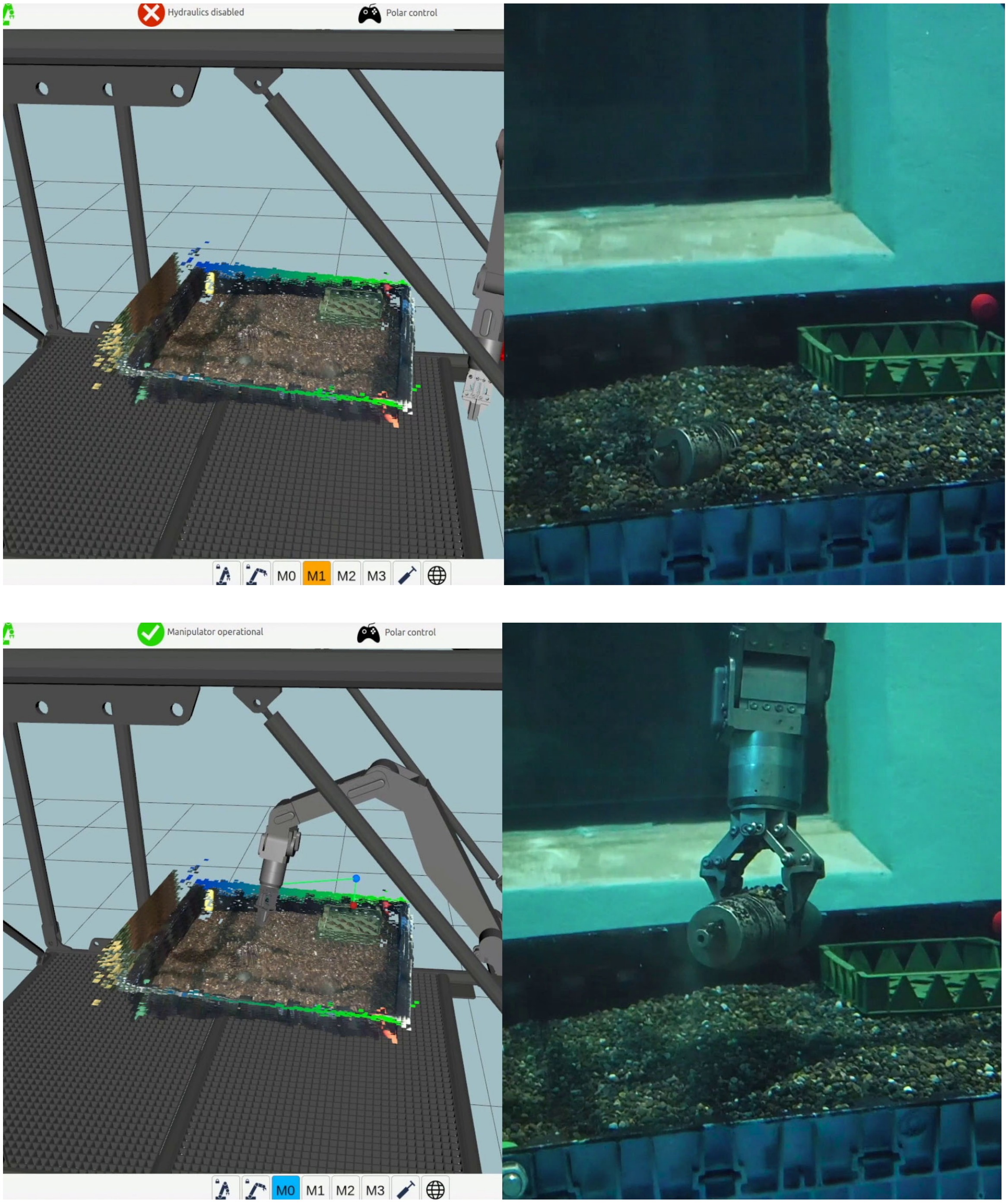

Figure 9a and b. Two scenes from the execution of the grasp. At top, the arm starts at its neutral position. The operator is able to move it forward (and backwards) along the planned trajectory, allowing the arm to perform the grasping maneuver (at bottom) without explicit real-time control from the operator. As the situation evolves, however, the operator is able to adjust and update the planned trajectory as needed.

This procedure was used to execute multiple grasps of the UXO at various levels of burial and orientations relative to the sensors and to the home position of the manipulator.

Conclusions and Implications for Future Research/Implementation

This program developed elements required for the advancement of tele-operation for UXO remediation. The developed test facility allows the testing of novel grasping and control strategies using a true subsea manipulator. However, the system as designed did not address serious questions regarding the suitability of the proposed technical solution for in-the-field UXO remediation. No effective metrics were defined for assessing the appropriateness of the selected manipulator for the real needs of in-the-field UXO remediation, nor for quantifying the performance of the manipulation system or benefits of the proposed autonomy solution.

Further, little consideration was given to the effective collection of the perceptual inputs required to visualize the scene and plan any subsequent actions. The tests shown here use the 2G Robotics ULS-200 laser scanner, which produces data of high accuracy and resolution, however its slow scan speed and high sensitivity to occlusions in the water, including turbidity, make it of limited use either in dynamic environments (e.g. if the manipulator is mounted on a moving platform like an ROV, rather than on a static platform) and in the shallow waters which motivate the experiment. The former could be ameliorated somewhat through careful design of a concept of operations, for example designing a system which must be firmly seated on the seafloor adjacent to the UXO before starting operations; the latter, however, is a serious impediment to operation in any shallow water scenario where manipulation of the object is likely to stir up obscuring silt.

Ultimately, the prospect of remotely-operated manipulation for the handling of submerged UXO remains a highly desirable outcome, as it would greatly reduce the risks of UXO handling. While any robotic system is unlikely to be disposable in any sense, the use of robotic analogues may moderate the precaution, and therefore reduce the time and cost, associated with each individual UXO handling event. However, further research into manipulation strategies must fully account for the actual needs of the UXO remediation community and be based on a realistic understanding of the environmental conditions and appropriate concepts of operations.

Literature Cited

Z. Gharaybeh, H. Chizeck and A. Stewart, "Telerobotic Control in Virtual Reality," *OCEANS 2019 MTS/IEEE SEATTLE*, Seattle, WA, USA, 2019, pp. 1-8, doi: 10.23919/OCEANS40490.2019.8962616.

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F. Rydén, A. Stewart and H. J. Chizeck, "Advanced telerobotic underwater manipulation using virtual fixtures and haptic rendering," 2013 OCEANS - San Diego, San Diego, CA, 2013, pp. 1-8, doi: 10.23919/OCEANS.2013.6741212.

Appendix A. List of Scientific/Technical Publications

Z. Gharaybeh, H. Chizeck and A. Stewart, "Telerobotic Control in Virtual Reality," *OCEANS 2019 MTS/IEEE SEATTLE*, Seattle, WA, USA, 2019, pp. 1-8, doi: 10.23919/OCEANS40490.2019.8962616.