FINAL REPORT
Haptically-Enabled Co-Robotics for Remediation of Military Munitions Underwater

SERDP Project MR-2323

AUGUST 2014

Howard Chizeck
University of Washington

Distribution Statement A
This document has been cleared for public release
**REPORT DOCUMENTATION PAGE**

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

<table>
<thead>
<tr>
<th>1. REPORT DATE (DD-MM-YYYY)</th>
<th>SEED Final Report</th>
<th>3. DATES COVERED (From - To)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-07-2014</td>
<td></td>
<td>10/15/2012-8/23/2014</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2. REPORT TYPE</th>
<th>4. TITLE AND SUBTITLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEED Final Report</td>
<td>Haptically-Enabled Co-Robotics for Remediation of Military Munitions Underwater</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5a. CONTRACT NUMBER</th>
<th>5b. GRANT NUMBER</th>
<th>5c. PROGRAM ELEMENT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>13 MRSEED01-006 / MR-2323</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>6. AUTHOR(S)</th>
<th>5d. PROJECT NUMBER</th>
<th>5e. TASK NUMBER</th>
<th>5f. WORK UNIT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chizeck, Howard J.</td>
<td>MR-2323</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</th>
<th>8. PERFORMING ORGANIZATION REPORT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>University of Washington</td>
<td></td>
</tr>
<tr>
<td>Office of Sponsored Programs</td>
<td></td>
</tr>
<tr>
<td>4333 Brooklyn Ave NE</td>
<td></td>
</tr>
<tr>
<td>Seattle, WA 98195</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)</th>
<th>10. SPONSOR/MONITOR'S ACRONYM(S)</th>
<th>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategic Environmental Research and Development Program</td>
<td>SERDP</td>
<td></td>
</tr>
<tr>
<td>4800 Mark Center Drive, Suite 17D08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alexandria, VA 22350-3605</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**12. DISTRIBUTION / AVAILABILITY STATEMENT**

Approved for public release; distribution is unlimited

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**

There is need for technology that can extend the reach and enhance the safety of teams that are tasked with finding, characterizing, and remediating unexploded ordnance underwater. The objective of this project is to develop co-robotic (human operator in partnership with a robot) removal of underwater unexploded ordnance. We propose to remove such ordnance from marine environments by leveraging human perceptive capability, and maximizing the benefit and performance of the human operator. This is done through the use of robotic manipulators, real-time non-contact sensors (optical and/or sonar), automatic control methods and haptic rendering to provide the operator with sense of touch feedback. Our approach involves use of underwater sensors, which are used to generate real-time data that can be processed by haptic rendering algorithms. Combined with a tele-operated robotic device, this allows human directed robotic removal of ordnance from lake, river or sea bottoms. We are pleased to report that all of the proof-of-concept objectives were successfully met in the SEED project. This technology has great potential to impact the cost and effectiveness of unexploded ordnance remediation operations.

**15. SUBJECT TERMS**

Munitions remediation, underwater, haptic rendering, virtual fixtures, telerobotics, teleoperation

**16. SECURITY CLASSIFICATION OF:**

<table>
<thead>
<tr>
<th>a. REPORT</th>
<th>b. ABSTRACT</th>
<th>c. THIS PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**17. LIMITATION OF ABSTRACT**

**18. NUMBER OF PAGES**

**19a. NAME OF RESPONSIBLE PERSON**

**19b. TELEPHONE NUMBER** (include area code)

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18
Table of Contents

0. Abstract 1
1. Objective 3
2. Background 5
3. Material and Methods 8
  3.1 Overall Design 8
  3.2 Robot Arm 8
  3.3 Sensor Systems 9
  3.3.1 Optical Depth Sensors 10
    3.3.1.1 Structured Light Depth Camera Tests 10
    3.3.1.2 Time-Of-Flight Optical Depth Camera Tests 14
    3.3.1.3 Optical Depth Camera Conclusions 18
  3.3.2 Real time Sonar 3D Imaging 19
  3.4 Haptic Rendering and Virtual Fixture Algorithms 23
  3.5 Testbeds for Evaluation 27
4. Results and Discussion 28
5. Conclusions and Implications for Future Research 32
6. Preliminary Design for Follow-On System 32
7. Literature Cited 34

Appendices

A.1. Publications, Presentations and Patents from Project 39
A.2. Videos Demonstrating Project Work and Related Activities 40
List of Tables

Table 1: Specifications of ARM 5E MINI Electric mini manipulator arm by ECA Robotics  8
Table 2: Measurements along straight lines of Figure 6  16

List of Figures

Figure 1: ARM 5E MINI Electric mini manipulator arm by ECA Robotics  8
Figure 2: Test tank at the UW/Applied Physics Laboratory  11
Figure 3: Combined spectrum of the 3 light sources  12
Figure 4: Comparison of broadband light transmission  12
Figure 5: Method for measuring viewing horizontal viewing angle  13
Figure 6: Point clouds for (a) air and (b) water  15
Figure 7: Depth data at the corners of the square target  16
Figure 8: View from above though air and through water  17
Figure 9: Working distance for various tested objects as a function of wavelengths  18
Figure 10: R/V Henderson and University Bridge  20
Figure 11: BluHaptics sonar viewing software in action  20
Figure 12: View of University Bridge foundation pylons and lake bottom  21
Figure 13: Second, rotated view of University Bridge pylons and lake bottom  21
Figure 14: Comparison of raw and processed point cloud images  22
Figure 15: Underwater real-time 3D sonar image, including the ECA arm  23
Figure 16: Visualization tool screen shot  27
Figure 17: ‘In air’ manipulation/haptics system test bed  28
### List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>2 dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>3 dimensional</td>
</tr>
<tr>
<td>2-DOF</td>
<td>2 degrees of freedom</td>
</tr>
<tr>
<td>3-DOF</td>
<td>3 degrees of freedom</td>
</tr>
<tr>
<td>6-DOF</td>
<td>6 degrees of freedom</td>
</tr>
<tr>
<td>AUVs</td>
<td>autonomous underwater vehicle</td>
</tr>
<tr>
<td>BFO</td>
<td>beat-frequency oscillation</td>
</tr>
<tr>
<td>BRAC</td>
<td>Base Realignment and Closure</td>
</tr>
<tr>
<td>CCD</td>
<td>charge-coupled device</td>
</tr>
<tr>
<td>CMOS</td>
<td>complementary-symmetry metal–oxide–semiconductor</td>
</tr>
<tr>
<td>CNC</td>
<td>computer numerical control</td>
</tr>
<tr>
<td>dBm</td>
<td>power ratio in decibels of measured power referenced to one milliwatt</td>
</tr>
<tr>
<td>DMM</td>
<td>Discarded military munitions</td>
</tr>
<tr>
<td>DoD</td>
<td>Department of Defense</td>
</tr>
<tr>
<td>FUDS</td>
<td>Formerly Used Defense Sites</td>
</tr>
<tr>
<td>EMI</td>
<td>electromagnetic interference</td>
</tr>
<tr>
<td>FRVVF</td>
<td>forbidden region virtual fixture</td>
</tr>
<tr>
<td>HD</td>
<td>High Definition (camera)</td>
</tr>
<tr>
<td>HIP</td>
<td>Haptic interaction point</td>
</tr>
<tr>
<td>IR</td>
<td>infrared</td>
</tr>
<tr>
<td>LED</td>
<td>light emitting diode</td>
</tr>
<tr>
<td>LiDAR</td>
<td>Light Detection and Ranging</td>
</tr>
<tr>
<td>MPC</td>
<td>Model Predictive Control</td>
</tr>
<tr>
<td>NIR</td>
<td>near infrared</td>
</tr>
<tr>
<td>PI</td>
<td>Principal Investigator</td>
</tr>
<tr>
<td>RGB</td>
<td>red green blue (image or video)</td>
</tr>
</tbody>
</table>
RBG-D RGB + Depth (Red Blue Green color image/video plus depth for each pixel)
ROV remotely-operated underwater vehicle
SNR single-to-noise ratio
SLAM simultaneous location and mapping
SXVGA super extended graphics array
ToF Time-of-Flight (camera)
UW University of Washington
UW-APL University of Washington – Applied Physics Lab
UXO unexploded ordnance
VGA video graphics array
VLF very low frequency

Keywords
Munitions remediation, underwater, haptic rendering, virtual fixtures, telerobotics, teleoperation

Acknowledgements
We wish to acknowledge the contributions of UW Department of Engineering, the UW Applied Physics Laboratory, the UW Center for Commercialization, BluHaptics Inc., and corporate friends who provided loans of necessary equipment.
Abstract

There is need for technology that can extend the reach and enhance the safety of teams that are tasked with finding, characterizing, and remediating unexploded ordnance underwater. The objective of this project is to develop co-robotic (human operator in partnership with a robot) removal of underwater unexploded ordnance. We propose to remove such ordnance from marine environments by leveraging human perceptive capability, and maximizing the benefit and performance of the human operator. This is done through use of robotic manipulators, real-time non-contact sensors (optical and/or sonar), automatic control methods and haptic rendering to provide the operator with sense of touch feedback.

The principal proof-of-concept objective of this SEED project was to demonstrate that telerobotic control of underwater robot tools for grasping objects can be accomplished, using haptic feedback. Our metrics and criteria for success include:

1. Successfully accomplishing telerobotic-controlled grasping of munition-like objects, in underwater tests, with real-time visual (computer screen) and haptic (force) feedback provided to the operator.
2. Developing or adopting sensors that allow for real time image and haptic feedback underwater, suitable for ordnance remediation tasks.
3. Implementing algorithmic assistance to the tele-operator, through haptic forbidden region virtual fixtures, to prevent contact with specified areas of the target object (essentially “no go” zones where the operator feels the interface device “push back” to resist motion).
4. Implementing algorithmic assistance to the tele-operator, through haptic guidance virtual fixtures and “haptic tools” to assist the operator in proper gripper orientation and location.

Our approach involves use of underwater sensors, which are used to generate real-time data that can be processed by recently developed haptic rendering algorithms, so as to provide a human operator with a ‘sense of touch’ of objects seen by the sensor. Combined with a tele-operated robotic device, this allows human directed robotic removal of ordnance from lake, river or sea bottoms. Our methodology is somewhat modified from what was originally proposed, because we were able to take advantage of and leverage significant external resources to use in the project.

Our proof-of-concept system consists of the following subsystems:

- **Robot Arm.** This is used to grasp the ordnance, and either move it or secure it to a sling so that it can be lifted. The original plan was to build this robot subsystem, but through fortunate circumstances, we obtained free access to a commercially available underwater robot arm for use in this project. This robot arm is suitable for attachment to an ROV, platform, or underwater vehicle. The use of a commercial robot arm reduces the technical risk of our approach.

- **Visualization Software.** This software allows the teleoperator to see the robot arm and surrounding objects in any desired prospective (allowing for full 3D rotation of the image, as well as zooming). It uses image and depth information obtained from the sensors, as well a dynamic model of the robot arm. This subsystem was not explicitly part of the proposal, but as work progressed it became clear that this is a necessary component for successful operation.

- **Sensors (Optical and Sonar).** As proposed, we used underwater video+depth optical cameras. These were lab-tested in air, and in a water tank. Given concerns about muddy
water, we also explored the use of a sonar device. This additional task was beyond what was originally proposed. It was possible to accomplish because we obtained access to a recently developed, commercially available sonar. We wrote software to process its data and to modify its use, so as to get near real-time 3D depth information. This was tested in local waters (Portage Bay, next to the Montlake Cut between Lake Washington and Lake Union in Seattle), from a research barge provided by the UW Applied Physics Laboratory.

- **Haptic Rendering Algorithms and Software.** At the time of the SEED proposal, we had developed and published a 3-DOF version of haptic rendering. During the project, we extended this to 6 degrees of freedom, using a borrowed 6-DOF (translations plus rotations) haptic rendering device. Virtual fixture algorithms and software were developed for forbidden regions, guidance and haptic tools. All were tested using different robot platforms, and have been published in the engineering literature.

- **Testbeds for Evaluation.** Two in-lab testbeds were developed. One was an in-air system, using the robot arm, optical sensing system, and software subsystems. The second was an underwater system, where testing was done in a large water tank. In addition, for the sonar subsystem, testing was done in a local freshwater body, from a research barge.

*We are pleased to report that all of the proof-of-concept objectives were successfully met in the SEED project.* The combined system was tested in air and underwater, and it performed all desired tasks well. The operator could successfully grasp and lift objects (including an inert mortar shell), avoiding specified contact locations. In addition, we demonstrated the feasibility of sonar-based haptics.

By demonstrating the effectiveness of these tools for use underwater, and studying the feasibility of integration with a number of platform options, we have shown that this technology has great potential to impact the cost and effectiveness of unexploded ordnance remediation operations. We believe that we have completely demonstrated this SEED project proof of concept.

This work will assist the DoD in mitigation of underwater munitions in a safe and cost effective manner. The proposed approach will reduce the risk to human life, when divers are required for these tasks. In addition, this SEED project has led to the development of algorithms, software and systems for enhanced telerobotics in underwater conditions. These are applicable for a wide variety of human-operator controlled robots and ROVs for diverse military, commercial and scientific underwater activities.
1. Objective

The proof of concept that is the objective of this SEED project is to develop and demonstrate co-robotic (human operator in partnership with a robot), which is applicable to removal of underwater unexploded ordnance. Our overarching goal is to remove ordnance from marine environments by leveraging human perceptive capability, and maximizing the benefit and performance of the human operator.

Our approach involves the use of robotic manipulators, real-time non-contact underwater sensors (optical and/or sonar), which are used to generate real-time data that can be processed by recently developed haptic rendering algorithms, so as to provide the operator with a ‘sense of touch’ feedback of objects seen by the sensor. Combined with a tele-operated robotic device, this allows human directed robotic removal of ordnance from lake, river or sea bottoms.

The principal proof-of-concept objective of this SEED project was to demonstrate that telerobotic control of underwater robot tools for grasping objects can be accomplished, using haptic feedback. Our metrics and criteria for success included:

1. Successfully accomplishing telerobotic-controlled grasping of munition-like objects, in underwater tests, with real-time visual (computer screen) and haptic (force) feedback provided to the operator.
2. Developing or adopting sensors that allow for real time image and haptic feedback underwater, suitable for munition remediation tasks.
3. Implementing algorithmic assistance to the tele-operator, through haptic forbidden region virtual fixtures, to prevent contact with specified areas of the target object (essentially “no go” zones where the operator feels the interface device “push back” to resist motion).
4. Implementing algorithmic assistance to the tele-operator, through haptic guidance virtual fixtures and “haptic tools” to assist the operator in proper gripper orientation and location.

The proposed deliverables for this project were: (1) A prototype of a underwater low-light video plus depth measuring camera, operating with a pair of robotic arms with haptic feedback; (2) Test results for this system, obtained using a water tank; (3) Published or submitted conference and journal papers regarding this system; (4) A preliminary design for a follow-on system suitable for use in a marine environment; (5) A final technical report.

The subsystems and overall design of our prototype are described in Section 3.1 of this report, and test results are provided in Section 4. A list of published and submitted conference and journal papers appears in Appendix 1. A preliminary design for a follow-on system is given in Section 6. This document comprises the final technical report.

Our prototype design is somewhat modified from what was originally proposed, because we were able to take advantage of and leverage significant external resources to use in the project, and because of test results obtained during subsystem evaluation.

Our proof-of-concept prototype system consists of the following subsystems:

- **Robot Arm.** This is used to grasp the ordnance, and either move it or secure it to a sling so that it can be lifted. The original plan was to build this robot subsystem, but through fortunate circumstances, we obtained free access to a commercially available underwater robot arm (ECA ARM 5E MINI) for use in this project. This robot arm is suitable for attachment to an ROV, platform, or underwater vehicle. It is an all-electric device, and avoids a significant source of pollution as it contains no oil. The use of a commercial
robot arm reduces the technical risk of our approach. This is described in Section 3.2 of this report.

- **Sensors (Optical and Sonar).** As proposed, we constructed underwater video+depth optical cameras, similar in spirit to the Microsoft Kinect, for this purpose. They were lab tested in air, and in a water tank. Details regarding the optical sensors used in this project are provided in Section 3.3.1. Given concerns about muddy water, we also explored the use of a sonar device. This additional task was beyond what was originally proposed. It was possible to accomplish this because we obtained access to a recently developed, commercially available sonar. We wrote software to process its data and modify its use, so as to get near real-time 3D depth information. This was tested in local waters (Portage Bay, near the Montlake Cut between Lake Washington and Lake Union in Seattle), from a research barge (R/V Henderson) provided by the UW Applied Physics Laboratory. This is described in Section 3.3.2.

- **Haptic Rendering Algorithms and Software.** At the time of the SEED proposal, we had developed and published a 3-DOF version of real time haptic rendering. During the project, we extended this to 6 degrees of freedom, using a borrowed 6-DOF (translations plus rotations) haptic rendering device. Virtual fixture algorithms and software were developed, for forbidden regions, guidance and haptic tools. All were tested using different robot platforms, and have been published in the engineering literature. This is described in Section 3.4. This effort included **Visualization Software** which allows the teleoperator to see the robot arm and surrounding objects in any desired prospective (allowing for full 3D rotation of the image, as well as zooming). It uses image and depth information obtained from the sensors, as well a model of the robot arm.

- **Testbeds for Evaluation.** Two in-lab testbeds were developed. One was an in-air system, using the robot arm, optical sensing system, and software subsystems. The second was an underwater system, where testing was done in a large water tank. In addition, for the sonar subsystem, testing was done in a local freshwater body, from a research barge. This is described in Section 3.5. Our criteria for success was to demonstrate, in water, successful telerobotic manipulation of munition-like objects using the robot arm, sensors, haptic algorithms and associated computer hardware and software. This was accomplished, as described in Section 4. The resulting system:

  - Lets the operator ‘feel’ the object (through a hand control interface), based upon the camera system image and dynamic haptic rendering.
  - Lets the operator guide the robot end-effectors to the target during removal, via teleoperation.
  - Establishes virtual ‘force fields’ around the protected areas of objects (such as locations that might result in explosion of the ordnance). If the tele-operator tries to move too close to the protected zone, he/she will feel this as the hand controls “push back.”
  - Assists the operator in correctly grasping the object, through guidance virtual fixtures and haptic tools.

In addition, we

  - Demonstrated that haptic information can be derived, in real time, from available sonar sensors. This makes operation in low light situations and in muddy or cloudy water feasible.
The work of the SEED project has established the essential feasibility of our approach. The combined system was tested in air and underwater, and it performed all desired tasks. The operator could successfully grasp and lift objects (including an inactive munition), avoiding specified contact locations. The generality of the visualization and haptic algorithms was also demonstrated by applying them to a different robot and sensor system (a mobile terrestrial robot for valve manipulation task). In addition, we demonstrated sonar-based haptics, which will permit operation in cloudy or muddy water, in low-light situations.

By demonstrating the effectiveness of these tools for use underwater, and studying the feasibility of integration with a number of platform options, we have shown that this technology has great potential to impact the cost and effectiveness of unexploded ordnance remediation operations. We believe that we have fully demonstrated the SEED project proof of concept.

This SEED project has demonstrated the feasibility of technology that will assist the DoD in mitigation of underwater munitions in a safe and cost effective manner. This proposal addresses the SEED Statement of Need in that it has developed an innovative method for underwater unexploded ordnance removal and mitigation. Our approach will reduce costs and increase the speed of the cleanup of Department of Defense (DoD) munitions-contaminated terrestrial and aquatic sites (sites contaminated with unexploded ordnance (UXO), discarded military munitions (DMM) and related items). It will reduce the risk to human life, when divers are required for these tasks. In addition, this SEED project has developed algorithms, software and systems for enhanced telerobotics in underwater conditions. These are applicable for a wide variety of human-operator controlled robots and ROVs for diverse military, commercial and scientific underwater activities.

With superior perceptive capability and dexterity provided by the haptic interface and manipulator system, a human operator will be able to touch and feel munitions, and carry out operations that wouldn’t otherwise be possible. Sensitive objects may be characterized and prepared for retrieval, all without any physical contact between the ordnance and the human operator or diver.

The results of this SEED project, including information about the performance of different subsystem alternatives and their advantages and disadvantages, together greaten reduce the risk of our approach, and provide the necessary information to develop a complete proposal for a more extensive follow-on project. A preliminary design of a follow-on system is given in Section 6.

2. Background

As a result of past military training and weapons testing activities, military munitions are present at sites designated for Base Realignment and Closure (BRAC), at Formerly Used Defense Sites (FUDS) and other closed ranges, as well as on active installations. The detection and remediation of munitions on ranges, munitions burning and open detonation areas, and burial pits is one of the DoD’s most pressing environmental problems. The characterization and remediation activities conducted at DoD sites using currently available technology often yield unsatisfactory results and are extremely expensive, due mainly to the inability of current technology to detect all munitions that may be present at a site and the inability to discriminate between hazardous munitions and non-hazardous items. Field experience indicates that often in excess of 90% of objects excavated during the course of a munitions response are found to be non-hazardous items.
false alarms. As a result, most of the costs to remediate a munitions contaminated site are currently spent on excavating targets that pose no threat.

This project is focused on an innovative, cost-effective approach to underwater munitions remediation. Underwater munitions response is a challenging task requiring several stages of operation and often prompting divers to take significant risks when it is necessary to have a human assist with remediation. Our telerobotic and haptic interface technology can extend the reach of teams that are tasked with remediating ordnance. It will keep humans out of harm’s way while also increasing the productivity and efficiency of response operations. By removing the need to put divers in the water, new tools for remediation promise to improve safety and cut costs.

Prior work in the field has focused on location and characterization of unexploded underwater ordnance, and its characterization and identification. Little work has been done regarding new mitigation technologies.

In prior work by the PI, innovative algorithms have been developed to perform haptic rendering of dynamically changing objects [25], as observed by an RGB-D (video and depth) camera (such as in the Microsoft Kinect).

**Haptic interaction** is the translation of forces in a virtual environment to a physical device. This generation of forces is referred to as haptic rendering. Using point clouds to represent physical objects in a computer has gained popularity much because of inexpensive RGB-D cameras, such as the Microsoft Kinect. The point clouds representing physical objects are captured and streamed to a computer, typically at 30 Hz. Any sensor that is capable of producing point clouds can be used, including appropriate structured light devices (like the first generation Kinect), Time of Flight (ToF) cameras (like the newer Kinect for Xbox One and recent Intel cameras), Flash LiDAR or Sonar systems.

In haptic interaction with these point clouds, ‘one-way remote touch’ is achieved. The haptic interaction point (HIP) represents the location of the user’s haptic device. A proxy tracks the HIP in the virtual world without passing through certain points. The user can move the HIP to “touch” different virtual objects (experiencing a force in the direction of the proxy). For our purposes, the virtual world is, in fact, a 3D scene constructed from RGB-D camera information. ‘Two-way remote touch’ is possible using the haptic rendering method presented, if implemented on a tele-operated robot. In this project work, the tele-operator, while controlling robot actuators for remediation, will ‘feel’ objects within the field of the underwater depth camera.

**Virtual fixtures** around critical parts of a target (e.g., locations that would trigger explosion of the ordnance) can be done by operator input, or through image recognition. For operator designation of a virtual fixture, the tele-operator can specify the boundaries of a virtual fixture either using the robotic end effector, or by using mouse (or touch screen) on the video display, or it can be generated by image segmentation. For automatic recognition, an image recognition capability (not part of the proposed work) can be used to specify the ‘no touch’ zone.

The robot end effectors are tracked in real time. Using the haptic rendering algorithms we provide haptic feedback to the operator (pushing back if the end effector gets too close to a protected location). In addition to providing haptic information to the tele-operator, we can also modify robot control actions. One option is to lock out certain motions. More interesting is the combination of providing haptic information and also to modify the dynamic response of the robot, slowing down motion that is too close to the virtual fixture boundaries.
In this work we modified our existing dynamic haptic rendering algorithm to operate on the type of data (and data rates) obtained from the underwater camera. We developed virtual fixtures around the portion of structures we wish to protect (that is, not touch) during the remediation procedure. The focus here is on force-feedback virtual fixtures designed to improve the economy, speed and accuracy of user motions in the teleoperated environment. In particular, we constructed both forbidden-region and guidance virtual fixtures that are driven by haptic rendering information obtained from the cameras. These are used in two feedback control paths in this co-robotic system: by the tele-operator, and by the robot’s position control system.

Our system allows for 'remote touching' of real, moving 3D objects. Our work is based on these technologies, which were originally developed by the Principal Investigator and colleagues for purposes of robotic surgery, where careful placement of tools and remotely-controlled dexterity are critical. In this SEED project, several different depth cameras (including a sonar system) were used.

The specific technical risks to our approach, which are addressed and have been resolved in this SEED project, are:

- **The development of underwater sensors that can provide 3D information in real time** (through the generation of point clouds)
- **Verification that these sensors can work in appropriate water conditions**
- **The development of haptic rendering algorithms** that provide a ‘sense of touch’ force feedback to the operator. In particular, prior to our work, this had only been done (by our group) for data from streaming point clouds, for 3 degrees of freedom. However, 6 degrees of freedom are needed (that is, including rotations) to allow for adequate manipulation of robot end effectors interacting with objects in different orientations. This required significant extension of existing theory and practice, and was perhaps the greatest technical risk in our approach. This was successfully resolved in the SEED project work.
- **The development and implementation of virtual fixtures**, to assist the operator in telerobotic control. In addition to enhancing safety and reliability of the intended operations, these virtual fixtures reduce the level of training and expertise required of the operator.
- **Validation of the overall system**, through testing of the integrated subsystems.

The development of these haptic rendering and virtual fixture technologies for telerobotic control has great potential beyond the immediate munitions remediation application. Recognizing the potential for underwater applications, such as cable connecting, valve turning, infrastructure repair, environmental cleanup, and research instrument deployment and recovery, the University of Washington researchers involved in this SEED project, in collaboration with the UW Center for Commercialization, have formed a start-up company, *BluHaptics Inc.*, to pursue these opportunities. This company (formed in July 2013) is described in two of the videos in Appendix 2. The creation of this company was in large part motivated by the challenges successfully met in this SEED project. We anticipate that *BluHaptics* will be a partner in the follow-on project.

The haptic rendering and virtual fixture technologies developed by our group have also been applied to mobile terrestrial rescue robots. This was demonstrated as part of the recent Smart America Challenge project in Washington DC, and at the White House.
3. Materials and Methods

3.1 Overall Design

The basic idea of our approach is as follows: a sensor system (either optical or sonar) will collect image and depth information in real time. The sensors and robotic arm(s) are mounted on an ROV or submersible vehicle. The robot arm is used to either attach a sling to the munition (so that it can be lifted to a barge above), or to move it into a container that can be hosted.

To test this concept, testbed systems, combining sensors, computer and haptic algorithm software, submersible robot arm and munition-like objects, were developed in this project. This provided excellent platforms to support the development of underwater manipulation using virtual fixtures. Experiments were carried out in the laboratory test tank with the prototype haptic rendering system, allowing the teleoperator to control the manipulator. The manipulator motion is governed using a combination of feedback control and an operator-specified reference signal. The operator receives both visual (computer screen) and haptic feedback to facilitate these tasks.

3.2 Robot Arm

Originally we proposed to build a series of small robotic arms. After evaluating the cost and effort required to build custom robotic arms for this project, we began to explore the possibility of adapting an off-the-shelf manipulator. In this SEED project we have used an ECA Robotics ARM 5E MINI (Figure 1). It is a five degree-of-freedom submersible manipulator that is suitable for carrying out a number of subsea tasks. An advantage of this electrically-powered manipulator is that it is non-polluting, as it uses no oil.

![Figure 1: ARM 5E MINI Electric mini manipulator arm by ECA Robotics](image)

This arm can be skid mounted, or mounted on inspection class ROVs or small submersible vehicles. It is mounted in the same footprint as a hydraulic arm. Additional specifications are given in Table 1.
An internal request to the UW/Applied Physics Laboratory for funding was successful, which provided approximately $40K in to obtain this commercially available robot arm for use in this SEED project, at no cost to SERDP.

For this project, we restricted our efforts to a single underwater robot arm (due to cost limitations). Extension of the system two or more arms is largely a systems integration issue (not an algorithm issues), which is mission-specific. This extension does not present a technical risk.

This particular robotic manipulator arm was used in the SEED project, allowing for more flexibility than the work originally proposed. However the methods, algorithms and software developed can be applied to a wide variety of robotic manipulators and arms, of different capacities and capabilities.

All control software for this robot arm is open source, lending itself to integration with our test beds and haptic rendering algorithms. However we discovered that significant effort was required to actually make this software work. This has been accomplished.

### 3.3 Sensor Systems

We have evaluated several image and depth sensors that can provide three-dimensional image data for use in the haptic feedback of a robotic underwater ordnance recovery system. Some of these depth are RGB-D cameras that rely on the structured light principle (as used by the Microsoft Kinect) where the displacement of an object is determined by variations of the geometry of a projected pattern. Others are based on Time-of-Flight measurements. In addition, we have explored the use of scanning sonar to obtain real time 3D images.
3.3.1 Optical Depth Sensors

Version 1—Structured Light Optical Depth Cameras: There are several approaches to depth imaging, including structured light, time-of-flight (ToF), triangulation, and interferometry. Our proposed work involved development an RGB-D (video+depth) camera that provides three-dimensional image data for use in the haptic feedback of a robotic underwater ordnance recovery system. The depth camera relies on the structured light principle (as used by the Microsoft Kinect), where the displacement of an object is determined by variations of the geometry of a projected pattern.

Based on our initial tests on the structured light camera system, we concluded that this structured light approach is not robust enough for our proposed underwater RGB-D camera system. We found that the camera system required a stronger light source with a similar operating wavelength and bandwidth for longer working distance in water. However the existing light source and depth camera position are pre-calibrated to work only in that one particular separation and orientation. The (proprietary) structured light pattern is also not easily replicated and has a special diffraction pattern for internal depth camera calibration.

For us to modify this existing camera system into our planned fiberscope configuration (suitable for the underwater application), the distance between the camera and light source must be flexible and must work at an arbitrary distance. This did not appear to be practical.

Version 2-Time of Flight Optical Depth Cameras: To sidestep these limitations of structured light depth cameras, we switched to using a commercially available time of flight (ToF) depth camera. ToF cameras can make use of an efficient in-substrate current assisted photonic demodulator, NIR or other more desirable wavelength light source, and a simple lock-in principle to measure the time-of-flight of a modulated light beam between the subjects and camera for each pixel of the image.

The use of a ToF camera allows for an arbitrary placement of light source and camera. The broadband LED light source also allows us to easily expand our intensity output and can be modulated comfortably with any waveform and frequencies required. It is interesting to note that the next generation Microsoft Kinect also switched to a ToF camera.

In an effort to gather preliminary data with off-the-shelf optical sensors, we constructed an imaging platform for controlled experiments with various targets underwater, as well as a mounting scheme for sensors to be evaluated. The platform is adjustable in depth (below the water surface) and distance from the sensor. This experimental setup is shown in the Figure 2. This water tank is at the UW Applied Physics Laboratory.

In the following discussion, we present some of the data that convinced us to switch from a structured light to time-of-flight approach. We then present an evaluation of the ToF depth camera for underwater use.

3.3.1.1 Structured Light Depth Camera Tests

The two commercially available structured light depth camera systems we considered are the Microsoft Kinect (for Xbox) and the ASUS Xtion Pro. These depth camera systems are low cost and commercially available, employing a similar depth measuring technologies. The size of the ASUS is smaller, and it is easier to disassemble for testing and modification. In initial tests, we have examined:

- Operation of the unmodified camera system under water
• Effects of modifying the system architecture (e.g., distance between projector and light source)
• Optical specification of the system components.

Figure 2: Test tank at the UW/Applied Physics Laboratory. In this initial test configuration, objects in the water are supported on the platform (closeup, on right), with the camera contained in a submerged aquarium (on the left, in the leftmost photo). Later, when a water-tight container was developed for the camera, it was also submerged.

The following tests were performed:

1. Spectra of the built-in narrow band light sources (in both the ASUS and Kinect cameras) were measured.
2. The spectral transmission through water was measured. The result was then compared to the spectrum of the depth cameras, as a first test of feasibility of operation of these cameras under water.
3. Optical performance of the cameras underwater was evaluated, using the test facility shown in Figure 2. Performance parameters such as the working distance and viewing angle were measured first in air, and then in the water tank with filtered water. The parameters were measured in the two different conditions were compared, to analyze the effects of clear water on the performance of the cameras.
4. Finally, we captured depth data of various test objects and made observations regarding object different type of surfaces, as well as the effects of different filtering software.

Figure 3 shows three units operating at slightly different peak wavelengths, with about the same bandwidth (~0.300nm). The units (dBm) are the power ratio in decibels of the measured power, referenced to one milliwatt. This figure shows that the depth measuring system have a tolerance to the wavelength of the light source. This is beneficial if the light sources need to be replaced to increase the working distance of the system. Also, the system is thus be somewhat tolerant to peak wavelength drift due to environmental condition such as temperature change.
Figure 3: Combined spectrum of the 3 light sources (a) Spectrum of Kinect light source; Peak Wavelength: 826.487nm; -3dB Bandwidth: 0.302nm (826.342nm-826.644nm),(b) Spectrum of Xtion Pro Unit 1 light source; Peak Wavelength: 827.428nm; 3dB Bandwidth: 0.312nm (827.314nm-827.626nm), (c) Spectrum of Xtion Pro Unit 2 light source; Peak Wavelength: 827.346nm; 3dB Bandwidth: 0.305nm (827.115nm-827.420nm)

Figure 4 illustrates the difference of broadband light transmission in the air and through clear water. In the top plot, note that even though clear water has a larger absorption for the wavelengths beyond 700nm, there is a transmission peak at ~820nm region.

Figure 4: Comparison of broadband light transmission in air (19°C) and through a body of clear water (20°C).

Based on our measurements, we determined that the minimum working distance is ~65cm and the maximum working distance is about 79cm. The maximum working distance can be improved by increasing the power of laser source to allow the light to travel further in water before it is
completely absorbed. The minimum working distance can be shortened via strategic placement of multiple cameras and by super-imposing depth data obtained by each camera.

We also evaluated the viewing angle, using the setup shown in Figure 5. The maximum viewing angle (based on the ‘width’ of the window that can be observed by the depth sensor when an object is at the known distance away from the sensor) was found to be approximately 35° (both vertically and horizontally).

![Figure 5: Method for measuring viewing horizontal viewing angle: (top) object at one edge of effective the viewing window; (bottom) object on the other edge of the viewing window.](image)

Distortions are introduced by camera optics when under water. We characterized these distortions by placing a flat plate (a checkerboard) in front of the camera at a known distance. By placement, the depth data of the board was uniform across all pixels. With distortion, the depth value in some of the pixels deviate from the actual value. This tedious procedure allows for an intrinsic xyz coordinate calibration of the camera.

In order to improve the working distance of the camera, we modified the depth cameras to change to more powerful light sources (with approximately the same frequencies). We also explored the effects of different locations for the light source, relative to the receiver.

Not surprisingly, for the Kinect system, depth imaging was most effective when the light source was positioned near its original packaged position. The Microsoft Kinect uses a scattering pattern from a light source and grating that is received by the camera and turned into depth imaging. This process requires the camera lenses to be precisely in the same plane as the light source grating. If the planes are misaligned, the depth image will be garbled and will not present the objects captured by the color image. Additionally, our experiments confirm that the location of the light source grating affects the depth imaging.
Two higher power laser light sources were explored to increase the power output, and hence the range, of the structured light depth camera systems. These were a Thorlab 830nm laser and a JDSU 830 nm laser. Both of these laser light sources shows peak wavelengths near the structured camera operating regions. They did increase the range of operation of the cameras.

However, we are faced with the following difficulties when attempting this type of modification:

- The light source’s relative position with the camera is not tolerant to variations; changing the position causes camera performance to decrease.
- For the camera system to recognize the structured light pattern, an exact pattern to the original equipment must be generated when using the different laser. To achieve this requirement, additional optics and a significant calibration and adjustment effort is required.

From our experiments we determined that the precise positioning and orientation of the light source and camera are sufficiently critical to this structured light system, to preclude their incorporation in our proposed fiberscope (underwater camera) design. Specifically:

- Structured light systems rely on the deformation of projected patterns for depth measuring (dot size changes in this case), which is greatly affected by environmental factors;
- The processing system of commercially available structured light RGB-D cameras is a “blackbox” (for proprietary reasons), with no way to recalibrate the system to compensate for environmental factors.

Given all this, we therefore examined alternative methods to structured light cameras. Time of Flight (ToF) cameras, unlike structured light cameras, do not rely on a projected dot pattern to perform depth measurement. This eliminates the constraints that were encountered during the modification of the structured light system, which allows for more extensive optimization of the system for underwater applications.

3.3.1.2 Time-Of-Flight Optical Depth Camera Tests

We considered and tested four different ToF camera/light source designs were constructed and tested. They were:

- Stock (SoftKinetic) ToF camera inside a waterproofing housing
- Stock ToF camera with an external light source
- Beam splitter camera with external light source
- Fiberscope camera with external light source

Repeating the same experiments with ToF cameras, we found that all of ToF camera configurations offer performance that exceeds the performance of the structured light camera. The new camera system with external light provides a larger working distance (2 to 183 cm tested), similar viewing angles (H= 45.2° and V= 34.2°), and excellent resolution (X = 200µm (solid) @ 2cm, Y = 300µm (solid) @ 2cm and Z = 1 mm (solid) @ 27cm).

Image distortion due to water was evaluated by comparing the measurement of a square object taken in air and in water. The depth image of a square object is measured in air (Figure 6a) and through a body of water (Figure 6b). Color represents depth. The square object is 27cm away from the camera. Lateral distortion is evaluated by first measuring the height and width across the object’s point cloud and comparing to check if there are any variations in the values. The
corners of the square are inspected further for small lateral distortions (Figure 7) and depth measurement distortion can be observed from the top view of the point cloud (Figure 8), for each experimental condition.

**Figure 6:** Point clouds for (a) air and (b) water. Here color denotes depth (*i.e.*, target distance).

Measurements from Figure 6 are along the lines marked in the figures are summarized in Table 2. From this data, it can be concluded that there is relatively little shape distortion due to the water, but transmission through water increases the perceived size of the target, due to refraction.
Through Air (Figure 6a) | Through Water (Figure 6b)
--- | ---
**Height**
Left Edge: -50 to -87 (37 pixels) | Left Edge: -46 to -92 (46 pixels)
Middle: -50 to -87 (37 pixels) | Middle: -46 to -92 (46 pixels)
Right Edge -50 to -87 (37 pixels) | Right Edge -46 to -92 (46 pixels)
**Width**
Top Edge: 63 to 99 (36 pixels) | Top Edge: 57 to 104 (47 pixels)
Middle 63 to 99 (36 pixels) | Middle 57 to 104 (47 pixels)
Bottom Edge 63 to 99 (36 pixels) | Bottom Edge 57 to 104 (47 pixels)

| Table 2: Measurements along straight lines of Figure 6.

**Figure 7:** Depth data at the corners of the square target measured (a) through air (b) through water

Consider the corners on the target under the two different conditions, as shown in Figure 7. The rectangles are superimposed on top of each corner to compare the straightness of each corner. The corners conforms well to the shape of the reference rectangle, indicating that no significant bending is observed. Lateral shape distortion is too insignificant to be observed by the camera during our test. Next, we explored the distortion effect of water on the depth values. The depth measurement of the square object is shown in Figure 8. Through air, the measured the depth of
the square is at approximately 23cm. Through water, the depth of the square is 29cm. Overall, distortion is minimal and the effects of refraction can be mathematically corrected for.

![Image]

**Figure 8:** View from above though air (top) and through water (bottom).

In evaluating the resolution of this camera, we observed that it is highly dependent on the intensity of the light source, as well as the optical properties of the object (reflection in the operating wavelengths, color or dielectric constant of the materials and surface roughness) as well as the camera resolution. For example, consider the color-versus-working distance data summarized in Figure 9. The working range improves with wavelength of the object color closer to the depth camera operating wavelength) range. The working distance is best for highly reflective surfaces.
3.3.1.3 Optical Depth Camera Conclusions

We have developed and tested a waterproof camera housing with a viewport and water-tight cable conduit. We successfully demonstrated the ability of NIR-based depth sensors to gather depth data in our water tank facility. Both structured light and time-of-flight cameras were considered. The evaluation of the capabilities of the available low cost RGB-D cameras. We characterized the (fairly significant) limitations in the working range of optical sensors, as well as limitations related to water clarity.

We explored methods to increase the range of these cameras. One of the ways to improve the working distance of the camera system is to replace the existing NIR projector inside the camera system with higher intensity laser with same spectral specification, so that it can reach greater distances underwater.
However, even with these modifications, the fundamental limitations of optical depth cameras for underwater use remain. Our evaluation of these systems has shown that these limitations include a small working distance and low depth resolution. It appears that some of these performance issues are due to surface effects; that is, reflections from the surface interfere with the ability to collect depth data.

The optical depth cameras are satisfactory for close range portions of the overall task, but the addition of other sensor modalities (such as sonar) will likely be needed in a practical system.

### 3.3.2 Real time Sonar 3D Imaging

Because of concerns about the feasibility of optical sensors (NIR depth sensors) in muddy water conditions, we explored an alternative method of capturing real-time depth data. Sonar is an obvious choice when water is not clear, but our haptic rendering technology needs real time, 3D information.

The traditional approach to 3D underwater vision with sonar has been to generate scans using 2D sensors. Such an approach would not lend itself to the application of generating virtual fixtures (haptic rendering) for real-time manipulation underwater. The data collected with scanning sonar systems is sufficient for a static haptic interface, but the refresh rate (~30 seconds to scan) does not allow for dynamic generation of virtual fixtures or for real-time manipulation underwater.

For our application, where short-range imaging is a priority, a higher frequency sonar system is desirable. The recent advent of interferometry for point cloud generation from sonar meets our requirements. A series of sonar heads are aligned side-by-side to generate an x-y image and also measure phase between signals. The difference in phase can be processed to provide a measurement of depth, z, resulting in a three-dimensional (point cloud) image with a magnitude for each point (x,y,z) underwater. This can be done using a series of 900 kHz sonar heads.

In collaboration with a sonar manufacturer, we have tested this type of system using the facilities of the UW Applied Physics Lab. These facilities include a 57-foot utility boat and a 70-foot, self-propelled, pontoon based floating laboratory that can serve as a wet lab where large instrumentation can be deployed and tested. From the R/V Henderson (Figure 10), moored under the University Bridge in Seattle, we tested this system, combined with algorithms and software developed jointly by the University of Washington and our spinoff company, BluHaptics. This software runs on an Intel Core i7 machine, with GPU acceleration.

The processing software includes filtering and geometric analysis. Only a single frame is necessary for filtering, and no temporal averaging is required. Processing is done instantaneously and presented to the user as it is being captured. That is, no post-processing is required. Blurring/distortion are significantly reduced by combining filtering with geometric analysis. In addition, outliers can be removed on-the-fly. Visualization can be enhanced using geometric features such as surface normal vectors or surface curvature.
Figure 10: (left) R/V Henderson pontoon-based floating laboratory with moon pool to support underwater systems development, calibration, and testing; (right) University Bridge (a bascule drawbridge) in Seattle. The Henderson can be seen docked in the far left of the image, under the bridge (which is temporarily open to allow the sailboat to pass through).

Figure 11 is a screen shot of this software in action. The two rectangular objects in the image are the underwater portion of supports for the University Bridge. This bridge spans Portage bay, near the Montlake Cut between Lake Washington and Lake Union (with a center channel depth of approximately 10 m (30 feet)). Note the sharp edges of the concrete supports in the image.

Figure 11: BluHaptics sonar viewing software in action

Figures 12 and 13 provide two different rotated view of the bridge. The software allows for full rotation of the images, so that different prospective can be seen by the operator, as desired. This is done in real time, while imaging continues.
Figure 12: View of University Bridge foundation pylons (the underwater portion) and lake bottom (in Portage Bay, near the Montlake Cut between Lake Washington and Lake Union, Seattle WA). Data is taken from research barge R/V Henderson (through access port in barge bottom). Shown is BluHaptics GPU-accelerated hybrid normal vector plus intensity overlay.

Figure 13: Second, rotated view of University Bridge pylons and lake bottom.
Points are colored according to their surface normal, to make it easier to distinguish small features. In Figure 14, the effect of this processing can be seen, comparing the raw point cloud obtained from the sonar and the processed version.

![Comparison of raw and processed point cloud images. The processing makes edges of objects clearer. This is done in real time, and is suitable for slowly moving objects.](https://www.youtube.com/watch?v=57gdbYqBIes)

**Figure 14:** Comparison of raw and processed point cloud images. The processing makes edges of objects clearer. This is done in real time, and is suitable for slowly moving objects.

While the fixed images presented above are representative of the performance of this combined sonar and processing system, the merits of this sensor can be much better viewed in the video linked, below, which demonstrate various features of the system.

[https://www.youtube.com/watch?v=57gdbYqBIes](https://www.youtube.com/watch?v=57gdbYqBIes)

In Figure 15, the ECA robot is included in the underwater image. From these tests, the use of this type of 3D sonar system to generate depth images in real time for haptic rendering and telerobotic control appears to be practical.
To summarize, the optical sensors developed and tested in this work will meet the desired needs for clear water, under some lighting conditions. The sonar system meets the requirements under a much wider range of water conditions, and is not affected by ambient light. Thus our several months of no-cost extension work related to sonar has removed a potential technical risk to follow on work, and enhanced the feasibility of our approach.

3.4 Haptic Rendering and Virtual Fixture Algorithms

In telerobotic applications such as robotic surgery or bomb disposal, robots primarily serve as extensions of people. In prior NSF-funded work by the PI and colleagues, real-time algorithms were developed to improve telerobotic control through the use of non-contact sensors (such as depth cameras) to obtain information about objects in the near environment of the robot end effector, in advance of contact. This methodology was initially developed to protect delicate structures during robotic surgery.

Because haptic rendering and virtual fixture algorithms are somewhat esoteric, in this section we provide an explanation of how they work, citations to prior and related work, and a description of our work with this technology.

The non-contact sensor information is obtained in the form of a point cloud, which is updated as objects and the robot end effector move. From the point cloud information, a haptic device (essentially a computer mouse that pushes back on the user) provides the operator with anticipatory force feedback in real time, guiding the remotely operated equipment along the best path towards a target, and preventing undesired contact with specified objects or structures. This approach to force feedback overcomes a limitation of traditional contact sensors, which do not allow object avoidance until contact is made (and which introduce a time delay in the overall human-robot control loop).

In this project, this point cloud-based haptic navigation technology is applied to the control of underwater robot arms, to enable improved precision, safety and speed of operation. Our haptic
navigation technology can also result in improved performance of equipment maintenance, repair and inspection tasks as well as a reduction in costly (and polluting) errors.

While sight is a paramount and perhaps the most intuitive form of perception for the human experience, oftentimes mere visual feedback is insufficient for completing more dexterous tasks. This is readily observed in the case of telerobotic manipulation, where there is an inherent and physical disconnect between a remote robotic manipulator and the operator and operator device. One method of rectifying this problem is the addition of haptic feedback through the use of virtual fixtures; defined as any “abstract sensory information overlaid on top of reflected sensory feedback from a remote environment” [1]. For this project, virtual fixtures are used to provide additional tactile or force feedback to effectively guide a teleoperator to complete a tele-manipulated task via robotic devices. These virtual fixtures can be generalized as implementing one of two types of functional modes: forbidden region virtual fixtures or guidance fixtures. When using forbidden regions, the robot is assisted by limiting its movement into restricted areas [2]. As an example, a forbidden region virtual fixture could apply a resistive force to the user when entering a dangerous region or orientation. Guidance fixtures involve influencing the robot’s movement along a desired path. In all cases, the challenge lies in conveying the remote robot’s environment to the operator while simultaneously assisting the user with some structured teleoperation task at hand. In this case, the assistance is provided with haptic feedback and virtual fixtures, and in most cases the virtual fixtures are implemented in software.

Haptic interaction with virtual objects in a computer, so called computer haptics, is a well investigated field. Some of the important works from the 1990s include [3], [4], [5], [6] although the idea had been around since the 1960s [7]. It has been shown that haptic feedback enhances the sense of presence in a virtual environment [8] and also the sense of being together in a multi-user shared virtual environment [9], [10]. Successful applications for haptics include medical simulators [11], [12], [13], [14], [15], scientific visualizations [16], [17], and for kinesthetic- [18] and tactile [19] feedback in teleoperation. Haptic feedback is typically subdivided into tactile and kinesthetic feedback; the latter is often also called force feedback, which is the approach used in our work.

**Haptic Rendering:** Haptic display presents tactile information to a human user in order to convey the presence of some type of stimulus during a sensory-motor task. The most basic haptic display problems involve providing force feedback for human interaction with a purely virtual environment, a computer generated mathematical model of physical objects. For realistic and effective haptic rendering, it has been widely accepted that a haptic update rate of one kilohertz is required. When the haptic interface point (HIP) servos towards the user’s position with force proportional to surface-to-HIP distance, pop-through is an inexorable problem (particularly with thin or multiple objects). In this situation, the HIP moves to the inside of the object image.

The ‘virtual coupling’ method [20] is the most common theoretical framework for haptic rendering methods. Here force feedback is calculated as a mass-spring-damper system between the HIP and a moving point called a god-object. The ‘god-object’ method [21] and the proxy method [22] for 3-DOF rendering are based upon this idea that a virtual object can be used to simulate the ideal outcome of haptic interaction in a virtual environment. That is, the virtual object never violates any collision constraints (such as forbidden region virtual fixtures) in the virtual environment. Forces are then calculated as translational (and torsional for the 6-DOF case) springs between this ideal tool configuration and the configuration of the haptic device, which behaves non-ideally.
With streaming point cloud data from an RGB+Depth (RGB-D) camera (e.g., XBox Kinect 30Hz at 640x480 resolution) representing objects for haptic interaction, the computational load requirements are burdensome. Intuitive solutions, such as interpolation to construct polygons prove too computationally heavy to satisfy the haptic update rate requirement. Instead, in our lab we extended the Ruspini proxy method to include three separate radii extending from the proxy center, designating states of entrenchment, contact, and free motion [23], [24]. Using only neighboring points to the proxy, a surface normal, if it exists, can be calculated in real-time. Proxy movement is then based on the number of points within the three radii, and force is rendered via Hooke’s law. Since the point cloud refresh rate was 30 Hz, it was still possible that the point cloud could move fast enough such that the HIP pops through. To rectify this, point cloud velocity is estimated and the HIP position corrected. In this way, our haptic rendering method can compute real-time force feedback from streaming point clouds without exhaustive computation. This is further aided by performing routine tasks on a graphics processor. There exist several methods for 6-DOF haptic interaction with voxels [25], polygons [26], implicit surfaces [27], static point clouds [28] and streaming point cloud data [25], [30] (which this work builds upon).

**Virtual Fixtures:** The term virtual fixtures was first defined in [31] as “abstract sensory information overlaid on top of reflected sensory feedback from a remote environment.” The reflected sensory information can for instance be visual, auditory, haptic or any combination of these. Often a bilateral teleoperation approach [20] is taken to achieve remote touch using a remotely controlled robot. A drawback with this method is that the control loop introduces delay in the haptic feedback. This delay arises from the controller as it usually takes a certain time before a manipulator reaches the desired location. But the main drawback with this method is that force feedback only can be sent after collision with the remote environment has occurred. The virtual fixture can however be arbitrarily defined according to the needs of the application. In [32] and [33], virtual fixtures were shown to increase the ability to position a remote manipulator and in [34] shown to increase performance in path following tasks.

Haptic virtual fixtures have been investigated by many groups, e.g., [35], [36], [37], [38]. Although these efforts successfully implemented simpler virtual fixtures (such as ‘virtual rulers’ etc.), virtual fixtures in an un-modeled and dynamic environment remain a challenge.

Our group applied the algorithm of [29] to the generation of forbidden-region virtual fixtures from streaming point cloud data in [39]. For these 3-DOF forbidden region virtual fixtures, the haptic feedback was based solely on the desired position of the robotic end effector, not taking rotations or torques into account. This was done by approximating the robotic end effector as a simple bounding sphere, which is not always a good approximation. The forbidden-regions were further defined by superimposing spherical regions where each sphere corresponded to a point in the point cloud captured by a depth sensor overlooking the robot task space. In this work, the three-dimensional structure of the robot’s task space is captured in real time. The forbidden-regions are defined in a similar fashion by finding the points that correspond to a virtual fixture and then produce a forbidden region sphere around each of those points. Rendering of haptic virtual fixtures then simply corresponds to ‘conventional’ haptic rendering of spheres (typically a large number of time-varying spheres) using a virtual-coupling method. The guidance virtual fixture can then simply be implemented as a spring to a desired target configuration.
In [25], [41] (supported by this SEED project) a novel method for rendering of 6-DOF haptic forbidden-region virtual fixtures and guidance virtual fixtures based on real-time sensor data was developed. Essentially this is done by running a real-time simulation of robot motions in the actual environment to calculate the effect of haptic virtual fixtures. This is then presented to the operator.

An important consideration in these virtual fixture algorithms is the speed of the haptic rendering. In order to meet the 1000Hz recommended haptic rendering rate, an efficient rendering method is needed. As haptic rendering can be seen as a simplified physics simulation, a fast collision detection method is required. A parallel collision detection method can be used in combination with a sphere tree data structure.

**Underwater Haptic Navigation:** The concept of virtual fixtures and assisted teleoperation is well-studied in many areas of robotics, yet underwater, remotely-operated vehicles (ROVs) lack this capability. There exists little work on rendering of dynamic virtual fixtures for underwater applications. However, sonar and subsequent three-dimensional imagery are often used for navigation and collision avoidance. Thus, there exists a set of relevant efforts that will are useful for achieving our goal of implementing haptic rendering for underwater applications.

Work in underwater survey and mapping, where “macro” imagery is collected with underwater cameras or sonar, often focuses on simultaneous location and mapping (SLAM) [43], [44]. Eustice et. al. [45], [46], [47] have used ROVs for ship hull inspection, developing three-dimensional models of structures underwater with both visual and sonar data. The authors of [48] used a sonar-equipped ROV to map ancient cisterns on the islands of Malta and Gozo where it is important to avoid potentially damaging collisions. Collision avoidance for AUVs (autonomous underwater vehicles) was evaluated in [49] using a 3D sonar and path planner that was updated at each time step. In [50], robust state estimation was achieved using 3D sonar.

In [51], a static point cloud was constructed using a laser scanner and then used for grasp planning. Similar in spirit to rendering fixtures in a virtual environment, in [52] an offline simulator for ROV/AUV intervention was presented. In the UNION project [53], dynamic disturbance rejection as well as robust underwater color segmentation was achieved. In [54] and [55], a method for underwater target localization using sonar and vision was presented. This information was then used to position an ROV or AUV relative to the target.

In [32] (part of this SEED project work), we reported high-resolution, small scale imagery to support dexterous manipulation of objects underwater. To generate virtual fixtures for an underwater task space, sensor data was captured underwater using an RGB-D sensor. The data was transformed to the robot base frame and spatially low pass filtered. A color segmentation algorithm was used to define the haptic virtual fixtures and package them in a sphere tree data structure that could efficiently be used for haptic rendering. The haptic rendering then uses the desired configuration of the robot end effector in combination with the virtual fixtures to present the force to the operator.

The virtual fixture rendering method was implemented on a Core i7-3930K CPU (Intel Corp.) with Radeon HD 6990 GPU (Advanced Micro Devices, Inc.). The force was rendered at 1000 Hz and sent to a W5D haptic device (Entact Robotics) with 6-DOF sensing and 5-DOF actuation (no actuation on the roll joint). The streaming point cloud data was captured in a water tank at the University of Washington Applied Physics Lab. The GPU processed the point cloud in real-time at 30Hz using the OpenCL API (Khronos Group); this includes transformation and filtering of depth and RGB data, color segmentation, as well as generation of sphere trees corresponding to
the virtual fixtures. The collision detection is performed in parallel on four cores on the CPU. Depth and RGB data was captured using a Xtion Pro depth + RGB sensor (Asus) and recorded using the Robot Operating System (ROS). We evaluated the proposed method by evaluating two different scenarios. First, two forbidden-region virtual fixtures and secondly a guidance virtual fixture in combination with a forbidden-region virtual fixture.

To summarize, key features our real time haptic rendering algorithm are that it uses streaming (time varying) point clouds to derive haptic information, such as surface normal vectors from viewed objects, in real time. This allows for tracking of moving objects. Our haptic rendering and virtual fixture algorithms can work for a wide variety of sensors (eg, RGB-D, scanning sonar, Flash LiDAR), a wide variety of robots and robot end-effectors, and the information can be displayed using any haptic device.

3.5 Testbeds for Evaluation

In this SEED project, we developed two testbeds for evaluation of combinations of sensors, haptic rendering and virtual fixture algorithms and robot end effectors. One of these testbed operated out of water, in the laboratory. The second testbed operated underwater, in the tank at the UW-Applied Physics Lab that is shown in Figure 2.

A key step in the development of both testbeds was generation of a computer visualization tool that helps the operator to use the overall system. This visualization tool superimposes depth and visual (or sonar) images on a monitor, along with information obtained from a dynamic model of the robot arm. A screen shot of this tool is shown in Figure 16 below.

![Visualization tool screen shot. The ECA robot arm (in green) is shown, along with a target shell (blue and red, resting on a plastic milk crate). The operator can rotate this image in all directions, and zoom and scale it, to get different prospective. A video image of the operation](image)

Figure 16: Visualization tool screen shot. The ECA robot arm (in green) is shown, along with a target shell (blue and red, resting on a plastic milk crate). The operator can rotate this image in all directions, and zoom and scale it, to get different prospective. A video image of the operation...
is also available (in this screen shot, minimized on the lower left). This visualization tool is in addition to haptic feedback that is provided to the operator.

The ‘in air’ testbed is shown in Figure 17. The tele-operator’s console (to transmit operator control actions as well as haptic feedback) shown here is using two Phantom Omni haptic devices (SensAble Technologies). As the operator moves the robot through the haptic telemanipulators, he/she will feel a “force field” of increasing impedance, as proximity of the tool tip to the virtual fixture boundary decreases. In some trials, a different haptic device was used.

![Figure 17: ‘In air’ manipulation/haptics system test bed.](image)

This testbed was used to integrate the tools and methodology developed in this work, to evaluate performance with a working system. It consists of an ECA Robotics 5-function electric manipulator, a series of imaging devices (both HD and RGB-D cameras), and a control computer with GPU.

For the ‘underwater testbed’ the target object, robot arm and sensors are submerged within a large water tank. The water tank is filled with filtered water to reduce particulate contamination. The camera is in a waterproof enclosure. The RGB-D camera uploads data to the connected computer system for haptic processing, display and recording.

4. Results and Discussion

In this section we discuss results obtained through evaluation of the overall system testbed, as well as from preliminary test setups. The results are best explained through videos, which are linked through the text and also listed and listed in Appendix A.2. These are described here in roughly chronological order.
A major theoretical result of this project was the extension of our real-time haptic rendering algorithms for streaming point clouds from 3 DOFs ([23], [32]), to provide six degree of freedom interaction [25]. This development is key to providing for the kind of interactions and virtual fixtures that will be required for the underwater tasks. A video which demonstrates some of this was presented at the 2013 IEEE International Conference on Robotics and Automation (ICRA) in May 2013, and can be seen at

http://www.youtube.com/watch?v=awT2h6DNlrQ

In this video, the Kinect camera is used to obtain depth information of objects, shown as point clouds (at 0:21). Surface normals are generated for all objects in the image in real-time (at 0:25). These can be used to provide haptic feedback forces and consequently virtual fixtures. In this video, haptic information is provided to the user through a Phantom Omni haptic rendering device (at 0:32). This device only renders 3 DOF, although it allows for 6 DOF commands to the robot.

We next combined our haptic rendering and forbidden region virtual fixture algorithms and underwater camera setup with an available robot in our laboratory (this cable driven robot has been developed for surgical applications, but for these experiments its end-effectors are underwater). In the narrated video at

http://www.youtube.com/watch?v=QLPaxARM6AA

the blue object can be touched by the robot end effector (the sharp pointy bit), when remotely commanded by an operator (1:06). The red object cannot be touched, due to a virtual fixture that is imposed in a virtual reality representation of the physical situation. When the robot end effector is commanded to approach the red object, the operator will feel an opposing force through the haptic device, and the robot end effector will be prevented from touching it. The blue object is not protected by a forbidden region virtual fixture, so it can be touched by the robot end effector (1:28). Control of the end effector through the haptic device can be seen at (1:34). On the screen, the operator sees the RGB-D point cloud image of the target object, and a visual (blue arrow at 1:46) an indication of the force feedback that he/she is feeling through the haptic device.

Using the developed optical camera system of this project, we successfully demonstrated our ability to render haptic forces from virtual fixtures underwater, and with 6 Degrees of Freedom. This effort included algorithm and software development. We have developed both guidance virtual fixtures (which help guide the telerobot operator along a desired trajectory) and forbidden region virtual fixtures (which inhibit robot end effector contact from specific objects or portions of objects). Results regarding this appear in [32]. In this work, a device that allows 7 DOF sensing and haptic feedback (iEntact W5D Haptics device plus a robotics system including a gripper from Entact Robotics) was used. The cost of this system (about $30k) was beyond the budget limitations of this SEED project, but we were able to borrow it for a period of time, for evaluation, from the manufacturer. We implemented six degree of freedom haptic rendering and virtual fixtures, obtained from streaming point clouds from an RGB-D camera, for manipulation of underwater objects. This is demonstrated with dynamically changing point clouds, using our underwater setup. In the narrated video at

http://www.youtube.com/watch?v=ZiFW-2daYBA
the robot is simulated (that is, it only exists in the virtual setting), but the point cloud data is experimentally obtained. Note that the virtual tool ‘gripper’ (shown in green at 0:55), which is the 6 DOF replacement of a HIP (haptic interface point), is free to move and rotate, as commanded by the operator. The red shape (at 1:00) around the left-most and center objects is a visualization of two forbidden region virtual fixtures. Note that the operator cannot penetrate them. A key feature here is that more than one (in this case, two) virtual fixtures can be generated at the same time. Starting at around 1:30, a forbidden region virtual fixture (red) protects the left object while a guidance virtual fixture (activated by key press at 1:40, shown in blue) drives the virtual tool (and, simultaneously the simulated robot end effector) to a desired position and orientation.

A narrated “final report video” for this project (prior to our no-cost extension to explore real time sonar imaging options) can be seen at

http://youtu.be/SoScCsM6hr0

The underwater testbed is seen at 0:07. The (inactive) mortar shell shown at the bottom of the tank at 0:11 is colored to indicate areas that should (red), and should not (blue), be touched. Components of the testbed are labelled (for the in air case) at 0:22. The visualization software is shown in action, beginning at 0:31. The visualization rotation capability is demonstrated at 0.52. A forbidden region virtual fixture is demonstrated, beginning around 1:22. At 1:34 the blue arrow superimposed on the robot image indicates the force or torque that the operator is feeling with his hand, from the haptic interface (the arrow size grows with the force magnitude). This keeps the operator from touching the blue part of the shell. At 1:42, a guidance virtual fixture is demonstrated.

The University of Washington Applied Physics Lab produced a high production value video featuring this work, as well as information about the spinoff company BluHaptics. This can be seen at either of the links below:

http://youtu.be/aEvdQiRdMC0

as well as several other sites. The ECA robot arm is shown in action at 0:16. A description of haptics is given starting at 0:48. At 2:25, the system is shown disconnecting an underwater cable connector. Starting at 2:27, information about the spinoff company, BluHaptics, is presented. This company was begun outside of SERDP project support, through a Commercialization Gap Fund grant and a Post-Doctoral Commercialization Fellowship provided by the UW Center for Commercialization. However the SERDP project benefited from this funding, through improvement of the algorithms and visualization software that these outside sources supported.

The University of Washington Center for Commercialization also produced a promotional video describing BluHaptics, and their support of it. This can be seen at

http://youtu.be/z1Zt-D3det8

One interesting item in this video is the operation of the robot remotely, from a different building on campus (starting at 0:32).
We believe that the project’s proof of concept has been met. We have developed system components that can be applied to underwater munitions remediation. A potential limitation of our work was our initial dependence on optical sensors, which may not work in less-than-clear water conditions. However, we have mitigated this by developing methods to that use recently available, relatively low cost commercial sonar systems as real-time 3D sensors.
5. Conclusions and Implications for Future Research

We can summarize our overall conclusions for this proof-of-concept research as follows:

(1) Six degree of freedom haptic rendering from streaming (that is, time varying) point cloud has been developed and demonstrated.

(2) Virtual fixtures to prevent a teleoperator from touching undesired areas of an object with a robot end effector, or guiding the teleoperator to correctly orient and place the robot end effector, have been developed and demonstrated.

(3) We have found and modified optical sensors that can obtain 3D information underwater, in real time, to drive these algorithms. These sensors are adequate for a limited working range, in clear water.

(4) We have developed visualization tools and testbeds that have let us verify the performance of the above subsystems. These have been tested underwater, in a test tank. In the underwater testbed we used a particular submersible robot. However the algorithms and software are applicable to other commercially available robots.

(5) We have developed novel sonar processing methods for streaming point clouds that permit the implementation of our haptic rendering, virtual fixture and telerobot control algorithms underwater, without requiring water clarity. These have been tested in a local freshwater site.

Together, these results establish the feasibility of our proposed approach to underwater munitions remediation. This successful SEED project has answered the key feasibility questions for our approach to underwater munitions remediation. Specifically: (1) the functionality of the proposed underwater video-plus-depth camera has been demonstrated; and (2) the performance of haptic rendering and virtual fixtures has been demonstrated. Together this will provide critical data and proof of concept for haptically-enabled co-robotics for remediation of military munitions in underwater settings.

6. Preliminary Design for Follow-On System

This section contains information for a preliminary design for follow-on work, in which a next stage prototype system will be constructed and evaluated in realistic underwater conditions. Key issues which will influence the design include:

- Size, weight and condition of submerged ordnance
- Depth of water and water conditions

There are several possible platforms that we envision using, each involving a combination of tools for classification and remediation of unexploded underwater ordnance. For example, a bottom crawling vehicle could be deployed from a floating barge vessel. The remediation would be performed by a screw-drive salvaging bottom vehicle equipped with robotic arms for gripping the unexploded ordnance or, in another concept, the ordnance might be handled by a munitions-carrying basket on a tow cable connected to a hoist on the barge. One approach would be to fix a harness, or lifting mechanism to the ordnance, allowing the platform to be removed prior to the final removal phase so that retrieval will not pose any risk of damaging the hardware. Sensitive objects might be first characterized without any physical contact between the ordnance and the robotic platform.
An alternative platform concept would be to use two remotely controlled robotic arms (with haptic rendering) suspended from the bottom of a vessel. This type of two stage hovering ROV platform allows for a range of environments to be managed, including rocky or uneven surfaces. Disturbances from surface effects (wind, waves, etc.) are mitigated using this approach. In addition to stability in a range of conditions maneuverability allows the vehicle to position itself in a way that maximizes the effectiveness of the manipulators.

For relatively light weight munitions, the ECA robot that we have used in this SEED project is appropriate. It can be mounted on a skid, ROV or underwater vehicle. The basic idea would be to use this device to either attach a sling to the target ordnance (so that it can be lifted to a barge or other container vessel), or to move the object into a collection container.

For heavier munitions, a more heavy duty robot would need to be used. We have identified information about several such robots from different manufacturers. This information, along with job specifications from SERDP, will be used to determine this part of the design.

We are also exploring commercially available underwater scanning and flash (time of flight) LiDAR cameras. A practical solution might be adapting existing commercial off the shelf equipment instead of designing and deploying our own. Our investigation revealed there are LiDAR systems actively deployed in deep water survey work supporting the Oil and Gas industry. All operate in the blue-green 532nm wavelength as opposed to infrared.

Water conditions (and cost) will determine the best choice of sensor. For muddy water and for objects that are not easily seen by optical sensors, the sonar based sensor is the best choice. We have developed preliminary versions of algorithms and software that can make this possible, and we are in contact with sonar manufacturers who could partner with us for a follow-on proposal. For some situations the addition of an optical depth sensor would be useful, as it allows for imaging closer to the target object. The optical sensors cost approximately 1000 times less than the sonar system.

For any of these choices of sensors and robot end effectors, we envision a command station (on a ship or on shore if feasible). It will include the computers, haptic device and monitors similar to those used in our testbeds. Communication would be done by fiber optic connection, given both security concerns and the necessary bandwidth needed to underwater subsystems. The system base station could also be connected to the internet (wirelessly or wired), or to a specific private network, to provide documentation of activities.

We have identified potential partners for a follow-on project, including BluHaptics, sonar and LiDAR manufacturers, and a company with extensive experience in a wide range of underwater operations (including infrastructure inspection, remediation, object placement and removal, mining and environmental cleanup).

Our basic strategy for follow-on work is to build a team with expertise in all of the needed subsystems. Our contribution will be the haptic rendering, virtual fixture and telerobot control algorithms and software, our visualization software, and systems integration. We look forward to working with SERDP to develop and perform a follow-on project to meet this critical need.
7. Literature Cited


[41] Nia Kosari S. *Haptic Virtual Fixtures for Robotic Surgery*. Electrical Engineering, University of Washington, August 2013


A.1. Publications, Presentations and Patents from Project

Publications


Presentations


CSAIL Seminar, MIT. Cambridge, MA. May 1, 2014. Reach Out and Touch Something. (Howard Chizeck)

Patents


A.2 Videos Demonstrating Project Work and Related Activities

http://www.youtube.com/watch?v=awT2h6DNLrQ
In this video, for the 2013 ICRA conference, the Kinect camera is used to obtain depth information of objects. These can be used to provide haptic feedback forces and consequently virtual fixtures. In this video, haptic information is provided to the user.

http://www.youtube.com/watch?v=QLPaxARM6AA
In this video, we combine our haptic rendering and forbidden region virtual fixture algorithms and underwater camera setup with an available robot in our laboratory.

http://www.youtube.com/watch?v=ZiFW-2daYBA
In this video, we implement six degree of freedom haptic rendering and virtual fixtures, obtained from streaming point clouds from an RGB-D camera, for manipulation of underwater objects. This is demonstrated with dynamically changing point clouds, using our underwater setup.

http://youtu.be/SoScCsM6hr0
This is a narrated “final report video” for this project (prior to our no-cost extension to explore real time sonar imaging options).

http://youtu.be/aEvdQiRdMC0
The University of Washington Applied Physics Lab produced a high production value video featuring this work, as well as information about the spinoff company BluHaptics.

http://youtu.be/z1Zt-D3det8
This video was produced by the UW Center for Commercialization also produced a promotional video describing BluHaptics, and their support of it.

https://www.youtube.com/watch?v=57gdbYqB1es
This video demonstrates visualization of force normal, suitable for haptic rendering, from a combined sonar and processing system.