Augmented Co-Robotics for Remediation of Military Munitions Underwater

Project Number MR-2734

Dr. Andrew Stewart
University of Washington
Applied Physics Laboratory

In-Progress Review Meeting
May 16, 2018

SERDP
DOD ▪ EPA ▪ DOE

MR-2734: Augmented Co-Robotics for Remediation of Military Munitions Underwater

Performers: APL-UW, UW EE Dept., BluHaptics

Technology Focus

- *Developing a co-robotic (robot assisting a human) system with associated sensors, processing, and actuators to safely and efficiently grasp underwater munitions.*

Research Objectives

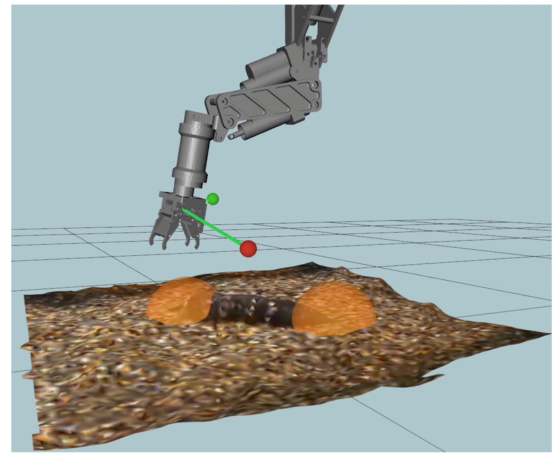
- *Research emphasizes safe, efficient, low-cost portable approach*
- *Spatial data is collected in real-time and integrated with processing and closed-loop control of robot end effector.*
- *In-water experiments validate approach and provide assessment of performance in user trials.*

Project Progress and Results

- *Progress: Initial data collected, virtual fixture library developed, real-time control capability developed and tested in simulation (with real data)*
- *Concerns: Commercially-available sensors have significant limitations and are costly. ECA manipulator has limited range & joint angle measurement faults.*

Technology Transition

- *Field-ready system to be developed*
- *Software system being commercialized by Bluhaptics*
- *Field demonstration (Sequim Bay?) with potential users*
- *Data dissemination*



BluHaptics

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Social Media Content

- *The APL-UW and Bluhaptics team has successfully completed an initial underwater data collection effort that is feeding in to future robotic subsea remediation user trials.*
- *Bluhaptics has developed a virtual fixture library and a real-time control interface that will be used to operate a subsea robotic system capable of removing UXOs from the seafloor.*
- *The UW and BluHaptics team has developed a system design for implementing an augmented co-robotic approach for underwater munitions remediation.*

Project Team

Dr. Andrew Stewart (PI)

University of Washington Applied Physics Laboratory

Expertise in human-robot interaction and ocean engineering

Dr. Howard Chizeck

University of Washington Dept. of Electrical Engineering

Expertise in controls, robotics, real-time haptic rendering

Dr. Fredrik Ryden

BluHaptics Inc.

Specialist in haptic manipulation in the ocean

Dr. Aaron Marburg

University of Washington Applied Physics Laboratory

Expertise in real-time 3D perception

Problem Statement

- A clean, safe, and efficient process is needed to execute response campaigns without reliance on divers or blow-in-place strategies.
- Existing munitions remediation strategies do not transfer to the underwater domain.
- Remediation tasks are dynamic and unstructured but subsea robots are ideal for routine tasks in structured environments

USA Environmental

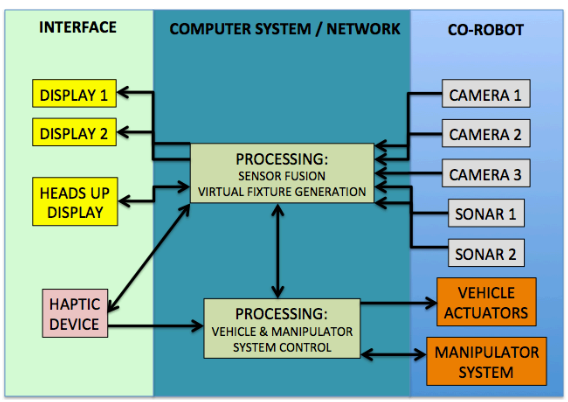
USACE

USGS

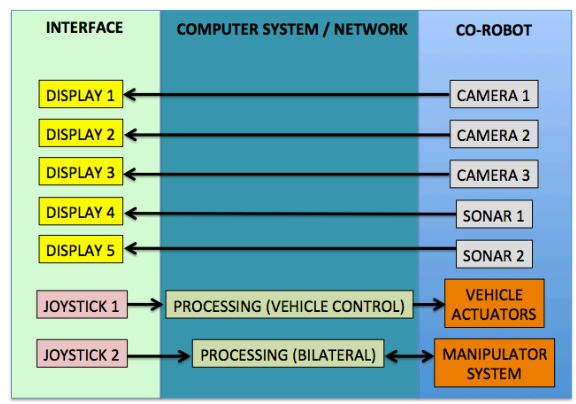
Technical Objective

Further develop and investigate the utility of a method of remotely operating robotic systems that require dexterous and precise motion – in particular when making physical contact with other objects such as munitions.

- **Research emphasizes safe, efficient, low-cost portable approach**
- **Co-robotic solutions remove personnel from the site.**
- **Augmented Co-Robotics afford greater precision, dexterity and adaptability.**
- **Expert knowledge is integrated into the system using "virtual fixtures" that guide operations.**



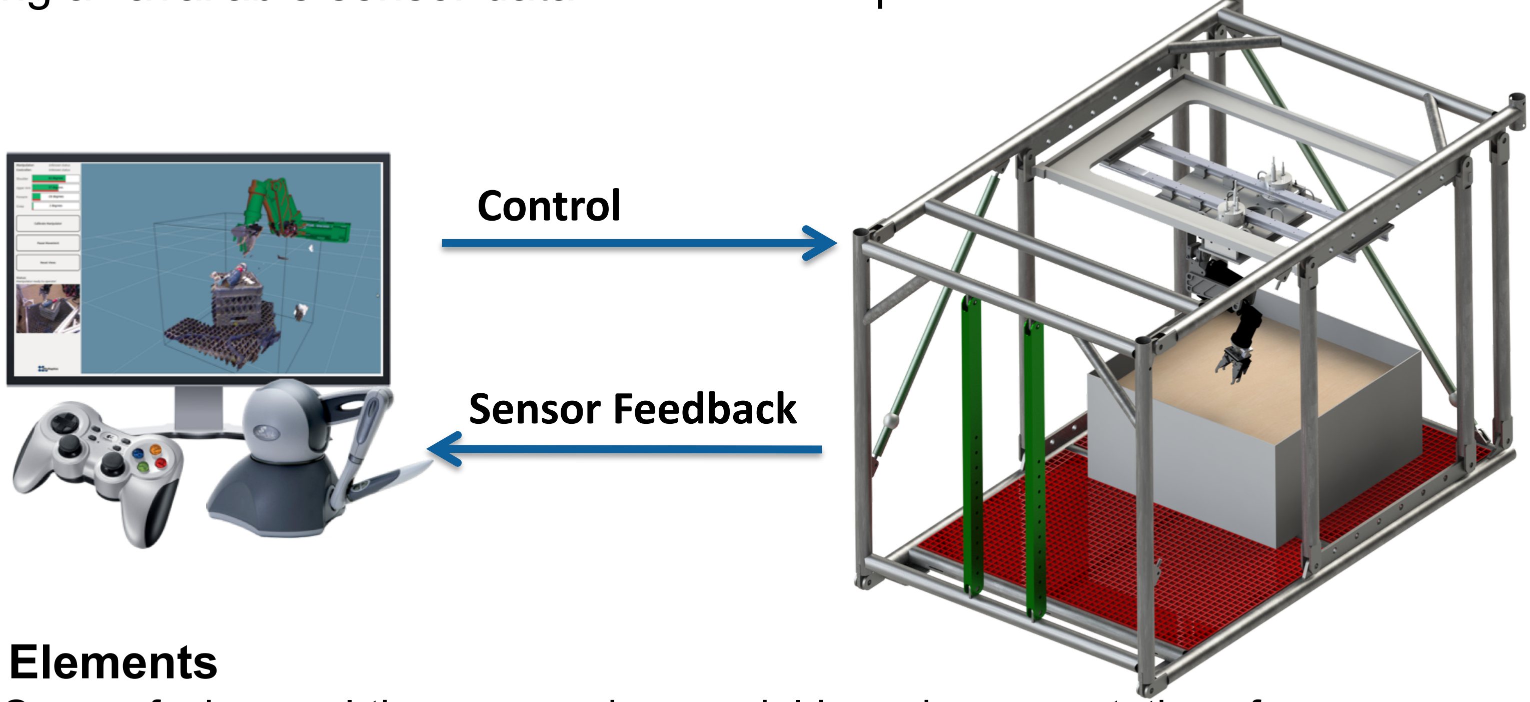
VS



Technical Approach

Real-time modelling of workspace using all available sensor data

Translation of intuitive operator motions to complex robot commands

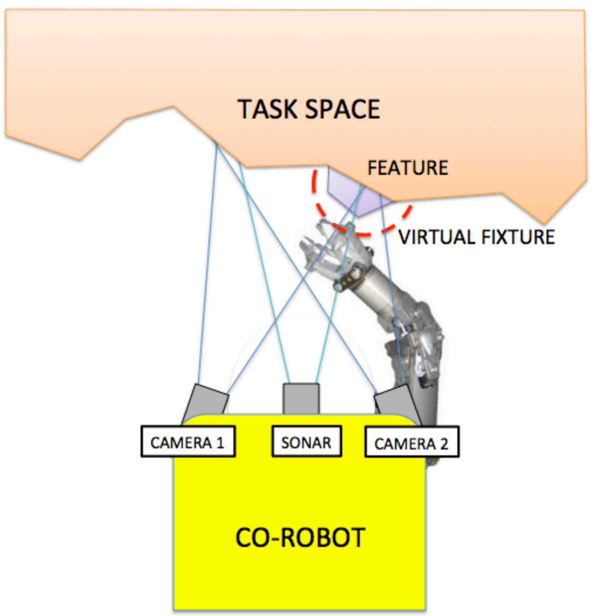


Key Elements

1) Sensor fusion, real-time processing, model-based representation of robot, manipulator & workspace/bathymetry
2) Feedback – Visual and Haptic, force feedback with guidance to enhance situational awareness and response time
3) The combination – User input drives closed-loop Cartesian control of robot

Technical Approach

Co-Robot: A robotic system designed to assist or guide a human.
Sensor Fusion: Method of combining measurements from multiple sensors to develop (compute or estimate) representation with decreased uncertainty.
Haptics: Recreating the sense of touch by applying forces, vibrations, or movements to the user.



Remote subsea ***end effector*** (manipulator) makes contact with and grasps "feature".

Operator uses interactive system to plan and execute precise maneuvers.

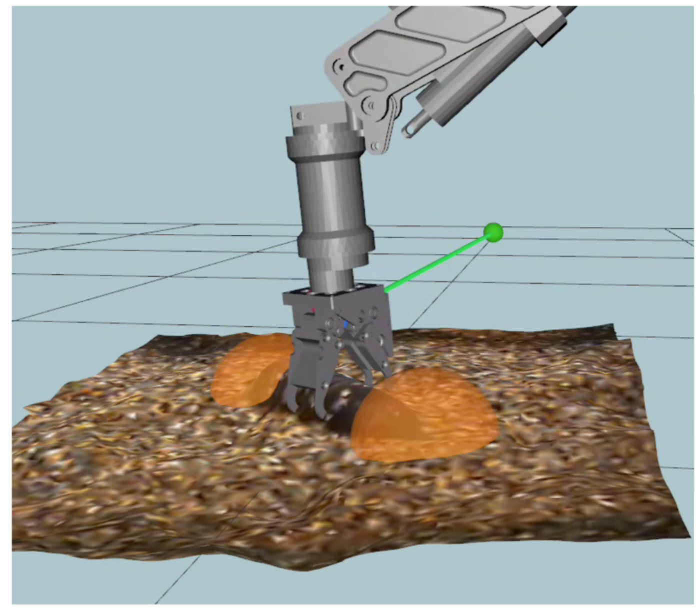
- 3D representation of workspace & munition using sensor fusion
- Interactive visualization of workspace, munition, and co-robot
- Haptic rendering of ***virtual features*** incorporates expert information in force feedback.

L. Rosenberg, "Virtual fixtures: Perceptual Tools for Telerobotic Manipulation," in Virtual Reality Annual International Symposium, 1993., 1993 IEEE, Sep 1993, pp. 76 –82.

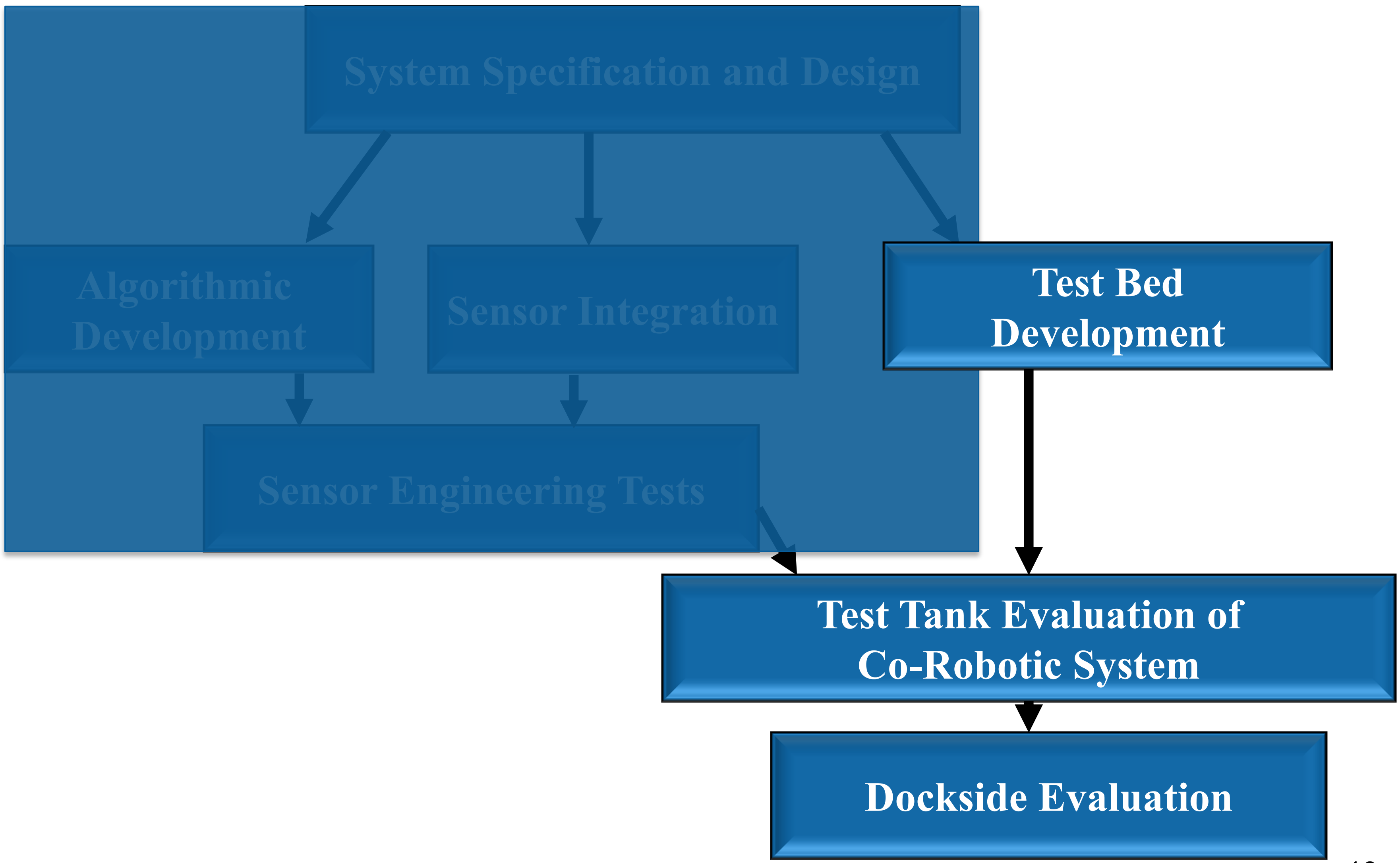
Technical Approach

Concept of Operations for Co-robotic Approach

1. Locate the ordnance to be remediated.
2. Transport/translate the co-robot to a position where the ordnance is in working range of the end effector.
3. Scan the workspace with integrated (and calibrated) sonar and optical range sensors.
4. Assign an appropriate virtual fixture (from library/database) to the ordnance being removed.
5. Using the interactive interface with haptic rendering and visualization, plan a feasible and safe grasp maneuver.
6. Execute the grasp maneuver and verify that the ordnance is secure and safe within gripper.
7. Extract ordnance from original location.
8. Transport/translate the co-robot and place ordnance within a fixture, or zone for final removal from seafloor.
9. Continue to the next ordnance location.



Technical Approach



Technical Approach

Virtual Fixture Library: an adaptable, parametrized virtual fixture set for range of UXO sizes/types

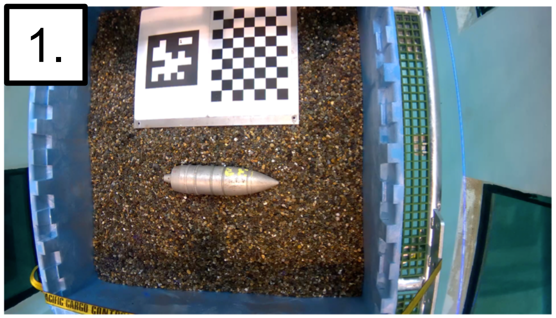
Credit: Joe Calantoni at NRL Stennis

Basic Principles and Assumptions:

1) There is a large number of UXO types that may need to be manipulated
2) Most UXOs can be approximated as a cylinder
3) UXO size and weight vary considerably, but remediation campaigns are likely to focus on a relatively small number of variants (at a time)
4) The ends, or extremeties, are likely to be areas with most sensitivity.

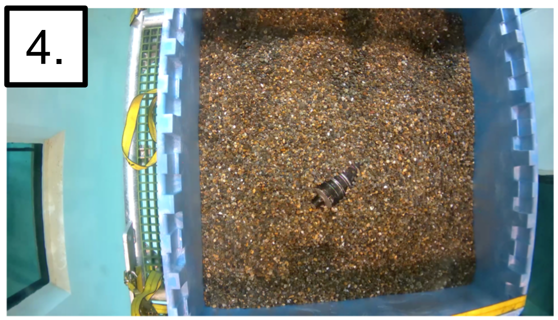
Results

Initial data collected in controlled test tank; 5 conditions evaluated.

1.


2.


3.


4.


5.

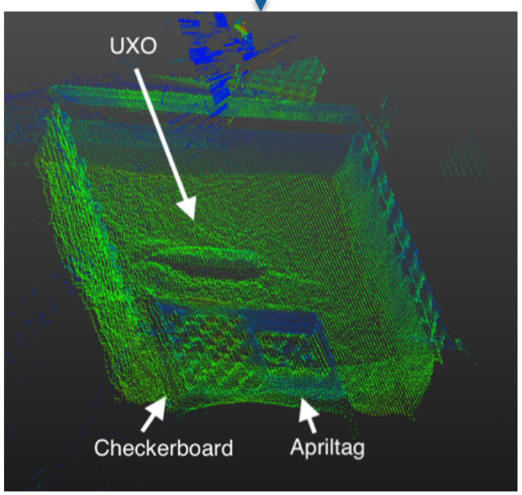

1. UXO resting on gravel, "horizontal" in image. With fiducials mounted to steel plate, also laying on gravel
2. UXO in same place as above but w/o fiducials
3. UXO in roughly same alignment but nose pushed down into gravel and tail proud
4. UXO oriented to ~45 deg to horizontal and partially buried
5. UXO oriented ~45 deg to horizontal and proud

Results

2G Laser Scanner → Calibration

IP Cameras → Calibration

Data Fusion



Initial Point Cloud

+

2D Image

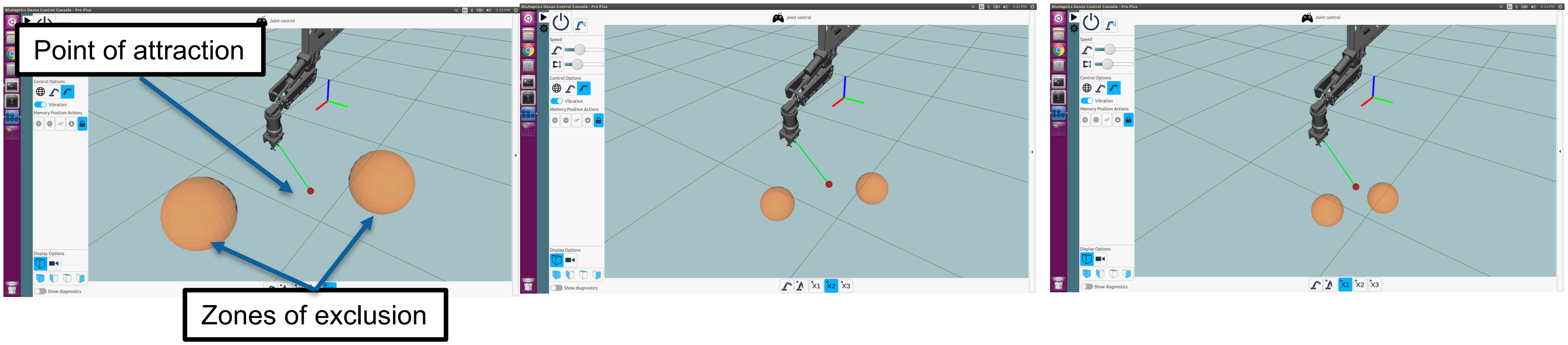
=

Final 3D mesh

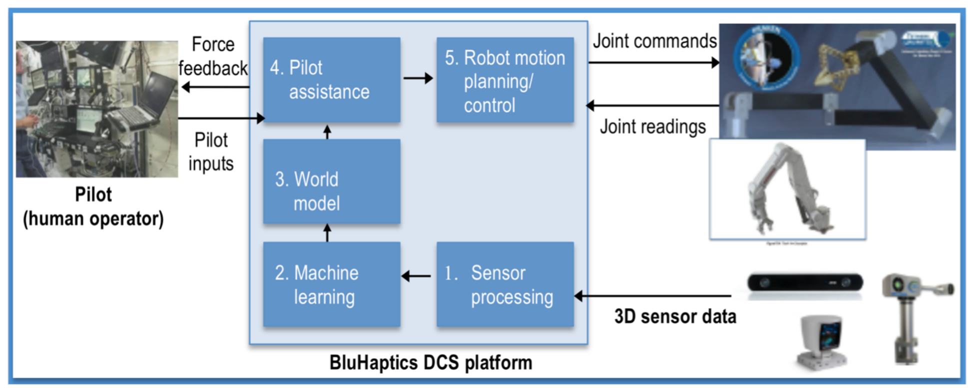
Results

Virtual Fixture Library

- Developed library comprised of VFs with 3 features each: 1 point of attraction for end effector centroid; 2 zones of exclusion for UXO extremeties
- Parametrized by size and separation of zones of exclusion and point of attraction location relative to axis



1. VF selected for munition to be grasped
2. VF assigned / registered to munition in fused sensor data
3. Pilot commands end effector (gripper) to desired position in response to visual and haptic feedback provided through interface.

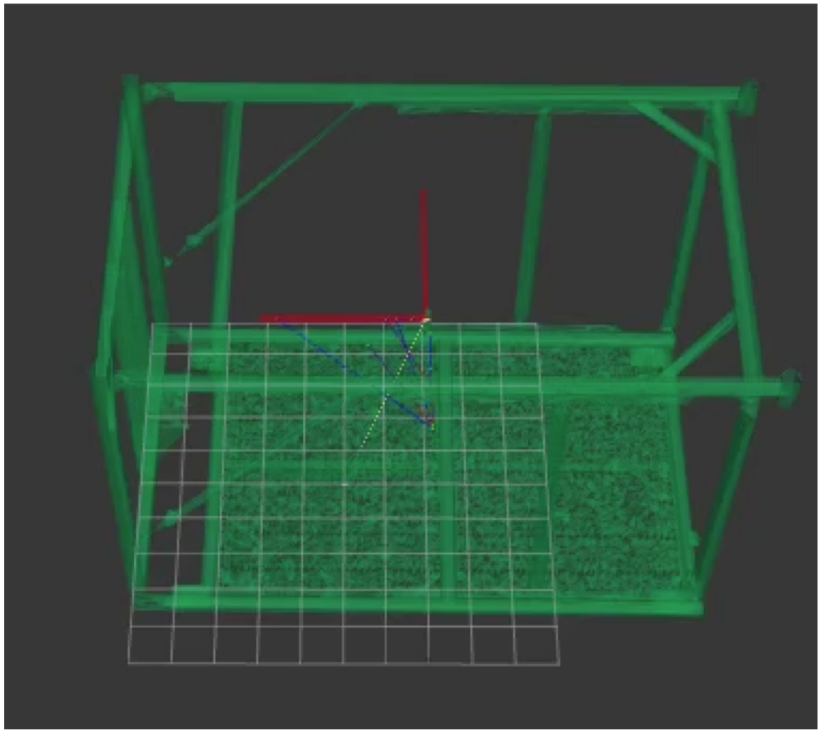


Architecture for real-time control interface

Results

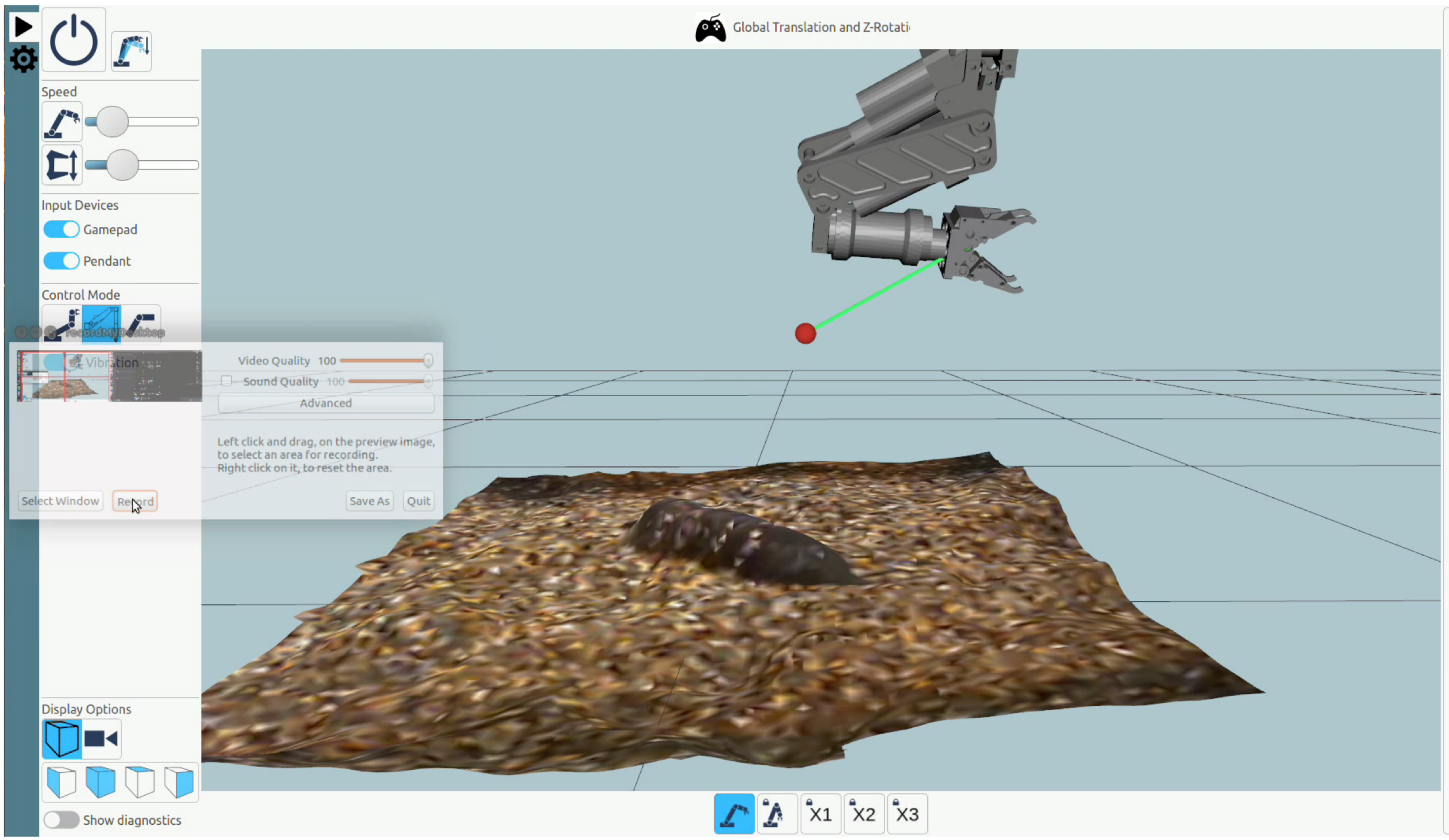
Developed ROS-simulink environment to control motion of underwater XY motion system and Robot Arm (ECA arm) in simulation.

- Visualized X-Y cartesian motion system with ECA arm attached within CAD model of tank in RVIZ
- User can publish desired path of the gantry in ROS and path is then reflected in RVIZ as a colored trail through terminal or through arrow keys on keyboard.
- Created software that randomly generates bounded paths every 10 seconds of a variable length for testing and demonstration.
- Created Simulink model to compute and simulate realistic motion of the gantry with constraints of underwater physics from the generated desired path in ROS.
- Configured a two-way ROS-Simulink pipe to allow for communication of environments. Created subscriber nodes in Simulink that retrieve relevant ROS variables to compute path and created nodes in ROS that retrieve computed path and visualize it in RVIZ.
- Created ROS interface for user to activate/deactivate gantry to let it move along the Simulink computed path, with the capability of stopping it mid-way.



Results

Developed real-time control, fusion of data, and implementation of virtual fixtures for haptics and visualization



Action Items

ACTIONS

1 OVERDUE	1 UPCOMING

System design report including drawing package for mechanical, electrical, and system level (block diagram) delivered.
Pending — Due Date: 3/27/2018 — Overdue 44 days

A BlueView MB 2250 3D scanning sonar and 2G Robotics UL 200 laser scanner are integrated with the existing submersible robotic test bed.
Pending — Due Date: 6/27/2018

Report delivered predicting performance (accuracy & stability) of prototype with specific focus on typical constraints faced by underwater UXO community.
Pending — Due Date: 7/27/2018

3D sonar system (leased) integrated with mobile, ROV-based, haptically-enabled prototype.
Pending — Due Date: 8/27/2018

Custom elements fabricated and integrated.
Pending — Due Date: 8/27/2018

ALL ACTIONS

Andrew Stewart Tuesday, 8th at 12:50 PM

In progress. Lead Mechanical Engineer is on paternity leave which has caused a delay with some documentation. IPR presentation will provide an overview of all work to date.

Transition Plan

- Functional components of the overall system comprise individual contributions to the field – including adaptation of sensor systems, data fusion, design of virtual fixtures, control interface (software), and a robotic system (hardware)
- The research will culminate with a series of demonstrations that the development of a prototype system. Industry partner, BluHaptics, offers the control software as a commercial product.
- Within the scope of this project we anticipate engaging the user community through attendance of conferences and tradeshows. In a future phase of the work we envision conducting field demonstrations at a test site.

Transition Plan

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BluHaptics

BluHaptics, Inc. is has commercialized haptic rendering and haptic navigation technology and currently offers a complete software solution to its customers. APL-UW is working closely with *BluHaptics* throughout this project to ensure tools are developed using best practices and result in professional hardware/software solution that can be deployed on a variety of platforms. We have selected readily-available, and widely-used components to be integrated into our proposed prototype system with an eye on providing a system design package to potential end users.

The robotic and software technology resulting from this contract can be directly provided to ESTCP or other institutions either through BluHaptics or an equivalent partner focused on the federal market.

Patent-Pending Technology

METHODS AND SYSTEMS FOR HAPTIC RENDERING AND CREATING VIRTUAL FIXTURES FROM POINT CLOUDS
by H Chizeck, F Rydén et al. Patent App. US 14/125,574.

METHODS AND SYSTEMS FOR SIX DEGREE-OF-FREEDOM HAPTIC INTERACTION WITH STREAMING POINT DATA
by H Chizeck and F Rydén. Patent App. US 14/164,114

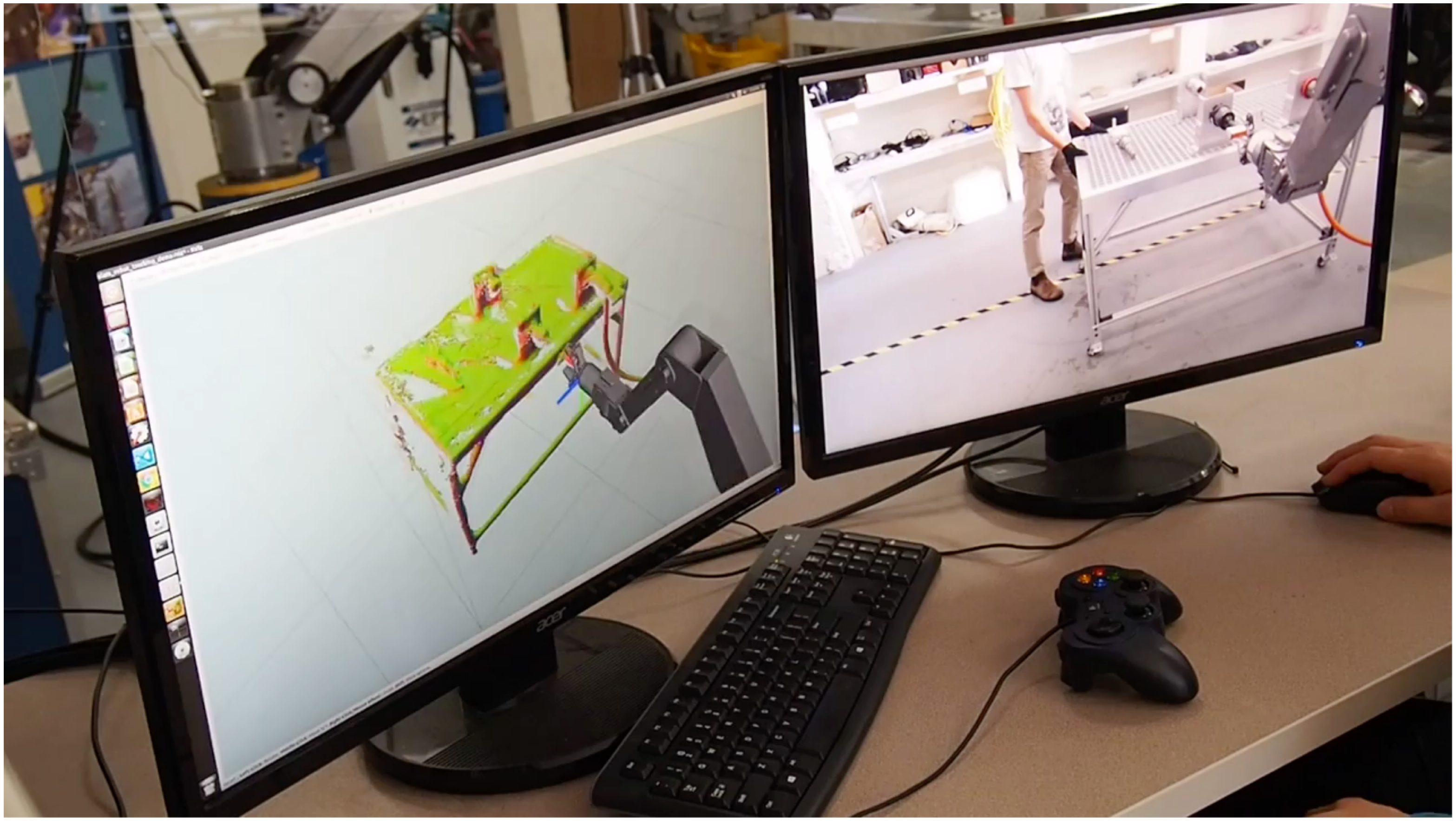
VIRTUAL FIXTURES FOR IMPROVED PERFORMANCE IN HUMAN/AUTONOMOUS MANIPULATION TASKS
by H Chizeck, F Rydén and A Stewart. Patent App. US 14/164,111.

HAPTICALLY-ENABLED CO-ROBOTICS FOR UNDERWATER TASKS
by H Chizeck, F Rydén and A Stewart. Patent App. US 14/164,115

Issues

- Issues with reflectivity of UXO model in laser scanner data
- Failure of white cap scientific stereo camera system (issue with vendor provided umbilical)
- Inability to fully implement closed loop control of ECA end effector due to lack of wrist encoder
- Opportunity to use Schilling T4 manipulator in trials

Schilling T4



(Bluhaptics Proprietary)

Project Funding

	FY17*	FY18*	FY19*	FY20*	Total
Funds received or *budgeted* ($K)	457	*401*			858
% Expended (thru Apr'18)	56%				
Planned % Expended	62%				
Funds Remaining ($K)	201				

NOTE: If substantial funds remain from FY13 (or previous years), please contact your Program Manager in advance of the IPR.

***NOTE: Include a column for all fiscal years in which funds have been or are planned to be received.**

Status of Funds for Federal Performers

- Report on the status of funds for each MIPR received by a directly funded Federal performer. Provide information on each fiscal year for which there has not been 100% expenditure of funds.

FY201X Funds			
Directly Funded Federal Performer(s)	**Funds Received**	**Funds Obligated***	**Percent Funding Obligated**
University of Washington Applied Physics Laboratory	457K	352K	77%

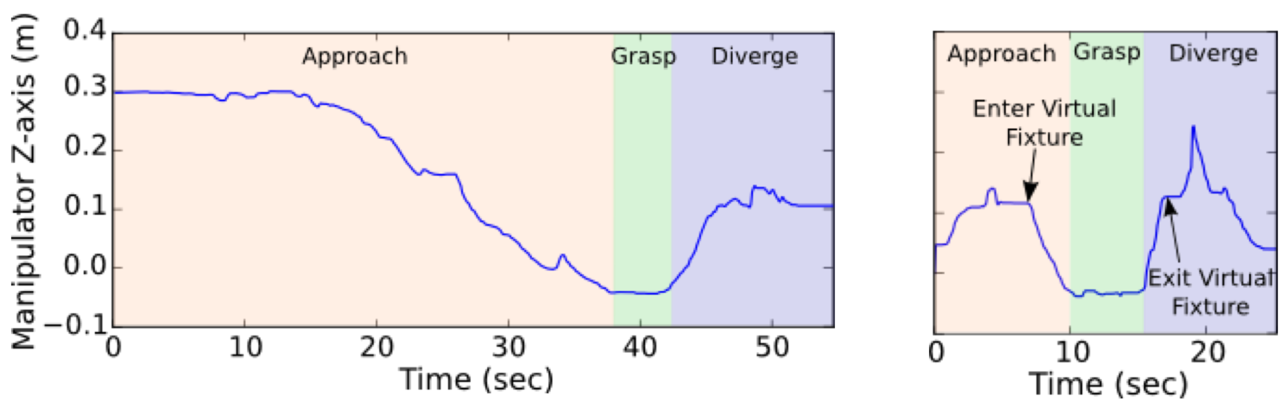
* Funds put on contracts and/or purchase orders that have been issued, and funds associated with internal labor or travel expenses that have been incurred.

BACKUP MATERIAL

These charts are required, but will only be briefed if questions arise.

Success Metrics

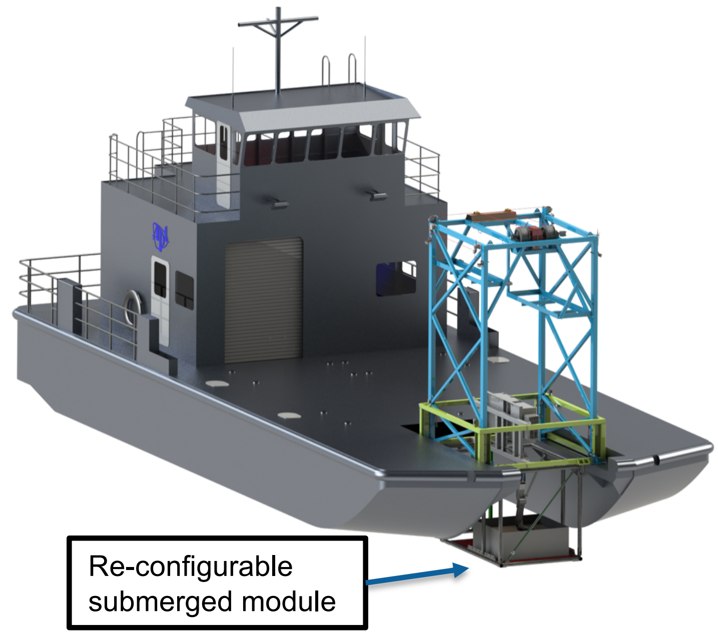
- Quantitative improvement in performance of robotic remediation tasks through haptic rendering:
  - Increased precision of end effector motion relative to target object
  - Fewer grasp attempts (i.e. # of movements); Reduced time to complete remediation tasks
  - Fewer unplanned contacts with munition
  - Reduced operator effort
- Improved (hardware) system performance
  - Overcome limitations of single sensor through multi-modal approach
  - Extend capability of low-cost manipulator
  - Assess ability to grasp and remove buried objects



Dockside testing on R/V ~~Henderson~~ Light

- System mobilized to R/V Light and integrated for vessel-borne operations.
- Field test and user trials in Lake Washington on a muddy bottom in approximately 15' depth (fresh water).
- Evaluate performance in series of remediation tasks (informed by results of previously conducted tank tests); parameterize testing to identify trends (subset of tank test parameters selected)

- 65 foot aluminum catamaran
- Diesel-electric propulsion,
- Re-configurable deck, and specialized gantry for working off bow.
- Projected speed of 6.5 kts



Modified R/V Light gantry for use dockside and potentially in field (Sequim Bay)

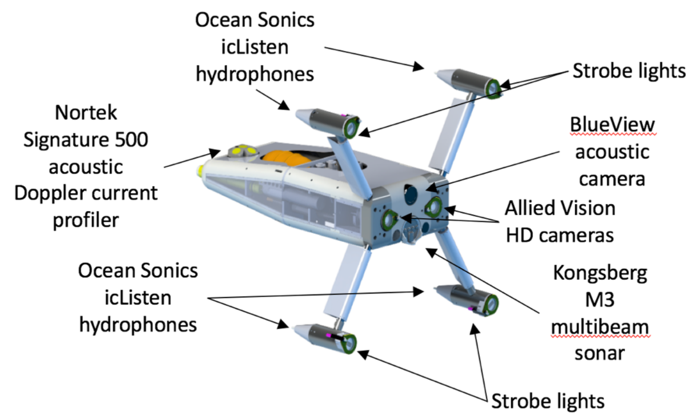
Related Work: Instrumentation & Sensor Fusion

Integrated Marine Environmental Monitoring

Multi-modal sensor package

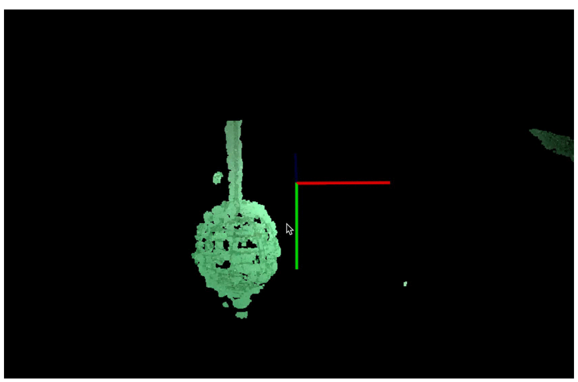
Integrated monitoring

Sensor fusion to decrease uncertainty In event detection & monitoring of marine activity



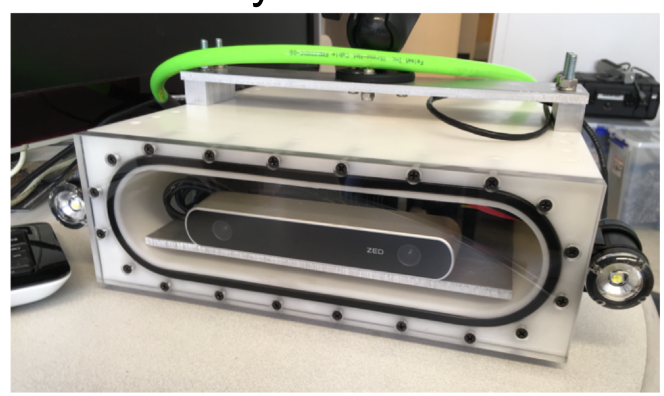
Sonar-Video Alignment

Toolbox for aligning and fusing BlueView sonar scans with video.



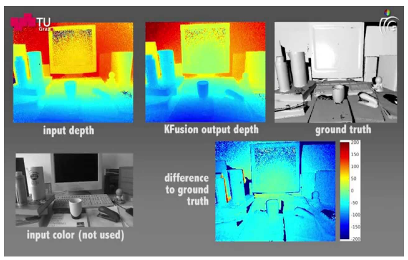
Marinized Stereo Camera Operational Testbed (MaSCOT)

Self-contained stereo sensing and 3D reconstruction system.



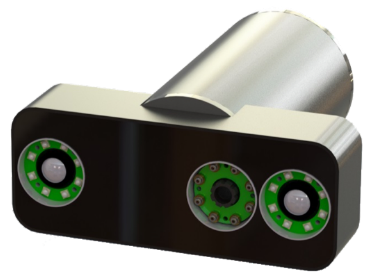
Related Work:UXO-DCLM System

Combine a Numurus Smart Sensor with APL supplied AI based classification algorithms to create a UXO optimized detection, classification, and localization solution



Smart Sensor Platform

- **3D** HD stereoscopic camera
- **3D** pulsed laser ToF camera
- **3D** electrically scanned ultrasound
- Inertial measurement unit
- Integrated Nvidia GPU
- Reconfigurable ROS based software



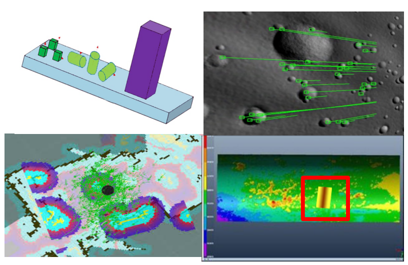
Real-Time UXO

Detection

Classification

Localization

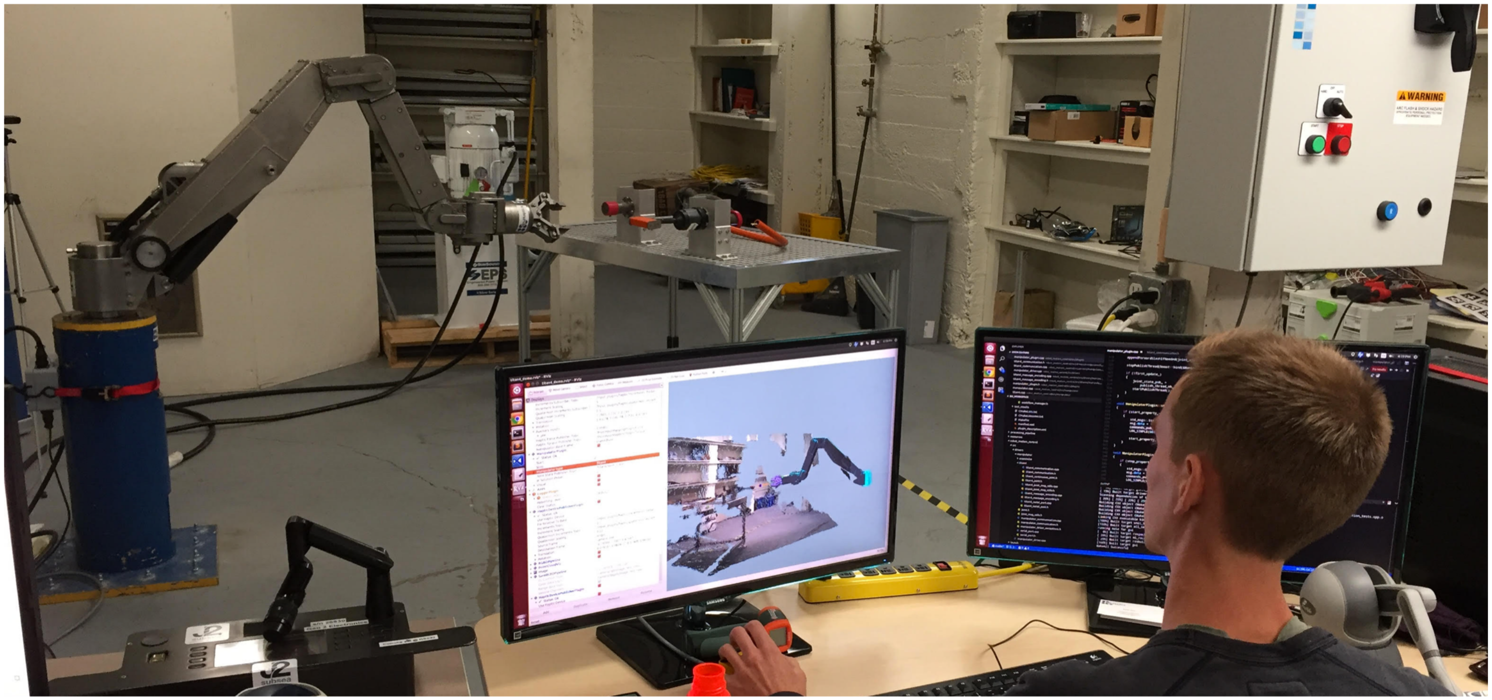
And Mapping



Embeeded Processing

- **D**etection using Computer Vision algorithms
- **C**lassify using Machine Learning Algorithms
- **L**ocalize using real-time 3D point cloud streams
- **M**ap using stitched sonar, laser, camera data and position data

BluHaptics Seattle Facility



The facility is equipped for software development on electrical and hydraulic manipulators, 3d sensors and tooling. This currently serves as the testbed for oil and gas applications.

Photo shows a work-class Schilling Titan 4 hydraulic manipulator with 6-foot reach and 300 pounds lift force at full extension.

Publications

- M.S. Thesis (in prep)
- Virtual Reality Conference Paper (in prep)
- Ocean Engineering Journal Paper (in prep)