Enabling Technology: Development of a Remotely Operated Vessel for Pier Inspection

Jonathan K. Marshall, Thad C. Pratt, Michael Hammons, William M. Hossley and Terry N. Waller

January 2017

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Enabling Technology: Development of a Remotely Operated Vessel for Pier Inspection

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Draft 1
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Prepared for Deputy Assistant Secretary of Defense for Emerging Capability and Prototyping
Under Joint Capability Technology Demonstration Program
Abstract: In order to expediently survey marine structures such as large piers, bridges, and harbor structures, an unmanned surface vessel was integrated with mechanically scanning multi-beam Sound Navigation and Ranging (SoNAR), 360-degree Light imaging, Detection, and Ranging (LiDAR) and high-definition photography. Combining point cloud data from all systems generates a high quality, above and below water, three-dimensional (3D) model of the target structure. The integration of a high precision positioning system was required for surveying in areas where GPS signal could be lost or degraded. HYPACK® survey software was used to operate all sensors as well as integrate the time and positioning signals into the data all from a 6ft long surface vessel. The small platform provides agile maneuverability among complicated structures with low overhangs and tightly spaced structural members. The goal in developing this unit was to create a fully-integrated survey tool that will allow a small team with minimal equipment to survey a pier facility and produce high fidelity point cloud data in 24 hours.

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Contents

Figures and Tables ........................................................................................................................................... v
Preface ............................................................................................................................................................... vii
Unit Conversion Factors ................................................................................................................................. viii
1 Introduction .................................................................................................................................................. 1
  Background .................................................................................................................................................... 1
  Objective ...................................................................................................................................................... 2
  Approach ..................................................................................................................................................... 2
2 Concept of Employment ............................................................................................................................... 4
  Background .................................................................................................................................................. 4
  Requirements ............................................................................................................................................... 5
    Platform ................................................................................................................................................... 5
    Sensors ..................................................................................................................................................... 5
    Transport and Setup ............................................................................................................................... 6
    Survey ....................................................................................................................................................... 7
    Processing and reach back ...................................................................................................................... 7
3 Engineering Study Results: Sensors and Integration .................................................................................. 8
  Integration concepts ....................................................................................................................................... 8
  Sensors and Equipment Investigated .......................................................................................................... 8
  Subsurface Sensors ......................................................................................................................................... 9
  Terrestrial Sensors ........................................................................................................................................ 9
  Above Water Sensors .................................................................................................................................. 11
  Contact sensors ............................................................................................................................................ 12
  Positioning system ....................................................................................................................................... 14
  Platform ....................................................................................................................................................... 14
4 Engineering Study Results: ROV Down-select ......................................................................................... 16
  Criteria for down-select .............................................................................................................................. 16
  Size and weight .......................................................................................................................................... 16
  Range and resolution ................................................................................................................................. 16
  Power Consumption .................................................................................................................................. 16
  Ruggedness ................................................................................................................................................ 17
  Software compatibility ............................................................................................................................... 17
  Selected Sensors ......................................................................................................................................... 17
  SoNAR ......................................................................................................................................................... 17
  LiDAR .......................................................................................................................................................... 20
  High Definition Photography .................................................................................................................... 21
  Positioning .................................................................................................................................................. 22
  Platform ....................................................................................................................................................... 22
Configuration of prototype .................................................................................................................. 23

5 Engineering Study Results: Data Capture and Storage ................................................................. 26
   Description of data management ..................................................................................................... 26
      Initial assessment .......................................................................................................................... 26
      USV survey ............................................................................................................................... 26
      Data Products ............................................................................................................................ 27

6 Technical Demonstration ............................................................................................................. 29
   Purpose ........................................................................................................................................ 29
   Data Collection Site ......................................................................................................................... 29
   Tasks ............................................................................................................................................ 31
   Data Collection .............................................................................................................................. 32
   Results ........................................................................................................................................ 35
   Findings ....................................................................................................................................... 37

7 Summary ..................................................................................................................................... 39
   Performance of the USV ................................................................................................................. 39
   Areas for improvement .................................................................................................................... 39
   Future work ................................................................................................................................. 40

Appendix A: Equipment Specifications ............................................................................................. 41
   BV5000 Model BV5000-1350 S3 Series: Specifications ................................................................. 41
      Teledyne BlueView Headquarters .............................................................................................. 41
      SoNAR & Software ..................................................................................................................... 41
      Mechanical ............................................................................................................................... 41
   Velodyne HDL-32E LiDAR Specifications ....................................................................................... 42
      Laser ........................................................................................................................................ 42
      Sensor ...................................................................................................................................... 42
      Mechanical ............................................................................................................................... 42
      Output ..................................................................................................................................... 42
   Ricoh G700SE-M Camera: Specifications ....................................................................................... 43
   GreenSea Systems Inc. INS (positioning): Specifications ................................................................. 44
      Gyro — 3 Axis FOG ...................................................................................................................... 44
      Acceleration — 3 Axis .................................................................................................................. 44
      Attitude ..................................................................................................................................... 44
      Heading .................................................................................................................................... 44
      Velocity — with 1200kHz DVL integrated or external ............................................................... 44
      Depth ....................................................................................................................................... 44
      Positioning — with 1200kHz DVL integrated or external ......................................................... 44
   Z-BOAT 1800 Platform: Specifications ......................................................................................... 45
      General Specifications ................................................................................................................. 45
      Physical .................................................................................................................................... 45
      Remote ..................................................................................................................................... 45
      Performance ............................................................................................................................... 45
Figures and Tables

Figures

Figure 1. The figure displays a flow chart of the Concept of Operations for the larger JCTD. This Enabling Technology portion is included in 3 Recon and 4 Assess. ................. 4

Figure 2 Vessel platforms considered, clockwise from top left; Kingfisher, Z-Boat, Autonomous Mobile Buoy, WAM-V 12. .................................................. 15

Figure 3. BlueView BV5000-1350 multibeam mechanically scanning SoNAR. ............. 19

Figure 4. Velodyne HDL-32E LiDAR. ........................................................................ 21

Figure 5. Ricoh G700SE-M high definition camera. .................................................... 21

Figure 6. Greensea Systems Inc. Inertial Navigation System. .......................................... 22

Figure 7. Teledyne Oceancosience Z-Boat 1800. .......................................................... 23

Figure 8. The external components of the fully integrated USV are shown here. They are 1: The Z-boat platform 2: The Velodyne lidar and 3: The BlueView sonar. Also the Ricoh camera which is not shown here can be mounted anywhere on the external frame. ................................................................. 24

Figure 9. The following components are found under the hatch of the USV. 1: Greensea INS 2: Onboard computer 3: Battery packs (4-6) 4: Navigation power and control interface 5: Network switch 6: Power distribution and conversion and 7: Velodyne lidar interface. ................................................................. 25

Figure 10. Base station work space. The base station for this test was aboard a support vessel which also aided in launching and retrieving the USV. .................................................. 25

Figure 11. Shown here is an aerial photo depicting the track of the vessel (left) and the geotagged data product (right). Screenshots were provided through the Google Earth photo viewer. ................................................................. 27

Figure 12. The pier and access bridge at the Port of Vicksburg ........................................ 30

Figure 13. The pier as seen from the observation barge. Note the deployed USV adjacent to the steel dolphin structure in the center of the photo. .................................................. 31

Figure 14. USV in harbor channel near the T-dock technical demonstration site. ............ 32

Figure 14. A depiction of the three collection methods employed during the technical demonstration at Vicksburg Harbor. The blue arrows show the path of the vessel during collection. Number 3 shows several points where the vessel collected 360° data. ........................................................................ 33

Figure 15. USV in close passes of the Vicksburg Harbor T-dock. Left: USV during pass 1. Right: USV during Pass 2. ................................................................. 33

Figure 16. Real time display of the base station computer. The display shows the point cloud data, sonar imagery, GPS status and the navigation camera feed. ................. 35

Figure 17. Integrated lidar and sonar data collected from the USV. The point cloud is colored by elevation. ........................................................................ 36

Figure 18. Colorized 3D point cloud of the T-dock generated using photos taken by the USV. ................................................................. 37
Tables

Table 1. Required sensor capabilities ................................................................. 6
Table 2. SoNAR units evaluated ................................................................. 9
Table 3. LiDAR units evaluated ................................................................. 9
Table 4. Cameras evaluated ................................................................. 11
Table 5. Contact Sensors evaluated ............................................................. 13
Table 6. Vessel platforms evaluated ............................................................ 15
Table 7. USV Enabling Technology Team ............................................. 29
Table 8. Tasks for technical demonstration ............................................... 31
Table 9. Technical demonstration activities and the estimated and actual target times to execute ................................................................. 35
Preface

This study was conducted for the Deputy Assistant Secretary of Defense, Emerging Capability & Prototyping (DASD(EC&P)), as a part of the Joint Capability Technology Demonstration Program, under the Port Improvement via Exigent Repair Remotely Operated Vehicle Enabling Technology (PIER ROV ET) project. Ms. Lenny Lopez was the Oversight Executive for (DASD (EC&P)). Dr. Michael I. Hammons of the U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory (ERDC-GSL) was the Technical Manager, and Mr. William M. Hossley of ERDC-GSL and Mr. Thad C. Pratt of ERDC, Coastal and Hydraulics Laboratory (ERDC-CHL), were the Principal Investigators.

The work was performed by the Structural Mechanics Branch (GSM), Geosciences and Structures Division (GS), ERDC-GSL, the Field Data Collection and Analysis Branch (HNF), and by the Coastal Engineering Branch (HNC), Navigation Division (HN), ERDC-CHL. At the time of publication, Mr. Bradford Steed was Chief, GSM; Mr. James Davis was Chief, GS; and Mr. Nicholas Boone, GZT, was Technical Director, Force Projection and Maneuver Support. The Deputy Director of ERDC-GSL was Dr. William P. Grogan, and the Director was Mr. Bartley P. Durst. Mr. Thad C. Pratt was Chief, HNF, Ms. Tanya M. Beck was Chief, HNC, and Dr. Jackie Pettway was Chief, HN. The Deputy Director of ERDC-CHL was Dr. Kevin M. Barry and the Director was Mr. José E. Sánchez.

COL Bryan S. Green was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director.
## Unit Conversion Factors

<table>
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<th>Multiply</th>
<th>By</th>
<th>To Obtain</th>
</tr>
</thead>
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<td>degrees (angle)</td>
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<td>radians</td>
</tr>
<tr>
<td>degrees Fahrenheit</td>
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<td>degrees Celsius</td>
</tr>
<tr>
<td>Megahertz (MHz)</td>
<td>1.0 E+06</td>
<td>Hertz</td>
</tr>
<tr>
<td>Kilojoules (kHz)</td>
<td>1.0 E+03</td>
<td>Hertz</td>
</tr>
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<td>inches</td>
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<td>knots</td>
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<td>microns</td>
<td>1.0 E-06</td>
<td>meters</td>
</tr>
<tr>
<td>Nanometers (nm)</td>
<td>1.0 E-09</td>
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<tr>
<td>miles (nautical)</td>
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<td>meters</td>
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<tr>
<td>miles (U.S. statute)</td>
<td>1,609.347</td>
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<tr>
<td>miles per hour</td>
<td>0.44704</td>
<td>meters per second</td>
</tr>
<tr>
<td>ounces (mass)</td>
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</tr>
<tr>
<td>pounds (mass)</td>
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<tr>
<td>square feet</td>
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<td>square inches</td>
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<td>square yards</td>
<td>0.8361274</td>
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<tr>
<td>yards</td>
<td>0.9144</td>
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1 Introduction

Background

U.S. Pacific Command (USPACOM) and U.S. Transportation Command (USTRANSCOM) share a common interest in countering anti-access, area-denial (A2AD) threats. A robust, organic capability to rapidly repair degraded ports in strategic locations presents U.S. adversaries with a more complex targeting problem while ensuring agile strategic logistics, namely the ability to discharge strategic sealift vessels at a time and place preferred by logistics planners.

Operators of large port facilities usually perform pier assessments by contracting with an engineering firm to conduct above- and below-water inspections. Trained pier inspectors supported by dive teams usually perform these assessments. Above-water inspections are typically conducted visually from a small vessel, while a dive team performs underwater inspections. The inspectors have no standardized protocols or equipment packages to assess piers other than an inspection checklist and visual observation. These field inspections are used in concert with detailed sketches to generate computer-aided drafting (CAD) drawings of the facilities. The port may also request specific products such as structural capacity calculations, SoNAR scans, LiDAR scans, and repair recommendations. The majority of these inspections/assessments is performed through contracted mechanisms and may take months to complete.

Technologists, engineers and program managers have collaboratively designed a new capability that directly addresses reconnaissance and repair of degraded port infrastructure, whether the degradation is from neglect, natural disaster or enemy action. This report describes the findings of the Port Improvement via Exigent Repair (PIER) Remotely Operated Vessel (ROV) Enabling Technology (ET), the first phase of a three-phase developmental effort, funded through the Deputy Assistant Secretary of Defense for Emerging Capability and Prototyping (DASD (EC&P)) Program. In the PIER ROV ET study, a commercially available small surface remote controlled vessel was integrated with a suite of sensors to optimally facilitate underwater and above water inspection.

The assessment of these types of facilities utilizing the technology developed in the first phase of this study (PIER ROV ET) generates detailed and complete information about the existing structure and the surrounding environment. The second phase of the three-phase approach, called Pre-amble Initial Look Leading to Accelerated Results (PILLAR), will deliver
the mature capabilities required to support a deployed engineering assessment team in the expedient reconnaissance and load-capacity determination of available offload structures. It is sponsored by USTRANSCOM’s Joint Deployment Distribution Enterprise (JDDE) Research, Development, Test and Evaluation (RDT&E) Program.

The capstone effort will be accomplished through the PIER Joint Capability Technology Demonstration (JCTD) in FY 2016 through FY 2019. PIER is planned to develop, demonstrate and transition robust, rapid, innovative repair capabilities for pilings, decking and berthing facilities (pier-side/dockside mooring and fender system solutions only). The program is designed to result in a minimally-capable, militarily strategic port. For the purposes of this JCTD, a “minimally-capable military strategic port” is defined as one which will provide the ability to safely moor and offload/on-load a non-combatant, strategic sealift vessel including Large Medium Speed Roll-on/Roll-off (LMSR) vessels conducting operations via the stern ramp, side ramp and/or ship-board cranes; and dedicated container vessels when employed in conjunction with a suitable crane ship.

Objective

The objective of the PIER ROV ET study was to select, integrate, and demonstrate a small, man-portable, radio frequency (RF) controlled, unmanned surface vessel (USV) with a suite of sensors optimized to collect above- and below-surface georeferenced data and with sufficient fidelity to facilitate a Level 1 inspection of a pier facility. The goal was to develop a prototype survey tool that will allow a small team with minimal equipment to survey a pier facility and produce high quality data in 24 hours. A Level 1 structural inspection consists of visual observations to detect the continuity of all structural members as well as any obvious damage or deterioration.

Approach

A suite of imaging sensors along with geo-positioning instruments and associated digital networking, control, and data storage hardware were selected and integrated to collect georeferenced data both above and below the surface of the water. Additionally, a commercially available RF-controlled surface vessel was selected and modified to serve as a sensor mounting and delivery platform to provide agile maneuverability among complicated structures with low overhangs and tightly-spaced structural members. After iterative testing and optimization of the sensor systems and platform, the system was demonstrated at a port facility to support collection and storage of field data for reconnaissance of pier facilities. The portability of the integrated system allows rapid deployment and data collection by a small team (four people). Data collection can be accomplished quickly, accurately, and efficiently; and, a subject matter expert
(SME), if available, can access the data at the site or the data can be transmitted electronically to a remote SME for analysis as required.

Chapter 2 of this report describes the concept of employment and technical requirements for the system. Chapters 3, 4, and 5 detail the selection and integration of the sensor suite, the selection and modification of the delivery platform, and the method of data collection and storage, respectively. Chapter 6 presents the plans and results of a technical demonstration conducted with the system at a port facility. The effort detailed here is limited to the collection of survey grade data. Processing and organizing the data into final data products will be part of the follow on work.
2 Concept of Employment

Background

This section discusses the concepts related to the development of this capability and the general description of the employment of this assessment tool.

Figure 1 graphically presents the Concept of Operations. Within 24 hours of notification of the need to deploy, Joint Task Force – Port Opening (JTF-PO) personnel and a four member Army Forward Engineering Support Team (FEST) proceed via commercial airlift with all required equipment. The FEST begins work immediately upon arrival employing PILLAR components including a Remotely Operated Vehicle (ROV), LiDAR, SoNAR, and other sensors, material quality and strength testing devices, load assessment tools, and computers enabled with tailored photographic and digital/data analysis applications. This equipment provides rapid, accurate evaluation of conditions above and below the waterline (down to the mud line) without the use of dive teams or boats. The FEST collaborates with engineers at the US Army Corps of Engineers (USACE) Reachback Operations Center (UROC) to develop a tailored repair strategy.

Figure 1. The figure displays a flow chart of the Concept of Employment for the larger JCTD. This Enabling Technology portion is included in 3 Recon and 4 Assess.
Requirements

Platform

The capability of rapid port facility assessment without the use of dive teams or manned vessels requires above and below water, field data collection. Data collection of this type can be accomplished with a remotely operated vehicle (ROV). There are several different types of marine ROVs in use, but most will only collect data below the waterline. The ability to examine the structural elements above the waterline necessitates a surface vessel. A remotely operated surface vessel that can deploy instrumentation above and below water is generally referred to as an unmanned surface vessel or USV. The deployment and operation of a small USV lends itself to a team of no more than four people to transport, setup, survey and send back the data from the assessment. The data collection can be done in a short period of time if the USV operates reliably, sensor data is collected efficiently, and the data can be quickly transferred back to the reach-back operations center.

The solution developed by this study can be deployed by a four person team, is capable of deployment using commercial aircraft, and uses a variety of sensors that can collect data both above and below the waterline.

Sensors

A suite of sensors is required to gather georeferenced data both above and below the water; possible sensors include LiDAR, SoNAR, and digital photographic cameras. Table 1 summarizes the required sensor threshold and objective requirements established for this study.
Table 1. USV list of requirements.

<table>
<thead>
<tr>
<th>Capability</th>
<th>THRESHOLD REQUIREMENT (Minimum)</th>
<th>OBJECTIVE REQUIREMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor ranges should extend across pier</td>
<td>20 m</td>
<td>30 m</td>
</tr>
<tr>
<td>LIDAR should resolve position, spacing, and diameter of piles. Scan should indicate areas with damage to piles and caps</td>
<td>0.5° resolution</td>
<td>0.25° resolution</td>
</tr>
<tr>
<td>Below water sensor should resolve pile integrity</td>
<td>1” resolution</td>
<td>0.5” resolution</td>
</tr>
<tr>
<td>ROV uses remote controls for each motor thrust and direction</td>
<td>1 person</td>
<td>1 person</td>
</tr>
<tr>
<td>ROV should not use Lithium-Ion batteries</td>
<td>Nickel-Metal Hydride batteries</td>
<td>Nickel-Metal Hydride batteries</td>
</tr>
<tr>
<td>ROV contains camera for navigation when not in line of sight</td>
<td>1000 ft range</td>
<td>5000 ft range</td>
</tr>
<tr>
<td>Maintain position lock when ROV is under structure.</td>
<td>60 sec lock</td>
<td>180 second lock</td>
</tr>
<tr>
<td>ROV contains navigation lights</td>
<td>1 light</td>
<td>2 lights</td>
</tr>
<tr>
<td>Hard points on ROV hull to facilitate lifting</td>
<td>4 points</td>
<td>4 points</td>
</tr>
<tr>
<td>Operating in currents representative of inlets and rivers</td>
<td>4 knots</td>
<td>8 knots</td>
</tr>
<tr>
<td>Lasers should be eye-safe</td>
<td>Class 1</td>
<td>Class 1</td>
</tr>
</tbody>
</table>

Transport and Setup

All of the equipment for the USV/sensor system can be prepackaged into a small number of shippable cases or crates. The crew and equipment can be transported to the airport or landing strip nearest the target location via airplane (commercial or military) and then to the site by truck. The setup includes the assembly and initialization of the USV, setup of the base station computer and antennas, power systems initialization (if shore power is not available) and a systems check.
Survey

A necessary step to meeting the requirement is to get information to the SME as quickly as possible. An initial assessment of the area can be conducted in less than an hour to get the first look of the facility back to the SME. The initial assessment can be performed with a hand held GPS-enabled camera to take pictures from the accessible portions of the facility. When this step is complete the team can move on to the full survey using the USV.

The vessel will be deployed from the deck of the structure and controlled via secure Wi-Fi radio. One operator will pilot the vessel while another controls and monitors the data collection instrumentation. It may be necessary for the vessel to navigate and collect data underneath the structure. The data collection operator will see in real time the coverage of the sensors and be able to determine when the survey is complete. For a large port facility this type of survey can be completed in about 6 hours.

Processing and reach back

A significant amount of data processing must be done after the data are collected in order to send back clear and detailed data products to the SME. This includes eliminating erroneous data, collecting and consolidating several datasets, and exporting the data into the final data product. Complete processing of the data may take up to six hours.

The methods used by the team to send this data back to the SME or reach back support staff will be dependent on the site. If there is Internet access at the survey site then the data may be sent back via email or protected file upload/download service such as AMRDEC. If Internet access is not available then the operators may travel to a nearby facility with internet access. If this is still not possible a satellite communications link may be established in order to transmit the data. This part of the operation is not included in the scope of this Pier ROV ET project, but is mentioned here to give the full depiction of the operation. Also, the data transmission, along with the 6 to 12 hours of time for data collection and processing shows the need to compress the data and transmit it in chunks to maximize the time for analysis and follow-on questions between the survey team and SME.
3 Engineering Study Results: Sensors and Integration

Integration concepts

The U.S. Army Engineer Research and Development Center (ERDC) has a well-established practice with remote sensors. The state of the art for this type of integrated, multi-sensor assessment includes the combination of LiDAR and high definition photography for the above water portion and multibeam SoNAR for the underwater portion. There are many types of contact sensors that can be used to assess the various properties of construction materials like concrete, steel and wood. The use of these sensors integrated on a remote vessel was also investigated.

The use of a remote unmanned vessel required an advanced positioning system, secure communications, navigational aids and an onboard computer. The positioning system is as important as the sensors because the vessel will be moving with six degrees of freedom (lat., long., elevation, pitch, roll, and yaw).

Sensors and Equipment Investigated

There were a number of different aspects of the equipment that were important to this investigation and as such many systems were excluded summarily. The components that at first glance seemed to fit our requirements were compiled, investigated and compared. As this integration was aimed at a small, relatively light and agile vessel there were some specific considerations taken for the selection of all the equipment. The criteria for the selection will be discussed more thoroughly in the next section, but will be listed here.

Criteria considered for all equipment:
- Cost
- Size and weight
- Range and resolution (for sensors)
- Power consumption
- Ruggedness
- Software compatibility
Subsurface Sensors

SoNAR is most often used for mapping bathymetry or object detection. In this application we want to use SoNAR to map a large structure with relatively high resolution. Table 2 summarizes the SoNAR units evaluated in this study. There is an inherent trade-off when selecting SoNAR instrumentation. When comparing the frequencies of the different system there is an inherent tradeoff between resolution and range which depends of the frequency. This application requires a SoNAR system that can give the best resolution at a range that makes it operationally applicable. One underwater lidar unit was also tested as it is capable of excellent resolution, although it proved to have too many limitations for use in this application. The underwater lidar requires relatively dark and clear water to be able to function. These conditions are not likely to be met when deploying to a coastal environment.

Table 2. SoNAR units evaluated.

<table>
<thead>
<tr>
<th>Model</th>
<th>Manufacturer</th>
<th>Range (m)</th>
<th>Frequency (KHz)</th>
<th>Resolution (cm)</th>
<th>Weight (lbs.)</th>
<th>Pan/Tilt</th>
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<tr>
<td>MB1</td>
<td>Teledyne Odom</td>
<td>120-240</td>
<td>170-220</td>
<td>3.6</td>
<td>22.5</td>
<td>No</td>
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<td>M3 SoNAR</td>
<td>Kongsberg</td>
<td>150</td>
<td>500</td>
<td>1</td>
<td>10.1</td>
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<td>BV5000-1350</td>
<td>Teledyne BlueView</td>
<td>30</td>
<td>1350</td>
<td>1</td>
<td>21.7</td>
<td>Yes</td>
</tr>
<tr>
<td>ULS-500</td>
<td>2G Robotics</td>
<td>10</td>
<td>LiDAR</td>
<td>.0122</td>
<td>100</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Terrestrial Sensors

Table 3 lists the LiDAR units considered in this study. The laser from the LiDAR system operates at a wavelength suitable for scanning underwater, but will reflect and scatter off of anything it hits including floating particles. The purpose of the testing was to evaluate its ability to collect high resolution data in an environment similar to the application of the USV.

Table 3. LiDAR units evaluated.

<table>
<thead>
<tr>
<th>Model</th>
<th>Manufacturer</th>
<th>Approximate Price ($)</th>
<th>Range (m)</th>
<th>Accuracy (cm)</th>
<th>Weight (lbs.)</th>
<th>Size (in) LxWxH</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiDAR Puck</td>
<td>Velodyne</td>
<td>7,999</td>
<td>100</td>
<td>3</td>
<td>1.8</td>
<td>4x4x3</td>
</tr>
<tr>
<td>HDL-32E</td>
<td>Velodyne</td>
<td>29,000</td>
<td>80-100</td>
<td>&lt;2</td>
<td>2.2</td>
<td>3.4x3.4x5.7</td>
</tr>
</tbody>
</table>
Discussion

The waters of port facilities typically have elevated levels of suspended particles in the water. During the testing, scans were taken in initially clear water. The results were excellent with the laser. After the clear water scans were complete a small amount of kaolinite clay was added into the testing tank. Even with only a very small amount of added particulates to the water column the system’s effective range was significantly degraded. The LiDAR system also had trouble with high ambient light conditions. It was clear that this system was best suited for very dark and clear water (usually very deep water) which is why it was ultimately eliminated for consideration.

There is one underwater LiDAR unit that was of particular interest as it can produce very high resolution. Representatives from 2G Robotics and Teledyne BlueView demonstrated LiDAR and SoNAR systems, respectively, at the Coastal and Hydraulics Laboratory in a side-by-side demonstration of their capabilities. The sensors were evaluated in a basin with controlled turbidity to the water. As expected the LiDAR performance degraded but the SoNAR performed consistently in all of the testing conditions. The ULS-500 Underwater LiDAR was able to capture extremely high quality data from our testing facility, but it showed significant limitations in range and scans took several minutes where the unit had to be kept still.

The SoNAR’s performance was unchanged in all of the testing conditions: light or dark, clear or cloudy water. This is because the sound or acoustic signals produced by the transducer pass through the water and soft particulates until they hit a surface solid enough to cause a strong reflection. The SoNAR could not get the excellent resolution of the LiDAR, but it was clear that it could perform better in this application than the LiDAR. The ability to pan and tilt (or point) the SoNAR quickly in any direction, and also to take 360 degree rotating scans, was advantageous.
Above Water Sensors

LiDAR

The LiDAR can be used to scan the structure and environment above the water surface. There are many different types of LiDAR units available all with somewhat different target applications. The Velodyne instruments appealed to this project right away as their target application is rapid environment mapping and object detection on moving platforms. The Opal-360 is of a similar design. The SICK LM531 is meant to be stationary and track movements in an industrial setting (container yard).

Range and accuracy were the primary criteria for LiDAR evaluation, but size became very important also as some of these units are quite large. Performing a demonstration of these units was not necessary as the experts at CHL have extensive experience working with LiDAR and each of these manufacturers had ample information and data examples readily available. Speaking with the representatives of each of the manufacturers also gave insight into their take on our specific application and how their unit would perform.

High definition photography

Table 4 summarizes the high-definition visible spectrum cameras evaluated in this study. The use of a camera for data acquisition was twofold. The still images, when properly cataloged and geo-referenced, are of great use for someone learning about the sight remotely. Also, photogrammetry analysis can be performed on a large set of geo-referenced photos to create a 3D model of sight that includes color and texture, unlike the point clouds generated from the SoNAR and LiDAR. The point cloud generated from the photogrammetry communicates a greater amount of detail and information, but it is not as accurate as lidar measurements and there are inherent differences between the characteristics of lidar and photogrammetry point clouds.

<table>
<thead>
<tr>
<th>Model</th>
<th>Manufacturer</th>
<th>Approximate Price ($)</th>
<th>Mode</th>
<th>Mega pixels</th>
<th>Weight (oz)</th>
<th>Size (in) LxWxH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hero 4 Black</td>
<td>GoPro</td>
<td>450</td>
<td>3 sec interval</td>
<td>12</td>
<td>3.1</td>
<td>1.2x1.6x2.3</td>
</tr>
<tr>
<td>G700SE-M</td>
<td>Ricoh\Geo-Tactical Solutions</td>
<td>2,095</td>
<td>5 sec interval</td>
<td>16</td>
<td>10</td>
<td>3.4x3.4x5.7</td>
</tr>
</tbody>
</table>
The biggest requirement of the camera was the ability to geotag each photo taken. The geotag is a longitude and latitude record of the cameras location which is stored as part of the same file as the photo. There are many cameras available that use geotags, but the position usually doesn’t update very often. Neither of these two cameras formed the ideal solution of taking and geotagging photos in real time using the vessel’s advanced positioning system to do so, but as discussed below, there is a workable solution for each camera.

Discussion

The GoPro camera was attractive as the HYPACK survey software used to control all of the other instrument functions could also interface with the camera. The GoPro receives a geotag from the software as well, utilizing the high precision GPS already on the vessel. However, the GoPro cannot tag the photos in real time. The geotags must be added after the data collection is complete. Furthermore, the GoPro has a fish-eye lens creating some distortion in the images. This can be corrected, but it introduces some error and additional processing time in the photogrammetry product.

The Ricoh camera is a very versatile unit that has been modified by the company Geo-Tactical Solutions, which specializes in military technology. They have taken the rugged Ricoh camera and added the GPS unit and additional capabilities such as a laser range finder. This camera geotags the photos in real time with a latitude longitude and a compass direction using a GPS unit that updates every second. The GPS unit is not as accurate as the onboard system, but the processing of the photos does not require a very accurate position. The software uses the initial photo positions and orientations to begin “stitching” the photos together into a mosaic. The precision comes from the ability of the software to identify specific points in different photos and then overlay them. The initial positions are used, in effect, as a starting point.

Contact sensors

Many contact sensors were considered for integration with the USV. A contact sensor is an instrument that measure material properties by making physical contact with the material. Six of these sensors are summarized here in Table 5. These were the best of each category of contact sensors as determined from a thorough market survey. The most critical portion of a marine structure is usually the tidal zone or the surf zone; the area around the water surface especially if the water elevation changes often. This area is only accessible by vessel or by diver. Integrating one or more of these capabilities into the USV would eliminate a lot of the diving work that would come later.
Table 5. Contact Sensors evaluated.

<table>
<thead>
<tr>
<th>Name</th>
<th>Manufacturer</th>
<th>Type</th>
<th>Pile Material</th>
<th>Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>IML Resistograph</td>
<td>IML Wood Testing Systems</td>
<td>Drill</td>
<td>Wood</td>
<td>Detailed data</td>
</tr>
<tr>
<td>239A Stress Wave Timer</td>
<td>Metriguard</td>
<td>Stress Wave</td>
<td>Wood</td>
<td>Portable, accurate</td>
</tr>
<tr>
<td>Concrete Test Hammer</td>
<td>Proceq</td>
<td>Rebound Hammer</td>
<td>Concrete</td>
<td>Small, simple operation</td>
</tr>
<tr>
<td>Windsor HP Probe System</td>
<td>NDT James Instruments</td>
<td>Penetration</td>
<td>Concrete</td>
<td>Simple operation</td>
</tr>
<tr>
<td>V-Meter MK IV</td>
<td>NDT James Instruments</td>
<td>Ultrasonic</td>
<td>Concrete, Wood, Ceramic</td>
<td>Detailed data</td>
</tr>
<tr>
<td>Pundit PL-200PE</td>
<td>Proceq Instruments</td>
<td>Ultrasonic</td>
<td>Concrete, Wood, Ceramic</td>
<td>Detailed data</td>
</tr>
</tbody>
</table>

Unfortunately, none of these instruments were suitable for integration with the USV. Each had a difficulty or complexity of operation that would make their use on the USV impossible or ineffective. The only type that could be integrated and used is the rebound hammer or Concrete Test Hammer. This instrument is operated by pressing the nose against the material with force while it takes a reading. The reading from the hammer is the surface strength of the concrete and provides no indication of the condition of the material under the surface. There may be subsurface cracks or voids or problems with the reinforcement that would go undetected. This information can be estimated using condition photos and standard knowledge of concrete structures so it was deemed not useful enough to warrant integration and testing on the USV.

The Resistograph requires drilling into timber piles for which the USV would not be a stable enough platform for this operation. The Windsor Probe works similarly to the rebound hammer, but it drives a spring loaded pin into the concrete material, which again would require more stability than a small craft can offer.

The V-Meter and the Pundit ultrasonic instruments appeared to be the most promising as they produce very good data about the internal characteristics of the material and can be used on concrete, timber and ceramics. Application of the ultrasonic contact transducers requires a clean surface and usually some kind of gel to ensure good contact.

Ultimately it was decided not to use any of these contact sensors on the USV and instead to focus on the integration and use of remote sensors.
Contact sensors may be used by the team by hand, but it was decided that integrating them into the USV would be more trouble than its worth.

Positioning system

The foundation of almost all surface-positioning systems is a GPS signal. This signal is accurate to around 20 feet. To increase this accuracy a second GPS antenna, separated by a distance of at least three feet, is added to obtain differential GPS positioning, bringing the horizontal accuracy to 2 cm in longitude and latitude. However, it does not increase the vertical accuracy. To get precise vertical positioning there are a few different methods to use, but the most common is a Real-Time Kinematic (RTK) signal. This is achieved by interfacing with a known stationary base station and will increase the accuracy of the vertical position also to 2 cm.

Both the SoNAR and LiDAR data accuracy is limited by the quality of the positioning system, and, therefore, positioning on a mobile survey unit is complex and critical. Additionally, intermittent loss of GPS signal can occur due to the proximity of the structure.

To address the problem of GPS loss or degradation due to interference from the structure, an additional navigation aid is necessary. An Inertial Measurement Unit (IMU) uses gyros and accelerometers and magnetometers (sophisticated compass) to track the relative position. The integration of this type of unit provides inertially aided GPS. In the event of GPS loss of degradation the IMU can track the position using internal sensors for a short period of time.

Additional navigation aids can be used also. The most appropriate for this application is a Doppler Velocity Logger (DVL). This device uses acoustic signals to track the bottom and provides a velocity vector that integrates very well with the IMU. The combination of GPS and other navigation aids is generally called an Inertial Navigation System (INS).

To produce this capability, proposals were solicited for the specific application of operating a USV near structures that could cause interference. Details of the positioning system selected will be given in Section 4.

Platform

In order to navigate around and possibly underneath marine structures, and to have a unit compact enough to be packaged and shipped easily, a very small craft is essential. The vessel also needs to be able to carry a significant payload and maneuver in tight areas. Table 6 summarizes four platforms that were considered for this project; images of each platform are in Figure 2.
Table 6. Vessel platforms evaluated.

<table>
<thead>
<tr>
<th>Model</th>
<th>Manufacturer</th>
<th>Approx. Price ($)</th>
<th>Propulsion</th>
<th>Payload (lbs.)</th>
<th>Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kingfisher</td>
<td>Clearpath Robotics</td>
<td>29,495</td>
<td>Electric jet</td>
<td>25</td>
<td>Compact, folds up</td>
</tr>
<tr>
<td>Z-Boat</td>
<td>Teledyne Oceanscience</td>
<td>35,000</td>
<td>2 prop, electric</td>
<td>55</td>
<td>Low profile, maneuverable</td>
</tr>
<tr>
<td>Autonomous Mobile Buoy</td>
<td>EmilyBoats Hydronalix</td>
<td>110,000</td>
<td>gas or electric</td>
<td>35</td>
<td>Endurance, survivability</td>
</tr>
<tr>
<td>WAM-V 12'</td>
<td>Marine Advanced Research</td>
<td>130,000</td>
<td>Dual gas jet</td>
<td>75</td>
<td>Versatility, stability</td>
</tr>
</tbody>
</table>

Figure 2. Vessel platforms considered, clockwise from top left; Kingfisher, Z-Boat, Autonomous Mobile Buoy, WAM-V 12.

Each vessel has excellent maneuverability and would perform well around structures. The comparison of weight capacity, portability, and cost were imperative to deciding the most effective vessel for this initial study.
4 Engineering Study Results: ROV Down-select

Criteria for down-select

For this report the term down-select is being used to describe the decision making process behind the selection of a particular device from the options investigated. At the beginning of Chapter 3 criteria was listed for the selection of the elements that were to be investigated. Discussion of these criteria in more detail will be given here to explain prioritization and why the specific equipment was chosen from each component group. Size and weight, range and resolution, power consumption, ruggedness and software compatibility are the general criterion used in this process. The ideal equipment will be: small and light; has sufficient range with high resolution; has power requirements that can be met by battery packs, has a rating of IP67 (or better) and able to operate in high temperatures, and will work well with the HYPACK survey software.

Size and weight

All of the platforms considered have challenging weight and physical size limitations that affect maneuverability. The fully integrated USV needed to be relatively small and lightweight in order fit and not overload the vessel. The physical characteristics of the SoNAR were as important as its performance as this instrument needs to be partially or fully submerged to operate which made it the most difficult to integrate. Submerging the instrument reduces its effective weight, but a specific mounting and/or control scheme must be fabricated to make this design practical.

Range and resolution

For nearly all remote sensing technologies, range and resolution are inherently connected, as discussed in Chapter 3, SoNAR. To survey the target in an expedient manor a relatively long range is needed so that large areas can be covered quickly. However, higher resolution is needed to give the structural SME the level of detail needed to make an accurate analysis. For this application a minimum range and resolution was set in order to make decisions on equipment. A range of at least 30 meters with a resolution of 1 centimeter or better was required.

Power Consumption

The remote sensing equipment is run on battery. Power consumption becomes important when large structural surveys are considered. If a large
structure requires 5 hours of survey or more, ideally the vessel should be able to operate for that duration, otherwise stopping to change batteries is necessary. This is a large part of the manufacturer’s consideration in designing technology to be used in remote applications. As such, most of the equipment considered had relatively low power consumption, but when many different electronic devices are used simultaneously power consumption and control is a critical factor.

**Ruggedness**

A ruggedness criterion is primarily for the components that are mounted on the exterior of the vessel. For all of the internal components, including the positioning system, the ruggedness is only a concern regarding the operating temperature. All of the SoNAR considered exceeded our needs for these criteria as they are generally made for much deeper applications. For the camera and the LiDAR and the smaller external components this was a critical factor. These components would be exposed to rain, splashing, dust, vibration, etc. The preferred ruggedness of external components was IP67 (International Protection Marking), indicating that the equipment is “dust tight” and “waterproof” to 1 meter submergence or better.

**Software compatibility**

All of the associated software must be compatible with HYPACK survey software in order to reduce operational complexity of the vessel. HYPACK® is a commercial off-the-shelf (OTS) survey software suite that is has widely used since the early 1990’s. It is very flexible and highly compatibility with various instrumentation; however, not every component tested had the drivers (software interface) to connect with the software. This is not much of an issue with the SoNAR and LiDAR as this functionality is one of HYPACK’s® primary applications. Nearly all positioning systems can be integrated; however, there was some difficulty in finding a camera that would synchronize with the rest of the components. Also, some of the equipment considered was very newly available and the drivers for operating them through HYPACK® were still in development.

**Selected Sensors**

**SoNAR**

The SoNAR was the most difficult component to select. There are not many types of SoNAR available that provide adequate, high-resolution 3D scans of structures. Generally, this work is done by divers or by SoNAR imaging. The BlueView® BV5000 (Figure 3) had just become available and it was designed specifically for high definition structural scans. How-
ever, integrating this technology was challenging because the driver for HYPACK was still under development. Ultimately, integration of this technology was leveraged with direct collaboration with the HYPACK development team to ensure a streamlined set up for this application.

Model specifications for the BlueView® BV5000 are given here. A complete list of the specifications of all of the elements can be found in the appendices.
**BV5000 Model BV5000-1350: Specifications**

**SoNAR & Software**
- Sector/Spherical Scan Area (°) 45 - 360
- SoNAR Field of View (°) 45 x 1
- Update Rate (Hz) Up to 40
- Frequency (MHz) 1.35
- Maximum Range 30 m (98 ft.)
- Optimum Range 1 - 20 m (3.2 - 65 ft.)
- Number of Beams 256
- Beam Width (°) 1 x 1

**Mechanical**
- Size (L x W x H in inches) 10.5 x 9.2 x 15.4
- Weight in Air/Water (lbs.) 21.7/8.2
- Depth Rating 300 m
- Communications Ethernet/RS485 (SoNAR/Pan & Tilt)
- Power Consumption (W) 45 max.
- Power Requirement (V DC) 20 - 29

![Figure 3. BlueView BV5000-1350 multibeam mechanically scanning SoNAR.](image-url)
LiDAR

The two smaller Velodyne LiDAR systems were both acceptable for this project (Figure 4). They both collect data in 360 degrees very rapidly with sufficient range. They are IP66 compliant, which is water-tight rather than submersible, but for this particular component this was sufficient. They are compatible and HYPACK. They are the smallest, lightest and least expensive units in the comparison. The HDL-32E was selected over the smaller version because it offered slightly more resolution and range.

*Velodyne HDL-32E LiDAR Specifications*

**Laser**
- Class 1 - eye safety (eye safe at any range)
- 905 nm wavelength
- Measurement range 1m to typically 80–100m

**Sensor**
- 32 laser/detector pairs
- +10.67 to -30.67 degrees field of view (vertical)
- 360° field of view (horizontal)
- 10 Hz frame rate (user selectable, 5-20Hz)
- Accuracy: <2 cm (one sigma at 25 m)
- Angular resolution (vertical) 1.33°

**Mechanical**
- Power: 12V @ 1 Amp
- Operating voltage: 9-32 VDC (volts, direct current)
- Weight: HDL-32E = 1kg (2.2lbs)
- Dimensions: 5.9" height x 3.4" diameter
- Environmental Protection: IP67

**Output**
- Up to 700,000 points/second
- UDP (Universal Data Protocol) packets containing
  - distances
  - calibrated reflectivity
  - rotation angles
The GoPro and Ricoh cameras were inexpensive enough that both were purchased and trialed with the system. The Ricoh’s versatility proved to be more effective for other tasks such as the initial assessment (image in Figure 5). The camera can be used as a hand held to collect images from the accessible portions of the structure and then mounted on the USV for its deployment. Some of the specifications for the Ricoh camera are listed here.

**Ricoh G700SE-M Camera: Specifications**

- **Resolution**: 12.10 million effective pixels
- **Focal Length**: 5.0 mm to 25 mm (5x optical zoom)
- **Recording Mode**: Still, Burst, Skew Correction, Fire, Macro, Video
- **Dimensions**: 118.8mm (W) x 71.0mm (H) x 41.0mm at thinnest
- **Weight**: Approx. 286 g (w/o battery & SD memory card)
- **GPS Accuracy**: 1 - 4 meters

---

*Figure 4. Velodyne HDL-32E LiDAR.*

*Figure 5. Ricoh G700SE-M high definition camera.*
Positioning

The INS from Greensea Systems was designed to provide an accurate position for 100 seconds after the loss of GPS signal (Figure 6). Although this is a limited amount of time to survey in a degraded GPS environment, this was the only system that specified its performance under these conditions. This INS uses dual Trimble GNSS receivers and a KVH inertial measurement unit (IMU). It is compatible with HYPACK and has a small form factor so it could be easily mounted inside the vessel.

Greensea Systems Inc. INS: Specifications

**Gyro — 3 Axis FOG (Fiber Optic Gyro)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum rate</td>
<td>+/- 490°/sec</td>
</tr>
<tr>
<td>Bias stability</td>
<td>0.05°/hr., 1σ (standard deviation) typical</td>
</tr>
<tr>
<td>Bias offset</td>
<td>+/- 2°/hr.</td>
</tr>
</tbody>
</table>

**Attitude**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>+/-90° pitch, +/- 180° roll</td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.2° RMS (root mean square)</td>
</tr>
</tbody>
</table>

**Heading**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>0.3° RMS</td>
</tr>
</tbody>
</table>

Figure 6. Greensea Systems Inc. Inertial Navigation System.

Platform

Once all of the different elements were investigated and the estimate of weight and size was made the Kingfisher did not have the capacity for the needs of this project. Keeping the vessel compact was still a major concern for the transport of the unit so the Z-Boat was selected as it was the next smallest and had sufficient weight capacity (Figure 7). The Z-Boat
also came with the majority of the communications equipment (antennas, radios, etc.) with very little additional cost.

Z-BOAT 1800 Platform: Specifications

**Physical**

<table>
<thead>
<tr>
<th>Hull Length</th>
<th>180cm (5.09ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hull Width</td>
<td>90cm (2.9ft.)</td>
</tr>
<tr>
<td>Weight</td>
<td>30kg (66lb.)</td>
</tr>
<tr>
<td>Payload</td>
<td>20kg (55lb.)</td>
</tr>
<tr>
<td>Hull Material</td>
<td>UV Resistant ABS</td>
</tr>
<tr>
<td>Motor</td>
<td>Z-Boat 1800 High Speed Dual Brushless 24V DC</td>
</tr>
</tbody>
</table>

**Remote**

- Navigation Remote Control Range: 1500 m (1640 yds.) at 2.4 GHz frequency
- Data Telemetry Range: 1 mile at 5 GHz frequency

**Performance**

<table>
<thead>
<tr>
<th>Typical Survey Speed</th>
<th>3-4 kts (1.5-2.0 m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Speed: Z-Boat 1800 High Speed</td>
<td>10 kts (5 m/s)</td>
</tr>
<tr>
<td>Battery Endurance: Z-Boat 1800 High Speed</td>
<td>Up to 240 min.</td>
</tr>
<tr>
<td>Battery Pack: Z-Boat 1800 High Speed</td>
<td>4 x 24V 11 Ah</td>
</tr>
</tbody>
</table>

![Figure 7. Teledyne Oceancience Z-Boat 1800.](image)

Configuration of prototype

Physically integrating all of the elements into the Z-Boat platform required significant design and fabrication work. The BlueView needed to be submerged without any obstructions. Suspending it from the keel of the vessel would cause problems with stability and buoyancy. Mounting it off of
the bow was the only feasible option, but having the SoNAR permanently down in the water would have presented a risk of damaging the transducers during launch and retrieval. The solution was to install a lifting arm with a remotely controlled actuator (as shown in Figure 8) in order to raise the SoNAR out of the water for launch and retrieval and remotely lower it into the water for scanning. Figures 8 and 9 show the fully integrated unit and list the integrated components.

The lidar was mounted up high to give it a clear vantage point. A navigation camera was installed over the front support frame to give the operator a view from the bow. Two GPS antennas were installed 3 ft apart as part of the positioning system. Two antennas, rather than one, with this separation provide the INS with a more precise GPS location (2 cm as opposed to 2 ft). Two communications antennas were mounted on the port side. The forward antenna is for navigation control and the aft antenna is for connectivity to the onboard computer.

Figure 8. The external components of the fully integrated USV are shown here. They are 1) The Z-boat platform, 2) The Velodyne lidar, and, 3) The BlueView sonar. Also the Ricoh camera which is not shown here can be mounted anywhere on the external frame.
Figure 9. The following components are found under the hatch of the USV: 1) Greensea INS, 2) Onboard computer, 3) Battery packs (4-6), 4) Navigation power and control interface, 5) Network switch, and, 6) Power distribution and conversion.

The USV is operated from a remote base station which is shown in the Figure 10. The base station operator can control the computer onboard the USV via Wi-Fi connection.

Figure 10. Base station work space. The base station for this test was aboard a support vessel which also aided in launching and retrieving the USV.
5 Engineering Study Results: Data Capture and Storage

Description of data management

Initial assessment

An initial assessment precedes the data collection from the vessel. It is meant to provide the SMEs with data as quickly as possible so a preliminary analysis can begin prior to the full data collection effort. It also allows the SMEs the opportunity to direct the onsite team to gather additional information in the most critical areas. The assessment consists only of geotagged photos that are input into pre-programmed software that displays the photos along with their location using pre-sourced satellite imagery. This initial product is rather small and can be rapidly transmitted to the UROC. Size of data files was of importance for this Enabling Technology, and more advanced products will render longer transmission timeframes. Improvements to transmission methods were not addressed in this study but will be in future work.

USV survey

All of the data captured by the USV is stored on the vessel using internal solid-state drives (SSDs). Once the vessel is retrieved the data can be transferred to the base computer for post-processing. One goal of this project was to automate the post-processing as much as possible. Post-processing of these types of data can be a subjective procedure. Finding discrepancies in the data and correcting for them is a large part of the process, but by developing filters and step-by-step procedures for processing, much of the subjectivity has been removed. This sped up post-processing and generated a more standardized data product.

Automated processing does, however, leave room for unexpected errors or anomalies that may arise in the survey data. Most of the post-processing effort is eliminating the data points that are a product of noise or interference. To produce a final product that is “clean” and accurate may require many hours of post processing. For this application a large portion of post processing is excluded in order to provide the SMEs with the required information in a rapid manner.
Data Products

**XYZ files**

The output from the SoNAR and LiDAR is a xyz file. This file consists of three number coordinates for millions of points that make up the point cloud. The xyz files can be viewed and edited with a variety of software. This is the primary dataset where the structural engineers can map out the overall design of the pier as well as make measurements of the structural members. The SME can also discern major damage, missing or failed components, details of the surroundings including, depth, scour and other situational concerns.

**Google Earth® photo viewer**

The ERDC has developed a program to interface with Google Earth in order to organize the geotagged photographs into a Google Earth kmz or kml file that shows the user where the photo was taken and also the direction the camera was pointing (if a compass angle was included with the geotag). The user can click on the reference point in Google Earth and view the photo that was taken at that location (Figure 11). This tool makes it very easy to do the initial assessment with photos and run a quick automated program to catalog and reference the photos to be sent back to the SME. This tool also has the option of reducing or compressing the image.

![Figure 11. Shown here is an aerial photo depicting the track of the vessel (left) and the geotagged data product (right). Screenshots were provided through the Google Earth photo viewer.](image-url)
6 Technical Demonstration

A technical demonstration of the operational USV was conducted at a pier facility on 27 April 2016 at the Port of Vicksburg, Vicksburg, Mississippi. The demonstration consisted of deployment of the USV, navigation and data collection of a 50 ft by 160 ft pier. The data was analyzed after the demonstration to assess its quality, but the processing of the data was not included in this demonstration. The demonstration was focused on the capabilities of the integrated sensor package which included the following:

- Multibeam SoNAR - BlueView, BV-5000 3D mechanically scanning SoNAR
- LiDAR Sensor – Velodyne HDL-32E
- High Definition Camera – Ricoh G700Se-M GPS-Enabled Tactical Camera
- Inertial Navigation System – Greensea Inertial Navigation System with 3DM-GX4-25 attitude heading sensor, KVH 1750 fiber optic gyroscope, Trimble GNSS receivers
- Acquisition Platform – Teledyne, Oceanscience Z-Boat 1800S

Purpose

The purpose of the technical demonstration was to show the suitability of various integrated sensors mounted to an unmanned surface vessel platform for scanning above water and underwater structural elements of piers for condition assessments. Table 7 lists the development team personnel at the demonstration.

<table>
<thead>
<tr>
<th>Name</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Michael Hammons</td>
<td>Technical Manager</td>
</tr>
<tr>
<td>William (Matt) Hossley</td>
<td>Technical Management Support</td>
</tr>
<tr>
<td>Thad Pratt</td>
<td>USV Development Team Lead</td>
</tr>
<tr>
<td>Jonathan Marshall</td>
<td>USV Development Team</td>
</tr>
<tr>
<td>William Butler</td>
<td>USV Development Team</td>
</tr>
<tr>
<td>Terry Waller</td>
<td>USV Development Team</td>
</tr>
</tbody>
</table>

Data Collection Site

The technical demonstration was conducted on a pier at the Port of Vicksburg. The pier is roughly 160 ft long and 50 ft deep (Figure 12). There is
a large crane on the deck of the pier for its normal operations. There is a 40 ft wide access bridge for ground transport vehicles. The structure is comprised of concrete piles with some steel bracing and a concrete deck superstructure.

Figure 12. The pier and access bridge at the Port of Vicksburg.

Data was collected using the USV sensors at the pier structure. Stakeholders and the USV Enabling Technology Team observed the testing from a barge moored several hundred feet from the pier (Figure 13).
Figure 13. The pier as seen from the observation barge. Note the deployed USV adjacent to the steel dolphin structure in the center of the photo.

Tasks

The demonstration tasks are shown in Table 8. Tasks 1 - 3 were conducted prior to the technical demonstration. Tasks 4 - 5 were conducted during the demonstration, and Tasks 6 - 7 occurred after the demonstration. The technical demonstration included a presentation describing the sensors selected for the demonstration, the method of data collection from the USV, and examples of processed data.

Table 8. Tasks for technical demonstration.

<table>
<thead>
<tr>
<th>Task</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Deploy USV and collect data on all sensors.</td>
</tr>
<tr>
<td>2</td>
<td>Check data quality and download data</td>
</tr>
<tr>
<td>3</td>
<td>Process data and develop 3D model of test structure</td>
</tr>
<tr>
<td>4</td>
<td>Technical demonstration for Stakeholders</td>
</tr>
<tr>
<td>5</td>
<td>Present processed data to Stakeholders</td>
</tr>
<tr>
<td>6</td>
<td>Structural engineers evaluate data suitability</td>
</tr>
<tr>
<td>7</td>
<td>Report of findings</td>
</tr>
</tbody>
</table>
Data Collection

The data collection process included three passes of the USV near the piles of the pier (Figures 15 and 16). Pass 1 collected data continuously as the USV passed around the outer edge of the entire structure (Figure 15, left). Pass 2 navigated the USV under the structure between pile bents to demonstrate its ability to survey with degraded GPS signal (Figure 15, right). Pass 3 (Figure 15, bottom) collected data from several stationary vantage points around the structure. This method utilized the 360° scan ability of both the lidar and sonar.
Figure 15. A depiction of the three collection methods employed during the technical demonstration at Vicksburg Harbor. The blue arrows show the path of the vessel during collection. Number 3 shows several points where the vessel collected 360° data.
Figure 16. USV in close passes of the Vicksburg Harbor T-dock. Left: USV during pass 1. Right: USV during Pass 2.

During each method of collection the operators were monitoring the data collection of the vessel in real time from the base station computer. The display of the base station is shown in Figure 17.
Figure 17. Real time display of the base station computer. The display shows the point cloud data, sonar imagery, GPS status and the navigation camera feed.

Results

Operation

A breakdown of tasks that were demonstrated is shown in Table 9 and includes a target time goal as a metric for success and the actual time for completion. The duration and schedule of the activities were performed this way to give the observers an idea of how quickly this operation could be completed based on early estimates. The times required to perform the passes indicate that the scan of a large pier could be done in a 4- to 6-hr window. An initial scan of a pier could be done first using the Pass 1 method. This would allow data collection to continue while the initial data is transmitted. This initial assessment would be used to identify areas of concern where additional scans and photographs would be needed.

The actual times of completion for the demonstration were 5 minutes for Pass 1, 5 minutes for Pass 2, and 15 minutes for Pass 3. Passes 2 and 3 were truncated due to an incoming thunderstorm. In Pass 2, the USV made only one pass under the deck of the access bridge on the land side of the pier. In Pass 3, the arrival of a thunderstorm resulted in stopping all data collection after the third stationary position of the eight planned locations.

Table 9. Technical demonstration activities and the estimated and actual target times to execute.

<table>
<thead>
<tr>
<th>Task</th>
<th>Activity</th>
<th>Target Time, min</th>
<th>Actual Time, min</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Deploy USV in water. Activate electronics, connect SoNAR head, check out motors, lower into water</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>Activate sensors</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Test remote control and boat maneuverability</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>Pass 1</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>Pass 2</td>
<td>30</td>
<td>5*</td>
</tr>
<tr>
<td>6</td>
<td>Pass 3</td>
<td>45</td>
<td>15*</td>
</tr>
<tr>
<td>7</td>
<td>Retrieve USV. Save data, deactivate sensors. Secure USV on boat.</td>
<td>15</td>
<td>10</td>
</tr>
</tbody>
</table>
*Pass 2 and Pass 3 were shortened due to inclement weather.

**Data Collected**

Figure 18. Integrated lidar and sonar data collected from the USV. The point cloud is colored by elevation.

Figure 18 shows a processed point cloud generated from the lidar and sonar data. Every pile was mapped from the deck down to the mud line, although some piles have limited data below water due to the limited time of collection. There is a visible gap between the lidar and sonar data. Neither the lidar nor sonar can collect data at the water line and just below it which creates the gap seen in the point cloud.
Figure 19. Colorized 3D point cloud of the T-dock generated using photos taken by the USV.

Figure 19 displays a point cloud generated from photos taken with the Ricoh camera from the USV. The photos have been used in a process called photogrammetry which is the digital stitching of the photos to match pixels and convert them into three dimensional points with a color value. Photogrammetry is not as accurate as lidar data, but it includes the colorized appearance of the target which provides an indication of the condition of the structure.

Processing of the data sets to produce these point clouds was not included in this demonstration, but was completed afterwards for this report.

Findings

The prototype USV is small and man portable (2-man carry). It can operate in calm water for up to 4 hours before changing battery packs. It was able to deploy and perform a limited survey of the T-dock structure at the Vicksburg Harbor and be retrieved in 65 minutes. The USV was able to collect high fidelity, georeferenced data above and below the water surface. This data includes a 2-cm accuracy point cloud of the structure and surrounding area, hundreds of high definition photos and a colorized point cloud generated by photogrammetry.

The data collected clearly depicts the structural members for identification, mapping and measurement from the point cloud. Also, the photographs collected give a clear understanding of the structure’s condition above the water. However, the ability to discern the condition of the structure underwater may be lacking compared to a conventional Level 1 survey. The piles were detected to the mud-line, but if any cracking or minor section loss was present, it would not show in the dataset.

Passes 1 and 3 were performed successfully and the data collected was of sufficient quality. Pass 2 was navigated successfully, but the data collected was not of sufficient quality as the Greensea INS was not able to record the position accurately under the dock. The loss of GPS signal due
to interference of the structure was expected and the Greensea INS was designed to perform under this condition, but it did not perform successfully for this portion of the technical demonstration.
7 Summary

The objective of the PIER ROV ET study was to select, integrate, and demonstrate a small, man-portable, radio frequency (RF) controlled, unmanned surface vessel (USV) with a suite of sensors optimized to collect above- and below-water georeferenced data with sufficient fidelity to facilitate a Level 1 inspection of a pier facility. The prototype described in this report has demonstrated these capabilities.

Performance of the USV

The prototype USV was able to deploy and perform a limited survey of the T-dock structure at the Vicksburg Harbor and be retrieved in 65 minutes. The USV was able to collect high fidelity, georeferenced data above and below the water surface. Analysis of the data showed that collection using the methods from Passes 1 and 3 produces sufficiently accurate point cloud information, but surveying under the structure as in Pass 2 did not produce sufficiently accurate data.

The data produced by the vessel is complete and detailed enough to meet the requirements of a Level 1 inspection on all counts but one. The sonar data does not have a high enough resolution to depict the condition of the underwater structure, although it clearly shows the shape and continuity of the piles. Reporting structural condition on a Level 1 survey is limited to major defects or section loss and undermining. The sonar can detect undermining, but most defects and minor section loss cannot be evaluated.

Areas for improvement

Navigation of the vessel around and underneath the structure was successful, but due to the extensive footprint of the equipment on the platform there was very little freeboard. The small freeboard of the vessel also limits the conditions the vessel can operate in. This issue will need to be addressed in follow on work.

Performance of the positioning system and the SoNAR were good, but more time to optimize these parts of the system is needed. In particular, data collection from the SoNAR near its maximum range was lacking precision. Limiting the range of acquisition (which is allowable in the software) will need to be investigated.

The methods of deployment and retrieval of the vessel was not a major area of concern in the ET, but these tasks were necessary for the tech-
technical demonstration. It became clear that alteration of the vessel to add lifting points would help to facilitate deployment and retrieval from a crane.

As shown in Figure 17, the internal equipment is enclosed in a relatively small space and there is no external air circulation. Some of the ports on the network switch burned out due to high ambient temperature. This component will need to be replaced with a switch that can perform at higher temperatures.

Future work

The PIER ROV ET was the first phase of the USV development. The next phase will continue in the PILLAR (Preamble Initial Look Leading to Accelerated Results) program. PILLAR will include the development of data processing techniques, data transmission technology, instructional material, and a training course. There will also be room to address the concerns stated above. Collaboration with the structural engineers who will evaluate the need for repairs will be integral to optimizing the workflow from survey to evaluation. Two evaluated demonstrations are planned which will display these developments.
Appendix A: Equipment Specifications

BV5000 Model BV5000-1350 S3 Series: Specifications

Teledyne BlueView Headquarters

18702 North Creek Parkway
Suite 100
Bothell, WA 98011
Tel: +1.425.492.7400
Fax: +1.425.492.7401

SoNAR & Software

Sector/Spherical Scan Area (º) 45 - 360
SoNAR Field of View (º) 45 x 1
Update Rate (Hz) Up to 40
Frequency (MHz) 1.35
Maximum Range 30 m (98 ft.)
Optimum Range 1 - 20 m (3.2 - 65 ft.)
Number of Beams 256
Beam Width (º) 1 x 1
Beam Spacing (º) 0.18
Time Resolution 0.015 m (0.59 in.)
Data Output Format .son, .off, and .xyz files

Mechanical

Size (L x W x H in inches) 10.5 x 9.2 x 15.4
Weight in Air/Water (lbs.) 21.7/8.2
Depth Rating 300 m
Coms (SoNAR/Pan & Tilt) Ethernet/RS485
Power Consumption (W) 45 max.
Power Requirement (V DC) 20 - 29
Velodyne HDL-32E LiDAR Specifications

Velodyne Acoustics, Inc.
345 Digital Drive
Morgan Hill, CA 95037
408.465.2800

Laser
- Class 1 - eye safety
- 905 nm wavelength
- Time of flight distance measurement with Calibrated Reflectivities
- Measurement range 1m to typically 80–100m

Sensor
- 32 laser/detector pairs
- +10.67 to -30.67 degrees field of view (vertical)
- 360° field of view (horizontal)
- 10 Hz frame rate (user selectable, 5-20Hz)
- Operating temperature -10° to +60° C
- Storage temperature - 40° to 105° C
- Accuracy: <2 cm (one sigma at 25 m)
- Angular resolution (vertical) 1.33°
- Integrated web server for easy configuration

Mechanical
- Power: 12V @ 1 Amps
- Operating voltage: 9-32 VDC
- Weight: HDL-32E = 1kg (2.2lbs); Cables = 0.3kg (0.62lbs)
- Dimensions: 5.9" height x 3.4" diameter
- Shock: 500 m/sec² amplitude, 11 milliseconds duration
- Vibration: 5 Hz to 2000 Hz, 3G RMS
- Environmental Protection: IP67

Output
- Up to 700,000 points/second
- 100 Mbps Ethernet connection
- UDP packets containing
  - distances
  - calibrated reflectivities
  - rotation angles
- Orientation - internal MEMS accelerometers and gyros
  for six-axis motion correction
• GPS time-synchronized with included GPS Receiver

Ricoh G700SE-M Camera: Specifications

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>12.10 million effective pixels</td>
</tr>
<tr>
<td>Focal Length</td>
<td>5.0 mm to 25 mm (5x optical zoom)</td>
</tr>
<tr>
<td>Memory Source</td>
<td>SD Card, SDHC Card, SD Worm Card</td>
</tr>
<tr>
<td>Recording Mode</td>
<td>Still, Burst, Skew Correction, Fire, Macro, Video</td>
</tr>
<tr>
<td>Video Mode</td>
<td>Up to 1280x720 pixel high-quality video</td>
</tr>
<tr>
<td>Geocoding</td>
<td>Stills and Video, Stills with Sound</td>
</tr>
<tr>
<td>Voice Annotation</td>
<td>16 seconds of sound per image</td>
</tr>
<tr>
<td>LCD Screen</td>
<td>Large 3.0” TFT LCD monitor</td>
</tr>
<tr>
<td>Dimensions</td>
<td>118.8mm (W) x 71.0mm (H) x 41.0mm at thinnest</td>
</tr>
<tr>
<td>Weight</td>
<td>Approx. 286 g (w/o battery &amp; SD memory card)</td>
</tr>
<tr>
<td>Power Source</td>
<td>Rechargeable Battery (DB-65) x1, AAA</td>
</tr>
<tr>
<td>Alkaline x2</td>
<td></td>
</tr>
<tr>
<td>GPS</td>
<td>WAAS/EGNOS/MSAS enabled</td>
</tr>
<tr>
<td>GPS Accuracy</td>
<td>1-4 meters, 2D RMS, WAAS enabled</td>
</tr>
<tr>
<td>GPS Acquisition</td>
<td>Time 1 sec (hot); 38 sec (warm); 42 sec (cold)</td>
</tr>
<tr>
<td>Data Transfer</td>
<td>USB, Bluetooth, EyeFi/Wi-Fi, WAN/LAN, Radio</td>
</tr>
</tbody>
</table>
Greensea Systems Inc. INS (positioning): Specifications

Greensea Systems, Inc.
10 East Main Street: PO Box 959
Richmond, Vermont 05477
802.434.6080

Gyro — 3 Axis FOG
- Maximum rate +/- 490deg/sec
- Bias stability 0.05deg/hr, 1σ typical
- Bias offset +/- 2deg/hr

Acceleration — 3 Axis
- Maximum range +/-2g
- Bias stability <0.05mg, 1X typical
- Bias offset +/-2 mg

Attitude
- Range +/-90deg pitch, +/- 180deg roll
- Accuracy 0.2deg RMS

Heading
- Accuracy 0.3deg RMS

Velocity — with 1200k Hz DVL integrated or external
- Accuracy +/-0.02m/s
- Resolution 0.001m/s
- Bottom tracking range 0.2m-50m

Depth
- Accuracy +/-0.1%FS,
- Resolution .0002%FS
- Range 100bar (1000m)

Positioning — with 1200kHz DVL integrated or external
- Accuracy 0.3% dt RMS
- Resolution 0.05m
Z-BOAT 1800 Platform: Specifications

Oceanscience, Teledyne Inc.
14020 Stowe Drive
Poway, CA 92064
USA
(760) 754-2400

General Specifications

- Oceanscience
- 2245 Camino Vida Roble, Ste. 100
- Carlsbad, CA 92011 USA
- T: (1) 760-754-2400
- F: (1) 760-754-2485
- E: info@oceanscience.com

Physical

- Hull Length 180cm (5.09ft.)
- Hull Width 90cm (2.9ft.)
- Weight 30kg (66lb.)
- Payload 20kg (55lb.)
- Hull Material UV Resistant ABS
- Motor Z-Boat 1800 High Speed Dual Brushless 24V DC Out-drives

Remote

- Navigation Remote Control Unit Hitec with vessel telemetry
- Navigation Remote Control Unit Frequency 2.4GHz FHSS
- Navigation Remote Control Range 1500m (1640 yd)
- Data Telemetry Range ~ 5 GHz ~ 1 mile

Performance

- Typical Survey Speed 3-4 kts (1.5-2.0 m/s)
- Top Speed: Z-Boat 1800 High Speed 10 kts (5 m/s)
- Battery Endurance: Z-Boat 1800 High Speed Up to 240 min.
- Battery Pack: Z-Boat 1800 High Speed 4 x 24V 11 Ah