Development of a Robust Line Capture, Line Recovery (LCLR) Technology for Autonomous Docking of AUVs

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***Abstract*—As AUVs continue to gain popularity around the world, the need for robust launch and recovery methods is growing as well. Larger vehicles with more capabilities are much more difficult to safely recover post-mission than smaller man-portable systems. Line Capture Line Recovery (LCLR) combines several key technologies developed by the Woods Hole Oceanographic Institution (WHOI) and provides the user with flexibility in terms of pick-up location and retrieval methodology. One of these key technologies is Digital Ultra-Short Baseline (D-USBL) navigation and homing. D-USBL acoustic navigation allows the vehicle to detect and home in on an acoustic transponder suspended from a vertical line. Once the line is intercepted and captured by the LCLR nose, the vehicle can be safely recovered in a variety of ways - even from a moving vessel. LCLR presents many operational benefits including moored-mission pause, robust sea-floor docking, and fully automated launch and recovery. WHOI and Hydroid are both currently incorporating LCLR into advanced launch and recovery systems which will enable fully turnkey operation of their AUVs. This will reduce the burden on the human operators and will even allow unmanned boats or vehicles to deploy and recover AUVs in virtually any area of interest.**

Keywords—LCLR; Line Capture; Line Recovery, Docking, Launch & Recovery; AUV; REMUS; Navigation; USBL; D-USBL;

I. INTRODUCTION

Autonomous underwater vehicles (AUVs) have become a mainstay in the fields of oceanographic research and defense. Their missions are usually well defined; typically, “mowing the lawn” with raster patterns designed to survey large areas that manned vessels either cannot or should not enter because of denied space or simply the cost of operation. AUVs have truly revolutionized these fields, however they still require a man-in-the-loop for deployment and recovery. A typical mission starts with launching the vehicle, either by crane, stern ramp, or simply pushing the vehicle overboard. The vehicle then goes about its mission while the support vessel waits or goes on a brief excursion. At the end of the mission the vessel must return to a predetermined location to perform a manned recovery of the vehicle. This is typically done with a grapple to a float-released line and a Launch and Recovery System (LARS), crane, or a diver/swimmer assist.

The LCLR concept is a product of multiple technologies developed by the Oceanographic Systems Laboratory (OSL) group at the Woods Hole Oceanographic Institution (WHOI) with funding from the Office of Naval Research and the Naval Undersea Warfare Center at Newport, Rhode Island. LCLR combines the proven Digital Ultra-Short Baseline (D-USBL) navigation and homing techniques with whisker-and-wire capture to redefine the end-of-mission steps of AUV operation. This not only provides the operator with flexibility in terms of pick-up location, but also enables new opportunities such as moored-mission pause, robust sea-floor docking, and fully automated launch and recovery.

II. HISTORY / EARLY DEVELOPMENT

Development of key technologies for LCLR were started during the earlier design of underwater docking systems and ship-mounted AUV launch and recovery systems. The OSL group at WHOI developed the first REMUS 100 seafloor dock in 1996 [2]. The AUV was programmed to swim along a track-line toward the dock, which had a large conical opening. The AUV used a nose-mounted, four-channel, diamond configuration, D-USBL acoustic array to determine its relative position to the fixed dock. A transducer on the seafloor dock would ping in response to acoustic pings from the approaching AUV. After receiving a return, the USBL array provided both azimuth and elevation angles to the dock. With each position update, the AUV would adjust its flight to maintain an approach to the seafloor dock along the planned path and gradually descend to the dock cone depth like an airplane approaching a landing strip. A later REMUS 100 seafloor dock included a rugged stab connector that improved battery charging and data transfer capabilities and acoustic communications provided transfer of seafloor dock critical parameters, such as depth and orientation, to the AUV [4].

In 2011 Hydroid applied the seafloor docking concept to moving vessel capture [7]. The Mobile Underwater Docking initiative used a REMUS 100 with the same diamond-pattern D-USBL to home in on a transponder housed in a PVC cone towed behind a vessel on a V-Wing depressor as shown in Figure 1.

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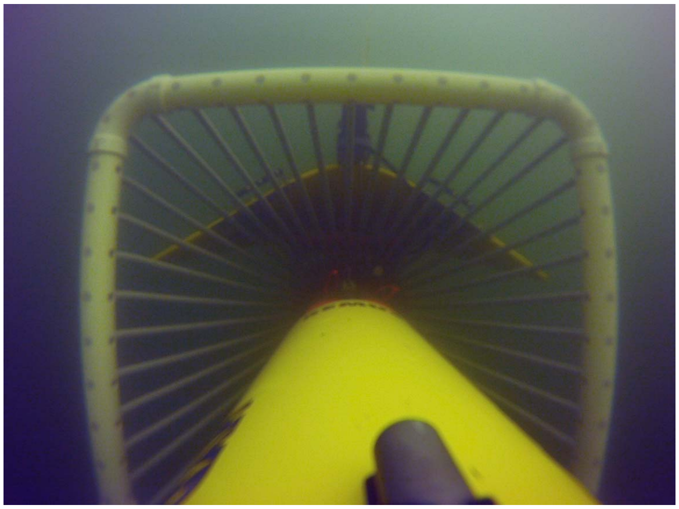

Figure 1. REMUS 100 Mobile Underwater Docking

OSL developed A-frame style launch and recovery systems for the REMUS 600, 6000 and 2500 AUVs [5]. In both cases recovery required grappling for a tethered float released from a surfaced AUV. The float tether was then attached to the docking head winch line and the AUV was recovered onto the vessel. Thousands of launches and recoveries have provided observations of the dynamics involved in these operations. A few recoveries have provided an understanding of the damage that can occur to the AUV as well as lost survey time that can occur when the process does not go as planned.

Kongsberg has also developed launch and recovery systems for the HUGIN AUVs. These launch and recovery systems also require grappling for a tethered float, but deploy a tray assembly into the water to recover the AUV. The float tether is attached to a recovery system winch that allows the AUV to be pulled up the tilted tray which then secures the vehicle.

The first LCLR work was accomplished with a REMUS 100 AUV. The diamond configuration D-USBL array was replaced with a four-channel linear array to provide improved azimuth resolution. In addition to the D-USBL array, the vehicle nose was fitted with motor-driven whisker and latch assemblies, Figure 2. The capture aperture was eight inches.

Figure 2. REMUS 100 Line Capture Nose

The transducer, to which the AUV homes, was mounted on a battery operated towfish. Initial tests were conducted with the towfish on a fixed mooring and then the towfish was deployed from a moving vessel. Considerable testing was completed to refine software controlling vehicle performance during approach, after capture, and after a miss. The capability to capture has been demonstrated from multiple platforms, one of which is shown in Figure 3.

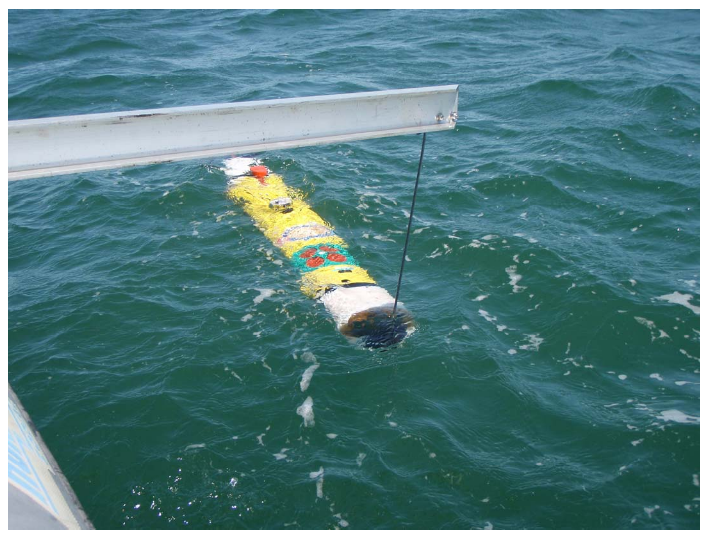

Figure 3. REMUS 100 on Surface After Docking to Capture Line

III. LCLR SYSTEM COMPONENTS

Although REMUS 100 was used almost exclusively during the early development of LCLR, typical systems are now employed on REMUS 600 AUVs. An LCLR system, shown in Figure 4, consists of an acoustic transponder attached to a line

(1) such as wire rope, EM cable, or synthetic rope and a vehicle equipped with an LCLR nose (2). The LCLR nose contains a linear D-USBL receiver used for homing and a pressure-compensated capture-drive which consists of two motorized whiskers to increase the aperture for capture, a titanium latch with integral optical line sensor, CT sensor, and, optionally, a forward-looking sonar and ascent weight release. The acoustic transponder can take many forms, but always contains a cylindrical transducer which listens for interrogation pings from the vehicle and responds with another ping that the vehicle then uses to home in and capture using the D-USBL receiver.

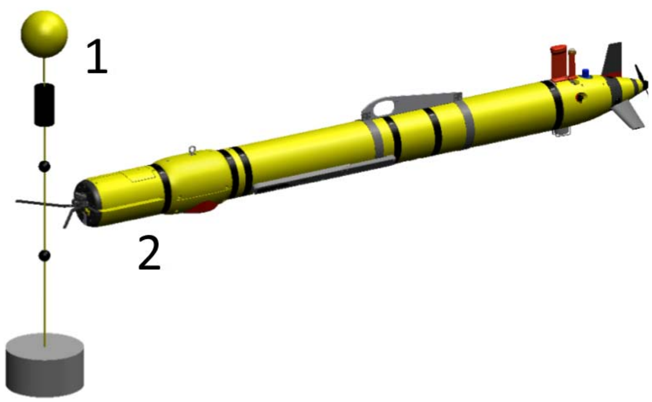

Figure 4. REMUS 600 LCLR System

The D-USBL receiver was developed at WHOI and licensed for production to Hydroid, Inc. This receiver is a potted assembly which consists of a four-channel linear hydrophone array with an integral receiver/processor circuit board, Figure 5. This board performs the analog signal amplification and conditioning, A/D conversion and digital signal processing to detect the incoming signal and estimate its time of arrival and azimuth angle. An RS-232 interface is provided to control the array and read the results [6].

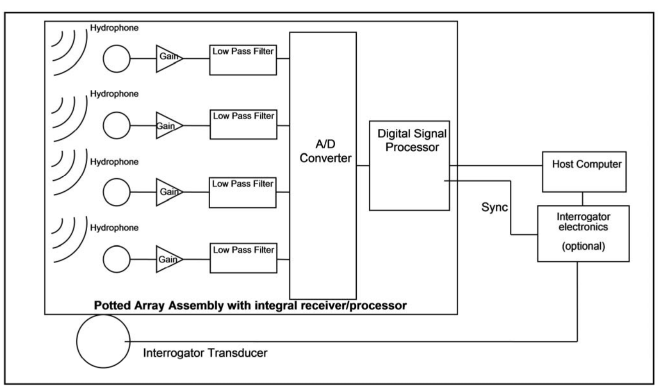

Figure 5. D-USBL Block Diagram

Digital Ultra-Short Baseline acoustic navigation is based on the principles of array processing. As sound waves pass across an array of closely spaced hydrophones, the relative phase differences across the array may be measured and act as an indication of the bearing of the incoming signal. Also the time delay between the interrogation ping and the receipt of the response can be used to estimate the range. The D-USBL array includes four hydrophones arranged in a linear configuration, such that they may estimate the range and bearing to the transponder [6]. The vehicle calculates the difference between this bearing and the vehicle heading and attempts to drive this to zero with its rudder control as it approaches the transponder. If there is a temporary loss of D-USBL pings due to blockage or sound velocity issues, the vehicle falls back on its navigation solution which either comes from an Inertial Navigation System (INS) or Doppler-Velocity Log (DVL) dead-reckoning. This keeps the vehicle on-course until D-USBL pings and homing can resume.

IV. CONCEPT OF OPERATIONS

The concept of operation (CONOP) can begin with a variety of initial conditions and reasons to use LCLR over the conventional means of recovery. These include, but are not limited to – facilitated manned-recovery, non-geo-located missions, hazardous weather, recovery from a moving vessel, denied areas, under-ice [1], etc. In all of these cases the need exists to either capture or recover the vehicle until further intervention can be performed.

The first step to initiate an LCLR event is to deploy the acoustic transponder into the water. This can be done prior to the mission at a predetermined location, or at end-of-mission from a stationary or moving vessel. As long as the vehicle is within ACOMMS range it can be commanded to drive toward the transponder by sending the start approach command along with the current transponder GPS location. The vehicle then uses D-USBL homing along with its navigation solution to set a course towards the transponder and home in and capture the line. As the vehicle approaches the transponder it deploys its whiskers to increase the aperture for capturing the line, Figure 6. Simultaneously, a latch mechanism is also opened.

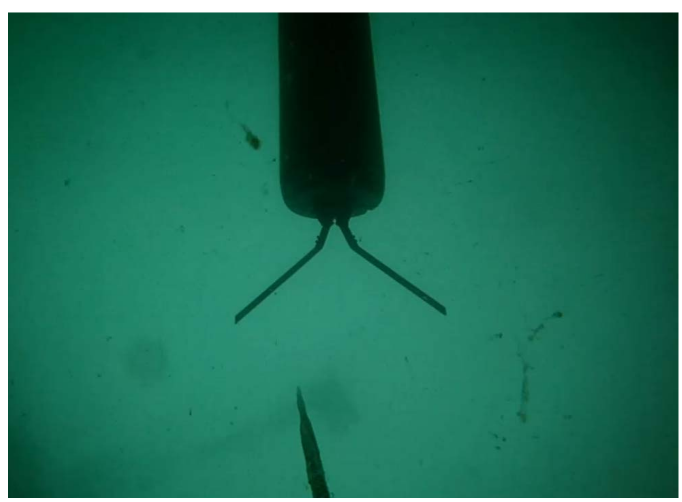

Figure 6. REMUS 600 Approaching Line for Capture

When the line is intercepted, an optical sensor detects the presence of the line and the latch is closed around the line. Once captured, the vehicle can remain on location, or, the line, transponder, and the attached vehicle can be recovered onto a manned vessel, an unmanned surface vessel (USV), or any other platform. The vessel or platform may be stationary or moving, as in Figure 7, during the capture process.

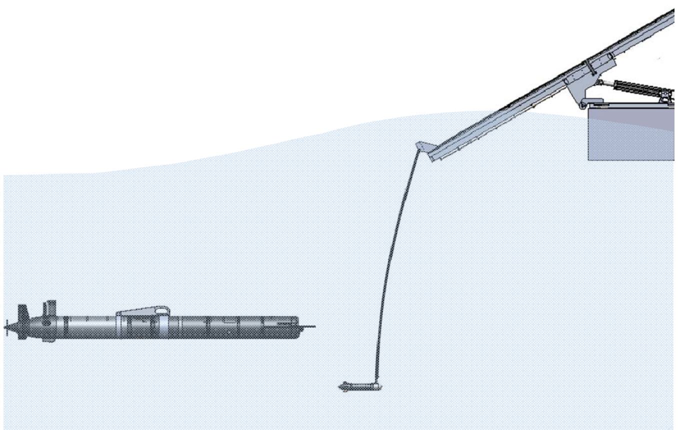

Figure 7. REMUS 600 LCLR Moving Vessel Recovery

The whiskers are designed to break away in case of accidental collisions with hard objects such as rocks or ship hulls. This is accomplished using two nylon screws that hold each whisker arm to its base. In the event of a collision the tensile strength of the bolts is exceeded and the whisker breaks off, preventing damage to the internal motors and gear-train.

V. OPERATIONAL BENEFITS

In addition to launch and recovery, LCLR could be used to increase the persistence of an AUV through the use of a dock. Multiple docks exist where the vehicle homes in and then swims into a cone or net [1] which captures the vehicle and, in some cases, a "stab" connection provides electrical power for battery charging and a wired Ethernet port for data communications. These systems are typically quite large due the size of the aperture required for successful docking and can require two-dimensional navigation. If a floating or subsea dock were equipped with an LCLR transponder on a line, an AUV could home in and capture a line simply using azimuth bearings and an approximate altitude, then be winched down to a compact cradle. Once docked in the cradle the vehicle could be charged and offloaded via a traditional stab connection or a wireless power transfer system with high-speed optical data communication system. With current inductive charging methods approaching 90% efficiency and free-space optics exceeding 100Mbps bandwidth, a docked vehicle could recharge itself for another mission and download terabytes of data without a human or ship in the loop in a matter of hours. This would create larger areas of operation for AUV surveying missions and could create observatories that are constantly patrolled by AUVs [8].

Further operational benefits from LCLR can be gained by allowing AUVs to be captured or recovered well below the surface. High winds and seas make operations on the surface difficult or impossible, and AUV missions are often canceled or cut short in these conditions. In most cases, the AUV could otherwise perform its mission but the problems arise when the mission is complete and the vehicle needs to be recovered. Using LCLR technology, an operator could command the AUV to latch on to a moored line underneath the orbital motion of the waves where it can safely wait in a low power state until the surface vessel can return. When the team returns after the storm, an acoustic signal could command the AUV to release its latch and come to the surface for recovery.

In another scenario, the AUV could be told to latch on and listen for acoustic queues from the environment similar to a sonobuoy. Once it detects an event it could release from the line and either investigate the source of the event or go to the surface to report it.

The ability to insert a long pause into the mission could solve many weather-related mission problems and adds a "wait and see" feature for missions with temporal uncertainly.

VI. CURRENT & FUTURE WORK

Hydroid and WHOI are currently using LCLR to simplify manned recovery of REMUS 600 AUVs and in the development of fully autonomous deployment, recovery, and sustainment systems for multiple commercial and military platforms.

For manned recovery, the LCLR transponder is typically deployed on a line from a crane of a large ship and the vehicle is commanded to approach and dock onto the line from its current location nearby. Once captured, an alert is sent over ACOMMs which tells the operator that the capture was successful. Then a special latch allows the transponder to fall away to a safer distance further down the line while the vehicle is recovered by crane or LARS.

In another program LCLR is used as part of a fully automated launch and recovery system for REMUS 600 AUVs. In this system the LCLR transponder is towed from a surface vessel while the AUV homes in and ultimately captures the tow line just above the transponder. Once captured, an automated stern-ramp type LARS pulls the vehicle onboard with zero human intervention. This was successfully demonstrated in 2016.

LCLR is also incorporated in an undersea docking system which uses a floating transponder to provide a homing and communications link with the vehicle. Once the vehicle has homed in and captured the line, it is pulled down into a cradle and charged through a wireless power transfer system and survey data is offloaded through a high-speed free-space optical system.

The goal in all of these further LCLR developments is to enable fully turnkey AUV systems from transom-to-transom and port-to-port and thereby eliminate the risks and expenses of manned launch and recovery.

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