TOWARDS A UUV LAUNCH AND RECOVERY SYSTEM ON A SLOWLY MOVING SUBMARINE

R. A. Irani, **D. Kehoe** and **W. W. Spencer**, Rolls-Royce Canada Limited
G. D. Watt, Defence Research and Development Canada – Atlantic (DRDC), Canada
C. Gillis, J. A. Carretero, and **R. Dubay,** Dept. of Mechanical Engineering, University of New Brunswick (UNB), Canada

SUMMARY

Unmanned Underwater Vehicles (UUVs) will play important roles in future naval operations by mitigating risk during dangerous tasks such as mine hunting and reconnaissance missions. However, a reliable UUV launch and recovery system (LARS) for naval platforms, especially submarines, has yet to be developed. This paper summarizes work on a Defence Research and Development Canada project to develop such a system for submerged slowly moving submarines under waves [1] and adapts the active dock from this work to concepts for a small UUV LARS installed under the deck but outside the pressure hull of a generic 70 m long diesel submarine. The LARS is located in free flooding, plausibly sized cargo space aft of the submarine's sail. The current paper focuses on system design considerations and LARS characteristics particular to UUV deployment from submarines. A range of UUV sizes are considered to highlight various system limitations and advantages, and various charging and data transfer possibilities that can be integrated into the cargo hatch are discussed. The goal is to explore the various technical issues a UUV/submarine LARS system faces to provide guidance for future UUV deployment strategies.

1. INTRODUCTION

Submarines that can deploy unmanned underwater vehicles (UUVs) expand their operational capabilities and reduce operational risk. However, a major roadblock to successful deployability is the current inability to recover UUVs to the host submarine in a reliable, timely, and covert manner. This is particularly true for diesel submarines operating in littoral waters where, because of their smaller size and proximity to the surface, they are much more subject to sea state effects than larger boats. Environmental disturbance, navigational error, position sensing error, and the need for covert underwater autonomous operations all complicate the UUV recovery problem.

This problem was discussed in detail by Watt et al. [1]. They noted that stationary UUV docks use funnels and broadcast a signal for the UUV to home on. This has the advantage that infrastructure on the UUV dedicated to docking is minimized, which is beneficial since this infrastructure must be carried throughout the UUV's mission, potentially compromising its endurance or increasing its size. The disadvantage of stationary docking is that the UUV must not only hit a 3D point in space within a certain tolerance but must also be coaxially aligned with the funnel well enough that the UUV is guided to the latch at the funnel apex rather than just bounce off the funnel side. Some docking methods incorporate a latch or hook to the UUV which is deployed when docking and used to catch a cable on the dock; this requires primarily only 2D positional accuracy and orientation is of much less concern, especially if the cable is vertical and perpendicular to the static waterline. However, UUVs with large latches add infrastructure to every UUV that is deployed (as opposed to just the dock) which compromises UUV endurance, adds cost to the UUV, and probably restricts the choice of UUV for the mission. Moreover, a large latch on the nose of UUV also imposes on valuable locations for many sensor payloads.

Few stationary autonomous UUV docking experiments described in the literature provide success rates but those that do cite success rates of 60% per docking attempt or 90% for five attempts [2, 3]. These experiments were generally located in harbour water in the presence of variable currents and took place over many days. The success rates are low because of:

- Position sensing error
- Navigational error
- Environmental disturbances
- Manoeuvring limitations

The Position sensing error is the inaccuracy with which the UUV homing device can locate the homing beacon in varying conditions. Most docking methods use acoustic sensing because it has good range (from several hundred metres to several kilometres); however, acoustic sensing has an error of +/- 0.5 m at best [2] and is subject to environmental anomalies. It should be pointed out that traditional acoustic UUV homing devices could pose signature and stealth concerns in contested waters. Electromagnetic sensing has much less range (30 to 50 metres) but a lower error of +/- 0.2 m [3]. Optical sensing may match or exceed the range of electromagnetic sensing but only in clear water; in harbour water, range can fall below 10 m [4]. Optical sensing has positional errors of about +/- 0.1 m and possibly as low as +/- 0.01 m if used the right way [5].

The navigational error, is the inaccuracy with which the UUV maintains its desired heading and depth, of particular concern for stationary docks where the UUV has to slow down (compromising hydrodynamic control) for final docking when positional accuracy requirements are greatest.

Environmental disturbance can affect the UUV docking. The disturbances can come from surface waves, internal waves, common where density stratification occurs [6], variable currents in littoral waters and the wake from submarine itself. These phenomena cause unsteady or unexpected relative motion between the UUV and dock.

Manoeuvring limitations of the UUV, is a major consideration for UUVs optimized for long range, high endurance missions. Such UUVs are streamlined (large length to diameter ratios make manoeuvring awkward), keep control surfaces to a minimum (to reduce drag), and travel slowly (power is consumed as a function of speed^3) using small propulsion motors (allowing for more batteries). Furthermore, a well optimized UUV mission will leave the UUV with minimal power for docking.

For naval platforms, operational tempo is an important additional consideration [7]. For submarines, unlike surface ships which can use man-in-the-loop control, autonomous docking is a necessity.

The UUV docking problem has been around for quite a while without satisfactory resolution. In 2010, DRDC initiated a collaborative project to address the problem within the context of a diesel submarine operating in littoral waters, possibly in high sea states. A study of the above issues made it clear that incremental engineering would not solve the problem. A new approach using an active dock was proposed [1] and the project is progressing in three major technology areas: position sensing using several methods, manoeuvrability using an active dock, and an autonomous docking strategy established through simulation.

1.2 MULTIPLE POSITION SENSORS

Position sensing must work for ranges from 0 to 1 or 2 km, it must be progressively accurate as the UUV and submarine converge, and it must be reliable in a variety of environmental conditions. Consider the following docking scenario in which a submarine is rendezvousing with a UUV that has completed a long mission.

Initially, acoustic sensing must be used [8]. The passively listening submarine locates the loitering, covertly pinging UUV and, when ready, begins overtaking it (Figure 1). The submarine turns on a homing signal that the UUV uses to estimate the submarine's bearing alpha (α). The UUV turns and keeps the submarine at new bearing gamma (λ) while proceeding at about half the speed of the overtaking submarine.

The submarine also generates a magnetic field that a sensor on the UUV can detect when within about 50 m of the boat; this provides the UUV with more accurate sensing as it closes with the submarine. As the UUV gets close to the submarine, it speeds up to match the submarine speed staying to one side just ahead of the docking envelope in Figure 2. The UUV drops back into the docking envelope and establishes modem communication with the dock.

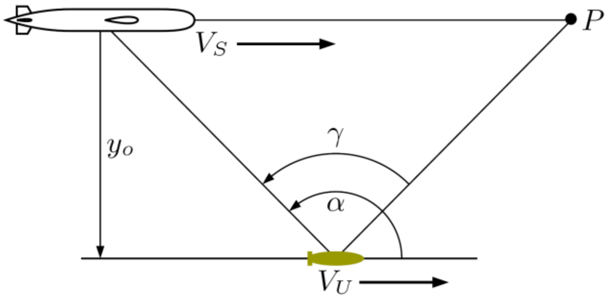

Figure 1: Plan view of a submarine moving at V_S ~ 2 m/s overtaking a UUV proceeding at speed V_U ~ 1 m/s. The vehicles initially proceed along the same docking course. When the bearing alpha (α) of the submarine to the UUV is optimal [8], the UUV turns towards the submarine and maintains new bearing gamma (λ) at the same low speed.

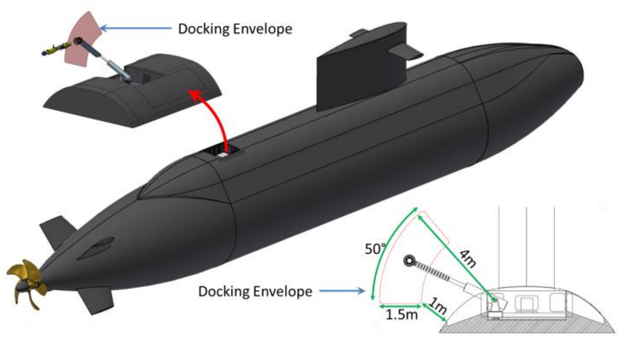

Figure 2: The Joubert diesel submarine [12] showing the location of an available hatch and the resulting docking envelope.

When communication with the dock is established, the UUV illuminates light emitting diodes on its extremities [4] and turns on a short range magnetic source. The dock uses both optical and magnetic sensing to locate and capture the UUV.

No sensing method works in all environmental conditions, so multiple methods are the key to reliability. They also satisfy both range and accuracy requirements. It may eventually be possible to reduce the number of sensors needed but it is too soon to know what the optimal combination should be, so all the above methods are currently being evaluated.

The sensors and sources do impose infrastructure requirements on the UUV. However, these are generally less onerous than docking mechanisms. Some would be required regardless of the docking method used and some have multiple uses that could augment UUV mission capabilities.

1.3 AN ACTIVE DOCK FOR MANEUVERABILITY

Neither the submarine nor the UUV have the necessary manoeuvrability to quickly and reliably correct for the time varying UUV positional error anticipated for final docking. Our solution to this problem is for each vehicle to do what it can and, for final docking, to use an active dock, a fast accurate robotic arm with a workspace that encloses the anticipated UUV positional error.

The submarine's greatest assets are its covert presence, speed, size, and power. Therefore, the submarine should be used to quickly reduce the space between the two vehicles, to power the long distance acoustic and magnetic homing sources, and to house, support, and power the dock. The UUV, short on power after its mission, should not have to go fast for a long period of time. However, the UUV has better manoeuvrability than the submarine; so the overtaking submarine should do nothing more than try to maintain straight and level flight while the UUV converges with it. The benign path of the submarine will also reduce the wake field and environmental disturbances which the UUV will need to pass through. The UUV will need to match the submarine's speed as it moves into the docking envelope and the subsequent increase in flow over the UUV control surfaces will improve the UUV manoeuvrability.

Stationary docking would require a stationary submarine which is undesirable. Not only do submariners not like to sit still but hovering can be noisy if achieved by actively pumping water between trim tanks. Furthermore, docking while underway has significant advantages over stationary docking:

- The faster the vehicles go, the better their hydrodynamic control and the less susceptible they are to ambient disturbance (disturbance velocities are a smaller fraction of the onset velocity). Of course, top speed is limited by the UUV (about 2 m/s) which is well within a diesel submarine's quiet speed range.
- Missed docking attempts do not require time consuming go-arounds. Modulating the speed of the UUV is all that is needed to set-up for another attempt.
- The active dock concept could work for stationary docks but moving active dock components quickly through water requires power and strong components [9]. This can be avoided when underway by using a wing dock that extracts its power from the onset flow around the moving submarine [10].

Many concepts for active docks have been evaluated by Watt et al. [1] and C. Gillis [9]. So far, the most promising variant active dock is shown in Figure 3. It is proposed that the arm be housed in the deck and deployed by moving it laterally into the flow. The onset flow drives the arm circumferentially about a passive rotary joint R_1 at its root when the wing that comprises the outer link is actively pitched R_P. The outer link with the hydrofoil telescopes over the inner link P_1. This translation allows for a radial adjustment about the base of the system relative to the submarine centre line. The motions allows the arm to position the capture mechanism at its tip anywhere over a large 2D sector in the transverse plane in which it operates.

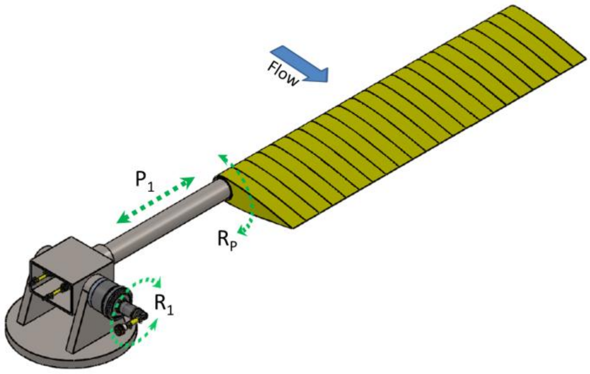

Figure 3 – The latest active dock concept flies circumferentially and telescopes radially across the 2D transverse plane it operates in.

Final docking takes place with the submarine doing nothing more than maintaining its speed in straight and level flight. The UUV stays within its docking envelope and responds to speed modulation commands from the dock. The dock continually measures the position and orientation of the UUV and moves its capture mechanism to intercept the UUV at the desired time and place. Neither the submarine nor UUV can make rapid transverse adjustments to their trajectories, but the wing dock excels at it.

1.4 DOCKING STRATEGY, AUTONOMY

Work is underway to design, prototype, and evaluate the individual components of this active docking concept. In parallel, a computer simulation of the fully integrated system is being developed so that the docking strategy can be evaluated [11]. This is a necessary and economic prerequisite to final design. Preliminary simulation results have already led to refinements in the concept.

The computer simulation will also be useful for making the docking strategy autonomous, and parts of it may ultimately be integrated into the actual system. As described above, the docking strategy does not account for things that will invariably go wrong. An autonomous strategy will incorporate algorithms that let the UUV and dock respond appropriately to unplanned events. Clearly, these algorithms are best designed and evaluated in a synthetic environment prior to real world testing and deployment.

1.5 CAPTURE AND PARKING

The primary focus of the DRDC project is to devise a method to bring the capture mechanism on the dock into `precise contact' with the capture point on the UUV. If precise contact can be achieved, then industry is well positioned to follow through with `capture' and `parking' solutions. The remainder of this paper, then, is concerned with adding a capture and parking option to the general docking concept discussed above, but doing so for a particular set of circumstances of plausible interest to large diesel submarine operators.

2. CAPTURE AND PARKING SYSTEMS

The capture and parking of the UUV is not a trivial task and one must consider the geometry and size of the UUV compared to the available space on the submarine.

The submarine chosen for this study is the theoretical Joubert diesel submarine design [12] shown in Figure 2. A small under-deck cargo space is added to this design behind the sail, a space likely available in many such boats to provide access to machinery over the engine room. Additional space is available next to this compartment along each side. Although the docking location is offset from the hull, docking is still expected to see some disturbance from the wake from the sail [13]. However, the conceptual design is transferable to a similar sized hatch forward of the sail or within the underbelly of the submarine.

Figure 4 provides the cross-sectional views of the hatch area. The mid-section of the hatch is where the active dock and associated sub-systems are to be housed. The two regions on either side of the mid-section are where UUVs could be stored. Figure 4 also shows the common sizes of UUVs relative to the available space. It becomes evident that the 21in diameter UUV cannot be stored in the space without significant changes. Consideration must be taken when selecting an appropriate sized UUV and the necessary support equipment to fit in the currently available space.

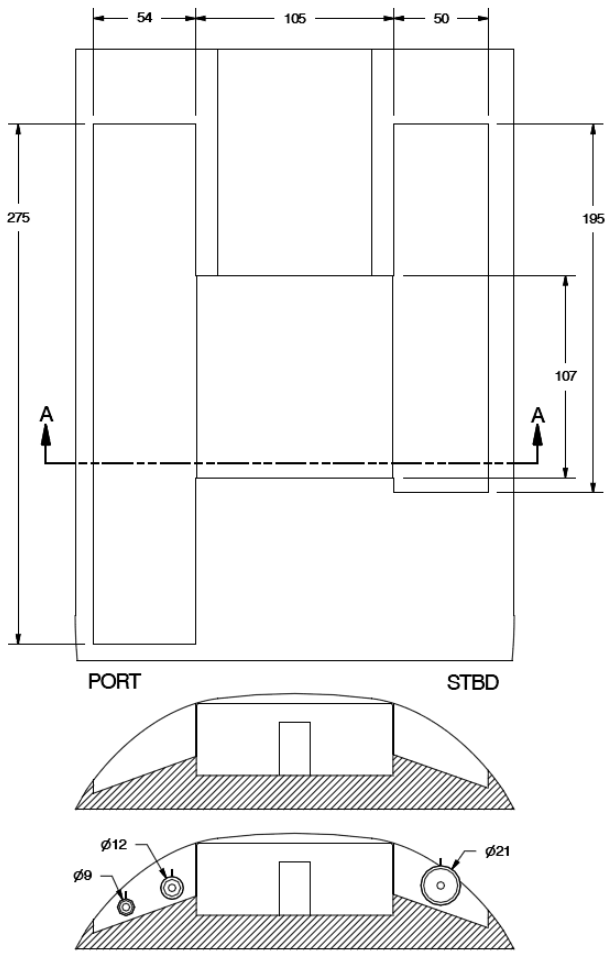

Figure 4 – Cross-Sectional view of the hatch (dimensions in inches)

2.1 SYSTEM OVERVIEW

Figure 5 shows the conceptual depiction of the active dock integrated in the hatch. The prismatic movement of the active dock is shown as P_1 and R_P is rotational pitch of the wing that causes the entire dock to rotate about the dock's base, the overall rotation of the active dock is denoted as R_1. The system allows for the main active dock pivot to translate across the cargo space (motion P_2). The active dock is then able to extend so that the end effector's most extreme radial position reaches over 4m from the hull surface, which minimizes the influence of the submarine wake. For simplicity, the athwartship translation P_2 is only used to deploy the dock; the planar docking envelope (Fig. 2) is achieved using joints R_1 and P_1 only. This variant of the system maintains a planar work envelope; however, it may be possible to have the athwart translating mechanism hinged to allow motion around the vertical Z axis. This added motion would permit the end effector, or capture head, to move in three dimensions. A schematic view of the three dimensional system is shown in Figure 6. Figure 6A shows a planform view of the three-dimensional system and the prismatic movement of the active dock is shown as P_1.

The athwartship translation of the system is shown as P_2 and for simplicity P_2 is currently not used in the active dock's work envelope. An actuator is shown to allow for the additional rotation R_2. This new actuator is currently depicted as a simple cylinder; however, a linkage system could use mechanical advantage to minimize power requirements. Figure 6B shows the planform view of a schematic representation for the new work envelop caused by the additional rotation R_2. Figure 6C shows the side view of a schematic representation of the work envelope, which is unchanged from the previous planar concept. The motion of R_1 is caused by the pitch of the active dock's angle of attack and rotational pitch R_p of wing. Finally, Figure 6D shows an isometric view of the new workspace, a spherical sector through which the end effector moves using joints R_1, R_2, and P_1.

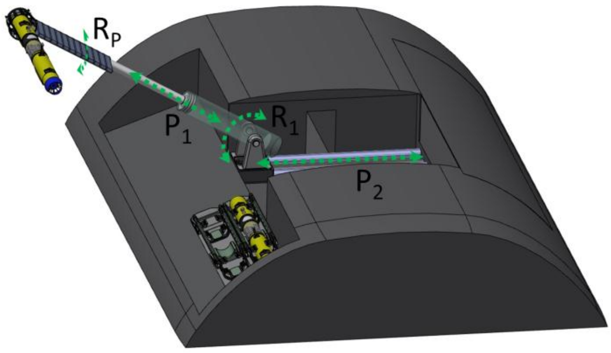

Figure 5 – System overview

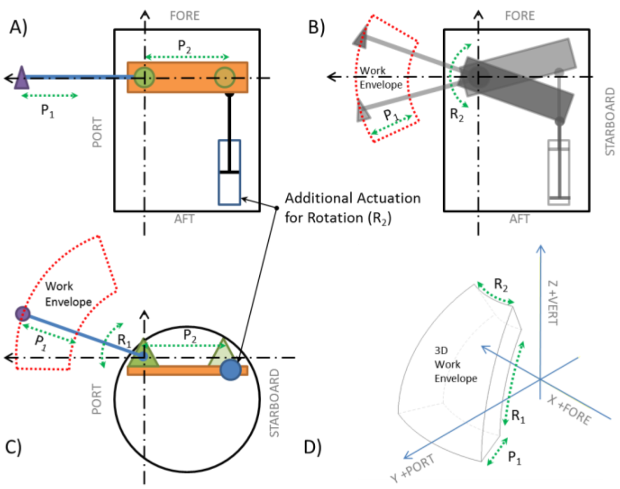

Figure 6 – Schematic representation of an active dock using a spherical coordinate system to achieve a three-dimensional work envelope.

There are several advantages to the increased degree-of-freedom provided by R_2 as it could:

- Allow for the docking system to move into the UUV and force mating.
- Compensate for axial disturbance caused by either waves or the submarine wake.
- Assist in the decoupling and storage sub-system.

However, by adding this degree-of-freedom the complexity, weight, infrastructure, cost and maintenance increase while the potential reliability decreases due to the added mechanical and electrical components. Future work will examine the true need and feasibility of the added joint.

As a first iteration of this conceptual design, Figure 5 uses a generic Man Portable UUV. Larger UUVs could be used; however, more significant modifications would need to be made for the submarine to house larger UUVs.

2.2 UUV SIZES

Table 1 highlights the variety of UUV sizes and capabilities. The USN has classified UUVs into four groups [14]:

- Man-Portable (MP),
- Light Weight Vehicle (LWV),
- Heavy Weight Vehicle (HWV), and
- Large Class

Man-Portable systems can typically be handled by one or two people. Their diameter is typically under 0.25m [12in] and often their length is shorter than 2m. An example of a Man-Portable system would be the Remus 100 and the BlueFin-9. The Light Weight Vehicles typically have a diameter of 0.32m [12.75in] and lengths ranging from under 2m to over 4m. Examples of a light weight vehicle would be the Remus 600 and the BlueFin-12D or -12S. A significant difference between the MP and LWV systems are their endurances and their depth rating.

Endurance is a function of the body's size for the storage of the battery cells; therefore, the larger the body, the longer the endurance. However, there is significant work under way to improve the power density of batteries [15-17]. Kang and Ceder [15] have examined various materials and compounds, particularly $LiFePO_4$, to achieve a high rate of charge. They report that the process was "so fast that the charging is ultimately limited by the surface adsorption and surface transfer, which is also the rate-limiting step in supercapacitors". Shih et al. [16] developed a 1 kW fuel cell system with 4 lead-acid batteries which powered a home-made one-man underwater vehicle to over 1 knot. Wang et al. [17] 2012 study extensively reviewed power systems for various UUV systems.

The rated operational depth is also a function of the size of the vehicle. The Heavy Weight Vehicles, such as the BlueFin 21 and Knifefish, Kongsberg Hugin and the Remus 6000 all have depth ratings over 4500m while the

LWV rage between 600-1500m and the PM systems are generally limited to 100m.

TABLE 1 – Common UUVs

UUV	Length [m]	Diameter [m]	Max Speed [kn]	Max Depth [m]	Class
Kongsberg Hugin [18]	6.5	.75	6	4500	HWV
Kongsberg Munin [19]	3-4m	.34	4.5	600-1500	HWV
Remus 6000 [20]	4	.67	4.5	4000-6000	HWV
Remus 600(-s) [21]	3.25 – 4.27	.32	4	600-1500	LWV
Remus 100 [22]	1.6	.19	4.5	100	MP
BlueFin – 21 [23]	5	.53	4.5	4500	HWV
BlueFin – 21 Knifefish [23]	5.8	.53	4.5*	4500*	HWV
BlueFin – 12D & – 12S [24, 25]	4.3(-12D) 3.7(-12S)	.32	5	200-1500	LWV
BlueFin– 9 & – 9M [26, 27]	2.5(-9M) 1.75 (-9)	.24	5	200-300	LWV
Oceanserver IVER3–580 [28]	1.7	.14	5	100	MP
Teledyne Gavia [29]	1.8 – 2.6	.2	>5.5	1000	LWV

*Assumed minimums, the Knifefish is a variant of the BlueFin-21.

Figure 4 and 7 highlight the very tight quarters that UUVs must fit into. Figure 7 shows that based on the footprint alone, it could be possible to fit 2 to 6 MP UUVs in the available space. However, with the complication of capturing the UUVs on the starboard and port side of the submarine this may prove infeasible for the current variant of the active dock with a purely passive joint at the base of the system. One must remember that the system primarily uses the hydrodynamic forces to actuate and therefore operating aft of the sail will introduce significant disturbances and could prohibit proper recovery from both sides of the submarine.

The two ghosted UUVs in Figure 7 TOP would require a complex translational system for either the UUVs or their entire cradles. A translational system is possible; however, a system that moves the UUV circumferentially around, the submarine could prove to be more reliable. However, special consideration would need to be made during the design of the submarine so that this circumferentially avoids exhaust, cooling and defence systems. One should be aware that it is not simply the amount of available space that is available to house UUVs but the rather the actual geometry of the space will play a critical role as to how many UUVs can feasibly be maintained by the submarine.

The size of the capture or docking head is directly related to the size of the UUV being recovered. The typical method of docking a UUV involves a funnel that is 2 times the diameter of the UUV with a mechanical solenoid latching system. These traditional docking systems will introduce a significant torque on the base, due to drag, and thus an alternative method is being explored.

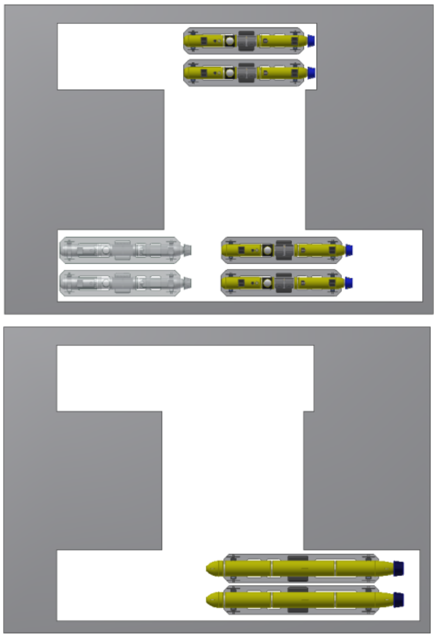

Figure 7 TOP: The Joubert diesel hatch with small UUVs the Bluefin 9, a LWV and possible storage locations. BOTTOM: the same hatch with larger UUVs the Bluefin 12, a LWV.

2.3 CAPTURE HEAD

It is typical in remote stationary docks to have a funnel or cone, 1m in diameter, at the entrance of the capture system [3, 31, 32]. The purpose of the funnel is to correct for UUV trajectory error and, to some extent, orientation; however, Stokey et al. [31] reported a 62% success rate per docking attempt, or an 88% success rate per mission, where each mission is defined as five docking attempts. Allen et al. [2], who used an updated version of this system, including a slightly smaller rectangular funnel, report a decreased mission success rate of 60%. The tests by Stokey et al. and Allen et al. each spanned several days in different locations.

The main purpose of an active dock is to substantially reduce or eliminate the need for a funnel even in the presence of substantial fluid dynamic disturbance. Research is ongoing with the objective of bringing the end effector on the dock into "precise contact" with the capture point on the UUV. In what follows, it is assumed that this can be achieved to within a few centimetres and a new capture method is presented which is based on the universal grappling fixture on the Canada Arm and space station [32].

The system consists of two concentric rings with cables connected to each ring and is illustrated in the TOP portion of Figure 8. As the red ring rotates the wires begin to intersect and converge to the centre of the circles.

The in the top planar view (Figure 8 TOP) of the capture system works well to centre and secure an object. However, in the reverse direction, releasing an object a new issue arises that is best summarized by the colloquialism, "You can't push a rope". If the two rings the system, of Figure 8 TOP, are concentric and in the same plane the loose the cables either need to be spring loaded on a spool which is exterior to the ring or very stiff and retract into one of the rings. To avoid this added complexity one can offset the attachment point axially to the rings, this is shown in Figure 8 BOTTOM. In Figure 8 BOTTOM only one wire has been illustrated for clarity. The figure shows that in the fully released state the wires are parallel to the flow and run fore-aft of the submarine and UUV. Once the rings start to rotate the rings will translate along the fore-aft axis and the wires will converge in three-dimensional space, Figure 9 shows CAD files and the rapid prototype of the new axial aligned grappling system. The axial system has two concentric parts, an inner ring and an outer cylindrical body. With the aid of guides the inner ring runs along a variable pitch helix which is on the outer body.

The required diameter of the docking head drives the axial length grappling system. Due to the complex motion in three-dimensional space of the wires also act as a funnel to guide the UUV into the correct position.

The advantage to this axial system is that it reduces the complexity of recoiling wires into one of the rings. The new axial system does require a variable pitch helical spline for the guides to run along. Future work on the axial grappling system will assess the systems retention and strength capabilities. An investigation of how to reduce the friction of the moving parts may also be needed depending on the required rotation to achieve a positive one a UUV.

The advantage of this style of system is that the cross-sectional area can be significantly smaller than a funnel system which can reduce the overall drag for the system. For this new system to be effective one must keep the capture head in line with the UUV/Submarine's major axis; however, the system is on the end of the active dock which is constantly adjusting based on the required angle of attack to the dominant flow. To counteract this added rotation, a second actuator can be mounted between the capture head and the active dock to apply the necessary counter rotation to keep the major axis aligned.

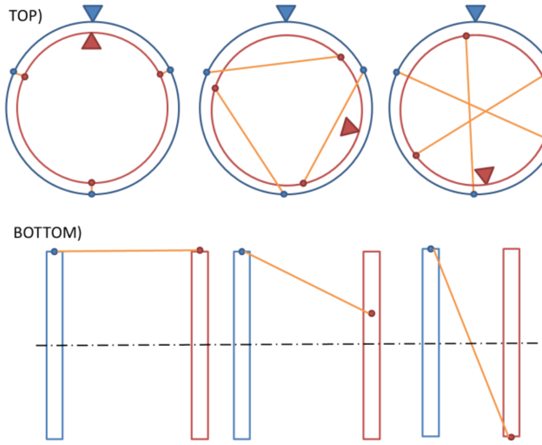

Figure 8 – Grappling system

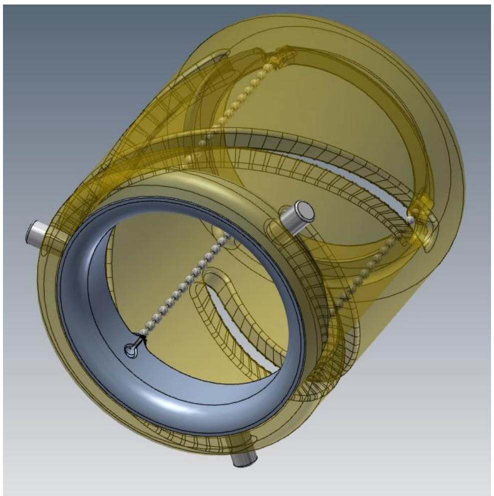
Figure 9 - CAD Image of grappling capture system

Once the UUV has successfully been captured the active dock retracts and an articulating cradle system transfers the UUV from the active dock's capture head to the storage position in the submarine's hatch.

2.4 CRADLE SYSTEM

Figure 10 shows the conceptual view of the cradle system. The active dock retracts into the hatch and the athwartship translation system positions the UUV in line with the cradle system. A simple linkage is actuated on the cradle so that it rises up to the UUV and locks it in the storage device. The docking head system is disengaged once the UUV is secured in the storage system. The cradle then retracts down to the folded position within the submarine hatch.

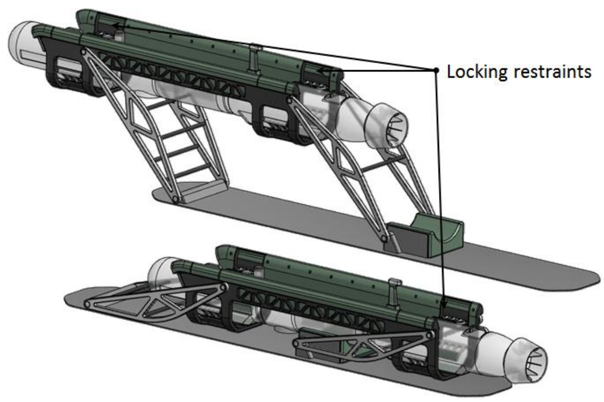

Figure 10 – Docking cradle

If one where to launch by simply releasing the UUV from the cradle, even in the extended position there is a potential for the UUV to contact the hull, or worse, the propeller of the submarine. Therefore, it is anticipated that the sequence to launch a UUV would be the reversal of the recovery process:

- The active dock would translate from its storage orientation to a position ready to receive a UUV from the cradle
- The cradle would raise the UUV in to the docking head.
- The grappling device would secure the UUV to the active dock and the cradle would retract.
- The active dock would extend to its maximum outreach and release the UUV.

One of the critical tasks for the cradle system is to regenerate the UUV by the transfer of data and charging the power cells.

2.5 REGENERATION

Making physical connections for data transfer and recharging is a challenge. Connector alignment is problematic and usually requires with extra mechanisms and actuators. The durability of these connectors also plays a role in the overall reliability of the system. Thus, inductive charging is an attractive possibility. For inductive charging the alignment and durability issues are not a factor. However, new issues arise such as efficiency, cycle time and cost.

Inductive systems traditionally are not regarded as very efficient and transfer a great deal of electrical energy into wasted thermal energy. As a result the charging times of inductive systems are longer than those of a hardwired system. The increased regeneration time adversely affects operational tempo. Moreover inductive systems are typically more costly as they are still in their technological infancy.

Some work has been performed in the area of underwater inductive regeneration. Yu et al. [33] provide a simulation of a wireless recharging scheme where they provide the structure and topology of the inductive circuit. Shi et al. [34] recently also developed an inductive system where the prototype output was only 45W but the efficiency was reported to be 84%. They report that as the power increases to 0.5kW the efficiency increases to 94%. This inductive work is in its infancy and further work needs to explore to improve the underwater inductive charging methods.

Underwater wireless data transfer is constantly improving. Recently Lloret et al. [35] have been able to achieve a 2.4GHz transmission in near field applications, less than 20cm. Bergmann et al. [36] have also examined wireless underwater communication in the 2.4 GHz regime. Their experiments show that low error was observed up to 70mm, but varied depending on the power output signal. They conclude that a wireless sensor coupling is feasible for underwater vehicles. All of these wireless and inductive methods for underwater system are in their infancy and will be explored and examined as the current active dock project evolves.

The next step for the active dock project is to build a mechanical prototype system to further develop and advance the technology.

3 ACTIVE DOCK PROTOTYPE

The University of New Brunswick is developing an active dock prototype. The prototype is an R⊥R⊥P serial manipulator and has three configurations. The multiple configurations provide the capability of testing one faired electro-mechanically actuated planar mechanism, and two hydrodynamically actuated (using an articulated wing) planar adaptations, through interchangeable non-structural cowlings all within one primary device. That is, the actuated wing can be interchanged between the base of the telescoping link or the opposing end, all with the same actuation system. The prototype is 4 m in length, consisting of a revolute joint at its base, allowing it to rotate in the vertical plane, and a telescoping link to provide radial translation.

Beginning in 2015, the prototype manipulator is to be tested in the Centre for Aquatics Research (CSAR) flume tank in St. John's, Newfoundland and Labrador. The CSAR flume tank is the largest flume tank in the world with dimensions of 4 m in depth by 8 m in width by 22 m in length and has a maximum flow velocity of 1 m/s.

The initial challenge of the prototype design is integrating the actuated wing into the telescoping link. An actuation method was required to allow the wing to travel with the link as well as pitch. Original design iterations considered using a lead screw and splined shaft running in parallel with a complex series of bearings to achieve translation and pitch. This resulted in a large link diameter for the device. Also, the mechanism would require guides to ensure it remained aligned and unable to back-drive itself on the lead screw.

These issues led to the concept of using a series of overlapping tubes and hollow shafts, all concentric to one another. This concentric method allows the lead screw to travel over the splined shaft; therefore, the spline shaft constrains the lead screw so it is not able to back-drive. The lead screw is driven by rotating a planetary roller screw nut at the end of the base link providing radial translation, relative to the revolute base, for the prototype. Planetary roller screws are robust, possess high dynamic load capacity, and due to their multiple contact points act partially as a support bearing. The pitch of the articulated wing is driven by actuating the splined shaft while maintaining translational position by using the planetary roller screw as a differential. Alternatively. the wing can be placed on the non-translating base link and the actuation method can be run in reverse to pitch the wing and use the splined shaft to drive the lead screw.

Due to the intended submersed use of the prototype all hardware and structural materials are low carbon stainless steel (A316L), while plastic composite hydrolysis resistant bushings are used instead of bearings. The prototype has a bore which runs the length of the device, through its centre, to allow for signal wiring to the end effector. All tubing and bushings are intended to have a 6 mm wall thickness at a minimum; this is to ensure structural integrity of the device during loading. The prototype design was shown in Figure 3. There are three Technadyne rotary actuators used, two
For the actuation P_1 and R_p by the splined shaft and roller screw and one high torque rotary actuator for actuation of joint R_1 in the RRP mechanically actuated prototype configuration. All actuators are oil-filled. Absolute multirotational encoders are built-in to the actuators and each actuator uses brushless DC motors with internal gears. Optional electronic brakes can be added within the stock sealed actuators.

4. CONCLUSIONS

This paper extends the active dock "precise contact" research to the "capture" and "parking" phases of the UUV/submarine docking problem. Consideration was giving to the space and packaging available for an active docking system. It became apparent through the course of this work that further development is needed in the following areas prior to the commissioning of a full system:

- Underwater charging
- Underwater data transfer
- Increased depth capability for appropriately sized UUV

Naval architects should take into account the future requirement of launch and recovery of UUVs from submarines and work with launch and recovery experts for appropriate access hatches for the a possible system, preferably away from the top sail.

The next steps in the on-going active dock project are to first build and then test the prototype active dock, which is scheduled over the course of 2014-15. Further work will also be done towards maturing the new low drag docking head for eventual amalgamation on the active dock system.

5. ACKNOWLEDGEMENTS

The authors would like to thank Natural Sciences and Engineering Research Council of Canada (NSERC) along with the Atlantic Canada Opportunities Agency for their financial support of this research.

6. REFERENCES

1. G.D. Watt, J.A. Carretero, R. Dubay, M.R. MacKenzie, "Towards an Automated Active UUV Dock on a Slowly Moving Submarine," P Warship 2011: Naval Submarines and UUVs, Bath, June 2011.

2. B. Allen, T. Austin, N. Forrester, R. Goldsborough, A. Kukulya, G. Packard, M. Purcell, R. Stokey, "Autonomous Docking Demonstrations with Enhanced Remus Technology," P Oceans 2006, pp 1-6, September 2006.

3. M.D. Feezor, F.Y. Sorrell, P.R. Blankinship, J.G. Bellingham, "Autonomous Underwater Vehicle Homing/Docking via Electromagnetic Guidance," IEEE J Oceanic Engineering, vol 26, no 4, October 2001.

4. J. Giesbrecht, J. Scrutton, "Underwater Optical Imaging to Aid in Docking An Unmanned Underwater Vehicle to a Submarine," DRDC Suffield TR 2012-197, December 2012.

5. S. Cowen, S. Breist, J. Dombrowski, "Underwater Docking of Autonomous Undersea Vehicles Using Optical Terminal Guidance," P Oceans 97, vol 2, pp 1143-1147, Halifax, October 1997.

6. H. Zaman and J. Millan, "An Overview of internal Waves in the Ocean." National Research Council Canada, Institute for Ocean Technology, TR-2012-03, March 2012.

7. L. Schuette, "Innovation Opportunities in Launch & Recovery," American Society of Naval Engineers Launch and Recovery

Symposium 2010, Keynote Address, PowerPoint presentation, December 2010.

8. G.J. Heard, G.D. Watt, G. Schattschneider, "Stage 1 AUV-Submarine Docking Acoustic Systems," DRDC Atlantic TM 2013-164, August 2013.

9. C.B. Gillis, "Dynamic Model Development and Simulation of an Autonomous Active AUV Docking Device using a Mechanically Actuated Mechanism to Recover AUVs to a Submerged Slowly Moving Submarine in Waves," Masters Thesis, University of New Brunswick, April 2014.

10. J. Currie, C. B. Gillis, J.A. Carretero, R. Dubay, T. Jeans, G.D. Watt, "Dynamics of Two Active Autonomous Dock Mechanisms for AUV Recovery," Trans. of the Canadian Society for Mechanical Engineering, 2014.

11. Roy, D. Steinke, R. Nicoll (Dynamic Systems Analysis Ltd.), "Dynamic Simulation of an Automated UUV Docking to a Slowly Moving Submarine in Littoral Conditions, Parts 1, 2, and 3," DRDC Atlantic Contractor Report in Review, 2014.

12. P.N. Joubert, "Some Aspects of Submarine Design Part 2: Shape of a Submarine 2026," Defence Science and Technology Organization, DSTO-TR-1920, December 2006.

13. R. Fedor, 'Simulation of a Launch and Recovery of an UUV to an Submarine,' Masters Thesis in Naval Architecture, Royal Institute of Technology (Sweden), October 2009.

14. United States of America, Department of the Navy, 'The Navy Unmanned Undersea Vehicle (UUV) Master Plan', November 9, 2004.

15. Kang, B., & Ceder, G. (2009). Battery materials for ultrafast charging and discharging. Nature, 458(7235), 190-193.

16. Shih, N. C., Weng, B. J., Lee, J. Y., & Hsiao, Y. C. (2013). Development of a small fuel cell underwater vehicle. International Journal of Hydrogen Energy, 38(25), 11138-11143.

17. Wang, X., Shang, J., Luo, Z., Tang, L., Zhang, X., & Li, J. (2012). Reviews of power systems and environmental energy conversion for unmanned underwater vehicles. Renewable and Sustainable Energy Reviews, 16(4), 1958-1970.

18. Konsberg Maritime AS, 'Hugin', 382309, Rev.A, April 2013, pp1-2.

19. Konsberg Maritime AS, 'Munin', 382308, Rev.A, April 2013, pp1-2.

20. Konsberg Maritime AS, 'Remus 6000', MKT 12-010, Rev.A 5, 2012, p1.

21. Konsberg Maritime AS, 'Remus 600', MKT 12-009, Rev.A 5, 2012, p1.

22. Konsberg Maritime AS, 'Remus 100', MKT 12-008, Rev.A 5, 2012, p1.

23. Bluefin Robotics Corporation, 'Bluefin-21 BPAUV', December 2010, pp1-2.

24. Bluefin Robotics Corporation, 'Bluefin-12D', December 2010, pp1-2.

25. Bluefin Robotics Corporation, 'Bluefin-12S', July 2011, pp1-2.

26. Bluefin Robotics Corporation, 'Bluefin-9M', October 2013, pp1-2.

27. Bluefin Robotics Corporation, 'Bluefin-9', December 2010, pp1-2.

28. OceanServer Technology, Inc., 'IVER3', REV 08-13.

29. Teledyne Gavia ehf., 'Gavia', 2012.

30. R. Stokey, B. Allen, T. Austin, R. Goldsborough, N. Forrester, M. Purcell, C. von Alt, 'Enabling Technologies for REMUS Docking: An Integral Component of an Autonomous Ocean-Sampling Network,' IEEE J Oceanic Engineering, vol 26, no 4, October 2001.

31. J.-T. Park, B.-H.Jun, P.-M.-Lee, J. Oh, 'Experiments on Vision Guided Docking of an Autonomous Underwater Vehicle Using One Camera,' Ocean Engineering, 36 (2009), pp 48-61, January 2009.

32. R. Vandersluis, E. Quittner, 'End Effector', U.S. Patent 4,929,009 May 29, 1990.

33. Yu, L., Wang, H., Li, C., Li, J., & Xia, G. (2013, June). Simulation of multiple AUVs underwater wireless recharging. In OCEANS-Bergen, 2013 MTS/IEEE (pp. 1-6). IEEE.

34. Shi, J. G., Li, D. J., & Yang, C. J. (2014). Design and analysis of an underwater inductive coupling power transfer system for autonomous underwater vehicle docking applications.

Journal of Zhejiang University SCIENCE C, 15(1), 51-62.

35. Jaime Lloret, Sandra Sendra, Miguel Ardid and Joel J.P.C. Rodrigues, 'Underwater Wireless Sensor Communications in the 2.4 GHz ISM Frequency Band', Sensors 2012, 12, 4237-4264.

36. Bergmann, N. W., Juergens, J., Hou, L., Wang, Y., & Trevathan, J. (2013, October). Wireless underwater power and data transfer. In Local Computer Networks Workshops (LCN Workshops), 2013 IEEE 38th Conference on (pp. 104-107). IEEE

9. AUTHORS BIOGRAPHY

Rishad Irani, PhD, PEng is a Senior Mechanical Engineer at Rolls-Royce Canada Limited, Naval Marine Division in Dartmouth Nova Scotia. He is also an Adjunct Faculty member at Dalhousie University in Halifax Nova Scotia. In the past he has worked with WHOI, MDA Space Mission, DaimlerChrysler and Siemens Automotive. Rishad has over 10 years of experience in computer simulation of mechanical systems, and design optimization.

Dan Kehoe is a Mechanical Engineering Technologist at Rolls-Royce Canada Limited, Naval Marine Division in Dartmouth Nova Scotia. He has over 10 years of experience in design primarily focused on the launch and recovery of marine equipment.

William (Bill) Spencer, MEng, PEng Engineering Manager at Rolls-Royce Canada Limited, Naval Marine Division in Dartmouth Nova Scotia. He has over 40 years of experience in design, analysis. Bill has worked on the Canada Arm 2 and he holds the patent for optical fibre slip-rings.

George Watt, PhD has been a Defence Scientist with Defence Research and Development Canada – Atlantic in Halifax, Nova Scotia for 26 years. He specializes in submarine/UUV hydrodynamics, maneuvering simulation, and analytical, experimental, and computational fluid mechanics.

Colin Gillis, MASc, EIT is a project engineer at the University of New Brunswick, Fredericton, New Brunswick. His MscE focused on the initial design and simulated control of the electro-mechanically actuated active UUV dock configuration.

Juan A. Carretero, PhD, PEng is a Professor in Mechanical Engineering at the University of New Brunswick, Fredericton, New Brunswick. He has 18 years of experience in robotics, computer simulation of mechanical systems, and design optimization.

Rickey Dubay, PhD, PEng is a Professor in Mechanical Engineering at UNB. He has worked in advanced process control for more than 20 years, specializing in the development and application of advanced control methodologies for nonlinear systems.