AUV Docking and Recovery with USV: An Experimental Study

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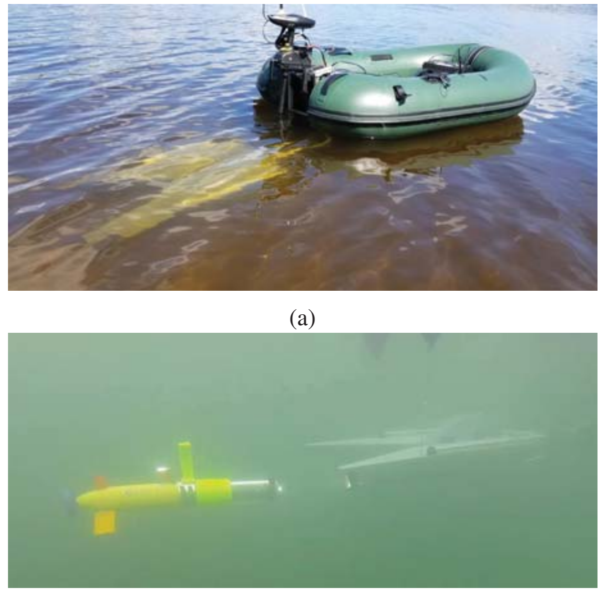
***Abstract*— This paper presents an early stage work on docking and recovery of Autonomous Surface Vehicles (AUVs) with Unmanned Surface Vehicles (USVs). The docking system is collapsible and adaptable to a wide range of AUVs. Control of the docking maneuver is completed based on a one camera, one light approach using a frontseat-backseat control setup. In this scenario, the vehicle navigates under frontseat control to within visual range of the dock. The backseat controller then takes over and performs terminal homing. Pool and open water testing was completed with docking to a small dinghy in both a manned and unmanned configuration. Two experimental docking attempts are presented, one docking to a slow moving target and another docking to a quickly moving target. The empirical results show that docking and recovery of an AUV from a USV while underway is feasible.**

***Index Terms*— Marine Robotics; Autonomous Underwater Vehicle (AUV); Unmanned Surface Vehicle (USV); Mechanism Design; Docking; Recovery**

I. Introduction

Many docking stations have been developed over recent years to support recharging of Autonomous Underwater Vehicles (AUVs) while submerged. These docking stations have typically used a large funnel design [1], [2]. Funnels excel at capture envelope, however their bulky nature leads to costly installations. Additionally, existing docking stations are designed to support specific AUVs. The large funnel design also does not lend itself towards mobile deployments due to large associated drag. Autonomous surface recovery of AUVs has gained interest in recent years, with developments such as the towed REMUS dock [3], [4] capable of capturing a vehicle near the surface. Recent deployments have shown autonomous launch and recovery using large funnel designs [5] or surface interaction based docks [6]. Significant work still remains to develop a mobile and adaptable docking station. Such a station must be able to dock with a range of AUVs near the surface and must also be able to be transported by a small Unmanned Surface Vessel (USV) in the deployed configuration. This station should also be transferable to deep ocean operation for fixed use.

The authors have developed a novel docking station design and prototype (Fig. 1) that is able to support a variety of torpedo shaped AUVs in addition to being collapsible and streamlined. The original design concept was presented and optimized in [7], [8] while applications and preliminary experimental data were presented in [9], [10]. The design is currently patent pending in the USA [11].



(a)

(b)

Fig. 1: The docking station follows a simplified funnel design approach. It is collapsible, lightweight, and streamlined for mobile applications. A docking adapter is mounted on top of the AUV to enable docking. (a) The docking system is small and streamlined enough to be mounted to an optionally manned 2 meter inflatable USV. (b) Underwater image captured during experimental docking in Lake Superior.

Docking to a free floating platform has seen very limited work with examples such as [12] seeing the most success. This paper presents the testing of the docking system in a mobile docking application. The dock is mounted onto a small (2 meter) inflatable dinghy. Experimental validation of mobile docking has been completed in pool and in the open water of Lake Superior.

Control during the docking maneuver has traditionally been broken into several phases: en-route, approach setup, approach, terminal homing, and capture [1]. In this paper, we focus on the terminal homing and capture stages as they are critical for successful docking operations and have not received as much focus as long range navigational challenges over recent years. En-route, approach setup, and approach phases can be accomplished with a wide range of methods including dead-reckoning and acoustic navigation using active beacons [13].

The remainder of this paper introduces details of the

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hardware and software design in Sec. II, the experimental results in Sec. III, and finishes with a discussion of potential impact and future work related to this project in Sec. IV.

II. Hardware & Software Design

The docking station is based on a novel simplified funnel design which was optimized to maximize capture envelope and minimize impact force [7]. In this design concept, the full 3D funnel of traditional docking stations is flattened into a planar cone. With a docking adapter mounted on top of the AUV in place of a mast, the docking station is able to achieve a large enough capture envelope with significantly decreased complexity. Due to the flat nature of the docking station, the dock is able to be folded and collapsed during transport and storage. Additionally, as the dock is a flat plane it can be towed behind any surface vessel with minimal impact on overall performance even while deployed. Mounted below the dock is a single beacon light that is used for navigation. The dock can be assembled by one person in approximately 10 minutes enabling a rapid testing cycle.

The docking adapter is a T-shaped mast mounted on top of the AUV. For prototyping purposes the docking mast is mounted in front of the existing AUV communication mast. If desired, the electronics from an existing mast (GPS/Iridium/etc) can be included in the T-shaped docking mast. For the purposes of this work, a Bluefin SandShark was modified with custom payload. This payload includes the docking adapter as well as a Raspberry Pi 3B located in a Blue Robotics 4” enclosure. The Raspberry Pi runs ROS and communicates with the main vehicle computer using NMEA commands [14]. At the current prototype stage, the wireless power system and latching tool are not included.

Implementation of the docking maneuver onboard the Bluefin SandShark AUV is achieved with a frontseat-backseat control strategy, Fig. 2 [14]. In this strategy, the AUV is capable of performing out-of-the-box, long range navigation towards mission waypoints. The AUV navigates towards the rendezvous location under frontseat control when determined by the mission planner [15]. As the AUV approaches the dock, the backseat controller takes over and performs the terminal homing process to guide the vehicle into the dock. For the purpose of this paper, we assume that the AUV has already completed the en-route, approach setup, and approach phases of docking and focus on control during the terminal homing and capture stages.

During terminal homing, the AUV navigates with a single beacon, single camera approach similar to [16]. In this approach, OpenCV is used to process a webcam image and search for the beacon. The beacon is currently identified simply by looking for the brightest pixel in the camera frame. Once the beacon is identified, the error from center is measured in pixels. This error is then fed into a standard PID controller that is used to directly control the rudder angle. To control vehicle depth, we assume that the dock is mounted at a constant, known depth. This assumption allows the AUV to achieve and stabilize at the target depth over a long distance. This is completed using a nested PID,

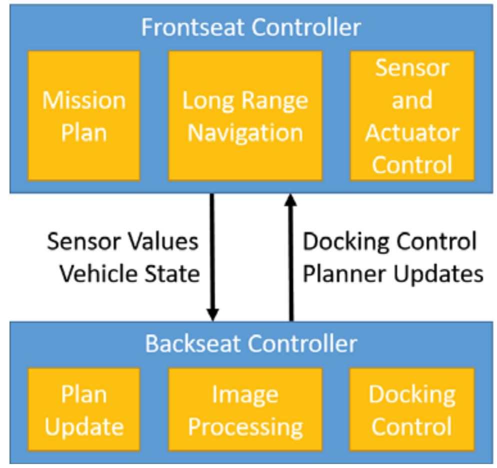


Fig. 2: The control software implemented onboard the AUV follows a frontseat-backseat architecture. The frontseat controller operates in its out of the box configuration to enable long range navigation and mission operation. The backseat controller (running on a Raspberry Pi) uses ROS and OpenCV to calculate controller outputs to drive the AUV into the dock. To account for failed docking attempts, the backseat controller must be able to modify the long range mission plan such that it can force the vehicle to go around and re-attempt.

where the inner loop controls vehicle pitch and the outer loop controls depth. Experimentally, this enables the AUV to achieve an acceptable docking depth in nearly all scenarios; except docking near the surface in strong wave states.

To test the feasibility of docking to a small mobile surface vessel, a 2 meter inflatable dinghy is used [17]. The dinghy can be driven autonomously with a customized trolling motor or manually with either a trolling motor or oars. For the purposes of this paper, the dinghy is manned and controlled with oars during the docking maneuver in pool testing. This is due to the small scale of the testing pool and lack of adequate GPS signal inside. When in open water, the dinghy was unmanned and drifted freely in the waves during docking maneuvers.

III. Experimental Results

Experimental docking to the dinghy has been completed both in the pool environment as well as in open water. Here, we present experimental trajectories for both AUV and dinghy during pool testing. Measuring an accurate trajectory for the AUV in open water has proven challenging and will be completed in Summer 2019. When operating in the pool, a GoPro Hero Session was mounted from the dive platform. These videos were then post-processed to isolate the location of the boat and AUV in pool coordinates. The videos were undistorted and rectified. Object recognition based on color was completed isolating the yellow of the AUV and green of the boat in MATLAB, Fig. 3. Due to the neutral color and dramatic impact of wave reflections on object tracking, isolating the location of the dock itself has been challenging.

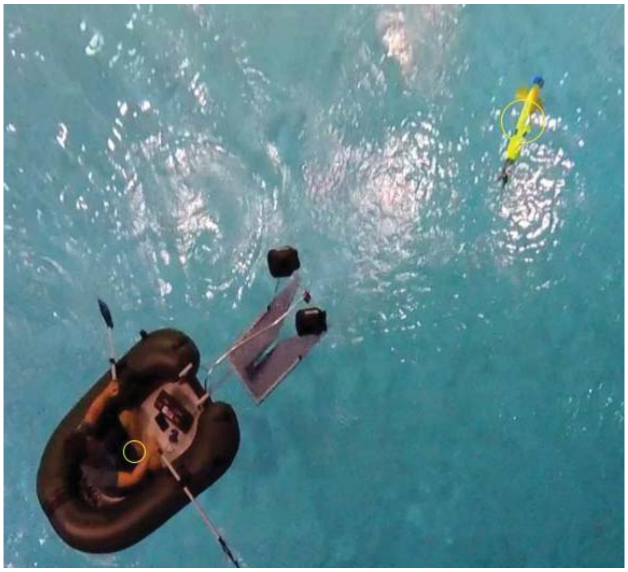
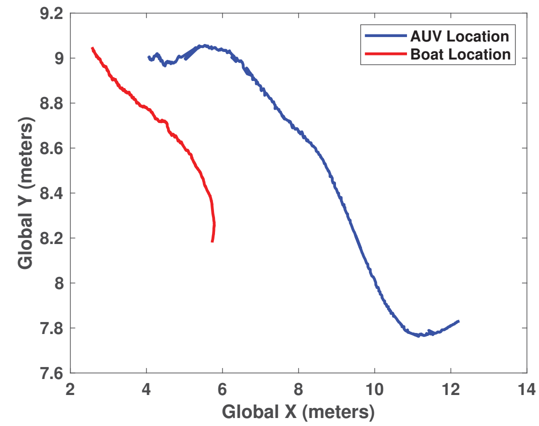


Fig. 3: Docking of the AUV to a small inflatable dinghy has been completed in pool and open water. Estimated locations of the dinghy and AUV are drawn as yellow circles.

In experiments, the dock was mounted off the rear of the dinghy and the boat was rowed in a variety of patterns to determine feasibility of docking to a moving platform. This paper focuses on two specific patterns. Rowing slowly (0.2m/s) away from the AUV and rowing quickly (0.4m/s) away from the AUV. During both tests the AUV traveled between 0.5 and 0.6m/s. The terminal homing controller was tuned for the stationary case and was not modified for these tests.

Fig. 4 shows the trajectories followed by the boat and AUV during the slow test (0.2m/s). In this scenario, the AUV was released in-line with the docking station. Fig. 4a shows the docking trajectory in the inertial frame. As shown, the AUV was released with a slight heading error towards the negative Y direction. It then corrected this using visual navigation before approaching the mobile dock. Fig. 4b shows the trajectory of the AUV in cross track error and along track error terms projected from the boat center. This representation shows the AUV achieve a cross track error near zero which enables successful docking.

Fig. 5 shows the trajectories during the fast test (0.4m/s). In this scenario, the AUV is travelling very slowly relative to the docking station (0.1-0.2m/s difference). Fig. 5a shows the pool referenced trajectories. As shown, the AUV was released on a diagonal transit of the pool with the boat starting approximately 6 meters away. The boat travelled in a mostly linear path away from the AUV while the AUV attempted to line up with and catch the dock. In the local coordinate frame, Fig. 5b, the navigation difficulty is more clear. From this figure, it is clear that the controller is not tuned for this operation as the AUV oscillates about the dock. The slow closing velocity caused control difficulties as the terminal homing controller was tuned to operate with a stationary docking station. Docking to this quickly moving target will require additional sensing capability and new control logic to be able to handle.



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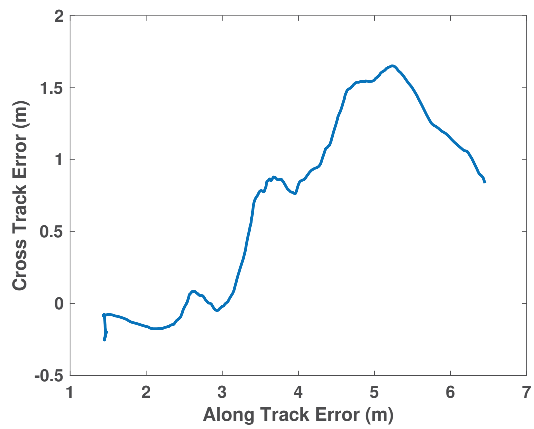
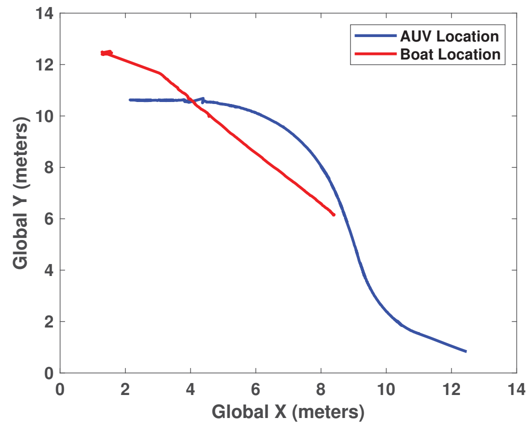


(b)

Fig. 4: Results from the slow moving boat trial (0.2m/s) (a) The global trajectories from both boat and AUV. (b) Local trajectory of the AUV in cross track and along track components.

Limited open water experiments with the docking system was conducted in the Summer 2018 in Lake Superior, Fig. 6. The transition to open water introduced new challenges that reduced docking accuracy significantly. The two primary challenges were relative localization of the dock and frontseat control stability on the SandShark. The identification of the docking beacon was more challenging due to reduced water clarity caused by severe flooding and an associated algal bloom in the local area. This was compounded with false identification of sunlight as the docking target, leading to many failed docking attempts. As a temporary solution, we completed all docking scenarios in open water facing away from the sun and far enough from shore to be away from the algal bloom. The second challenge was associated with control stability of the SandShark. The AUV would become unstable at sharp corners when operating in frontseat control mode. The unstable frontseat controller did not allow longer missions involving multiple waypoints. The manufacturer has



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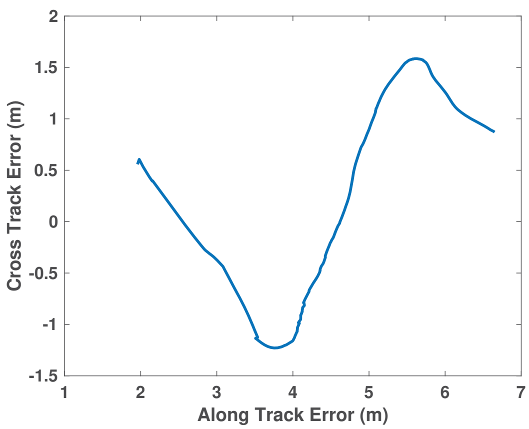

(b)

Fig. 5: Results from the fast moving boat trial (0.4m/s) (a) The global trajectories from both boat and AUV. (b) Local trajectory of the AUV in cross track and along track components.

since taken the vehicle back to continue development of the frontseat controller in an attempt to remedy the issues that we experienced. Extensive video of our development over the Summer 2018 is available at: `https://youtu.be/TAWWhnr2Rw4`.

IV. Conclusion & Future Work

This paper presented an early stage work on docking of AUVs to USVs. We have experimentally shown that docking between an AUV and a moving surface platform is feasible using the developed docking system. Further, we have shown that a simple control system based on one camera and one light is suitable for terminal homing in some scenarios. These experimental results prove that the docking system design enables docking while underway. This is particularly significant for autonomous launch and recovery as it enables the AUV to rendezvous with a moving boat platform. Further work is needed to tune the docking controllers to operate when the boat travels at a high speed relative to the AUV. Additionally, verification of the feasibility of docking when

Fig. 6: Open water testing of the docking system. In this scenario, the AUV was released from approximately 10 meters away from the dock which is mounted onto a dinghy. The AUV successfully homed and docked to the station. The bright light to the left side of the AUV is the docking beacon.

the boat is travelling faster than the AUV is of interest as this could enable recovery of AUVs without the need to slow down the surface vehicle.

Future work aims to transition this work to operational reality. Validation of the wireless power and latching systems is currently underway and will enable true persistent missions to fixed charger locations. Following this, efforts will focus on mid-range navigation using acoustic localization followed by integrating online path planning to account for changing conditions. With these two additions, the AUV/USV team will be able to coordinate to choose optimal charging locations and docking heading. This full system will be deployed in open water for extended operation for long-term, large-scale system testing.

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