# UNMANNED RECOVERY OF AN AUV FROM A SURFACE PLATFORM MANUSCRIPT, OCEANS '13 MTS/IEEE SAN DIEGO

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*Abstract* — **Autonomous Underwater Vehicles (AUVs) are commonly used for a variety of applications, which require launch and recovery (L&R) of the vehicle from a surface craft. Here we describe work in support of an automated recovery of an AUV from an unmanned surface vehicle (USV), whereby longer endurance / range may be achieved for such applications as underwater surveys of remote sites. This may be one of many possible complex scenarios that involve multiple unmanned autonomous vehicles of various types working together autonomously to complete a multitude of tasks, maximizing their combined performance. The AUV used in this project is the Hydroid REMUS 100. The USV, which will serve as the moving surface platform that recovers the AUV, is a 14 foot Wave Adaptive Modular Vessel (WAM-V).**

**In order to implement this type of system, various L&R methods need to be studied and analysed. This will help define a precise working environment, in which the system will be effective. Conceptual designs of two different recovery systems have been considered. For each design, an operating environment is defined, based on the characteristics of the model. Merits of each approach are being evaluated. To do so, "simple proof of concept prototypes" are built to test the feasibility and the effectiveness of each design. Here we describe one of the methods being considered. The main areas of focus of this project are device *reliability, repeatability, robustness and precision*. The desired outcome of this project is to provide a clear understanding of the ideal recovery method. The results of these studies will facilitate implementation of an effective automated recovery system, aiming to achieve a high degree of autonomy.**

***Index Terms – AUV, USV, Automated Recovery System.***

## I. INTRODUCTION

AUVs, such as REMUS 100, can perform a variety of tasks for various applications, such as inshore and offshore surveys, oceanography, archaeology, exploration, environmental protection, monitoring, scientific research, surveillance, and port security [1]. One of the main limitations of small AUVs is their inefficiency in travelling to a distant location where a survey mission may need to be conducted. Very often, the AUV is loaded on a research vessel or other ship and brought to the mission location, where it is then deployed and later recovered at the end of the mission.

The WAM-V USV has good sea-keeping characteristics, due to its ability to mitigate the vehicle response to surface waves [2] and can travel significant distances at reasonable speed. Various surface missions can be performed with this vehicle, due to its ability to easily navigate between locations, while also carrying a payload.

REMUS 100 and a USV together provide a system that can perform a variety of tasks that could not be accomplished by using either vehicle individually. In particular, the nature of the interaction between the two vehicles needs to be established in order to be able to extend the workspace between the water surface and the seabed. The WAM-V may in fact be used to carry the AUV to a specific deployment location, where the latter can start its mission (Fig. 1). In order to do this, the AUV needs to be launched and recovered from the USV autonomously. Here we describe possible methods to recover REMUS 100.

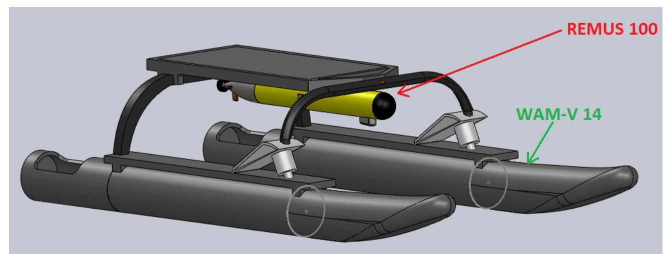


Fig. 1 WAM-V 14 carrying AUV REMUS 100 [3]

Many challenges are encountered when trying to recover an AUV:

1) Vehicle Positioning: The AUV needs to be precisely located with respect to the USV for recovery.
2) Retrieval: The AUV needs to be captured and retrieved from the water in a specific way to avoid damage.
3) Environmental conditions: Currents, waves, and other conditions can make the recovery process very challenging.

In the past decade, the process of unmanned launching and recovering an AUV has been considered and tested in multiple ways [3, 4, 5, 6, 7, 8, 9, 10]. Most of the time, the process has involved docking the AUV to a stationary platform, which may be anchored to the seafloor or connected to the mother ship. In order to dock accurately, the AUV uses Ultra Short BaseLine (USBL) Navigation, which allows the AUV to accurately navigate to a specific target (the recovery device on which a transponder is mounted).

## II. UNMANNED METHODS TO RECOVER AUVS

Among the most common recovery designs is a funnel shaped docking station [3, 6, 7, 8, 9]. This consists of a 1 to 3 m diameter cone, into which the AUV can dock after completing its mission. One of the great advantages of this design is the fact that the AUV does not need to be extremely accurate when entering the dock, since the funnel shape naturally guides the AUV into the docking station.

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The main limitation of this device is related to its size, which is very large for the purpose it serves. Another important disadvantage is the fact that the AUV needs to be properly oriented when docking, or else the vehicle will crash haphazardly into the station.

Another common method to recover an AUV is by having it latch to a submerged pole [4]. This type of system requires the AUV to be modified with a latching mechanism. The latching mechanism needs to be installed on the nose of the AUV. This kind of design introduces a unique and very rare characteristic to the recovery process: the possibility of omnidirectional docking. However, the vehicle is required to be very precise when homing to the pole, since a small error, O(10cm), might not allow the latching action to take place.

The two methods just described are representative of previous approaches for recovery systems.

## III. Proposed New Designs

A similar concept of operation, with a slightly different approach, can be applied to recover the REMUS 100 using the WAM-V. Ideally, a variation of each method of recovery described in the previous section will be implemented for the purpose of this project. Since pros and cons of each method are known, particular considerations are taken to limit the restraint of each device.

The funnel shaped device needs to be redesigned in order to be carried by the USV. This means the device needs to be compact, while still allowing the AUV to be guided into a locking mechanism. Fig. 2 shows the preliminary design of this type of recovery system. As it can be seen, the cone structure is completely redesigned to have two horizontal guides and one vertical guide. In order for this system to be effective the AUV needs to be implemented with a "stinger", which hangs below the vehicle. This stinger will serve as a contact point and will allow the AUV to be guided into a locking mechanism where the vehicle can be docked. After the docking process is successfully completed, the recovery device and the AUV can be lifted out of the water onto the USV.

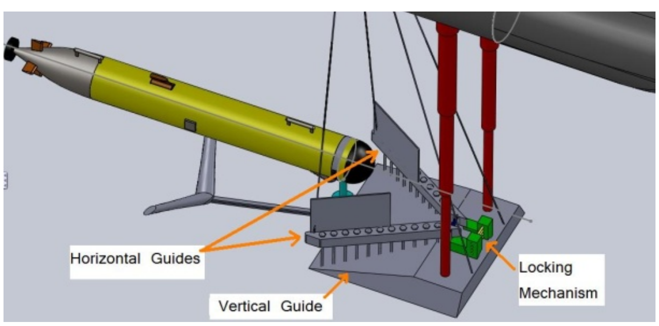


Fig. 2 "Adapted Funnel Shaped Design"

The idea of latching to a pole is a simpler mechanism; however it needs to be modified to allow for a larger margin of error. Fig. 3 shows the preliminary design of this type of recovery mechanism, which permits the AUV to home to a pole, with less precision. This is made possible by moving the latching mechanism from the nose to the sides of the AUV. This mechanism or implementation consists of multiple "trap doors" that can latch the AUV to a pole. We consider the latter design in further detail below.

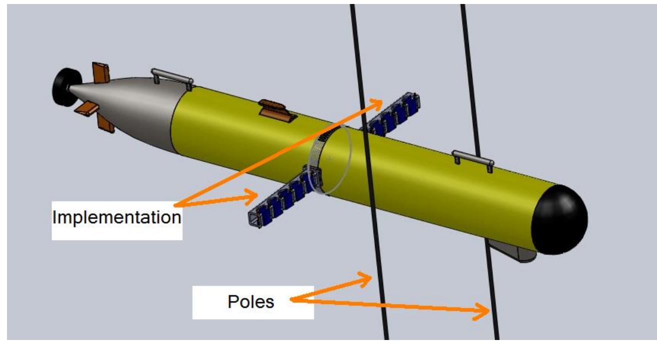


Fig. 3 "Adapted latching to a pole" mechanism

The latching system requires a significant mechanism to be mounted on the AUV, which will definitely affect the vehicle hydrodynamics during operations. Although some negative effects on the AUV motion may be considered acceptable, buoyancy and ability to maneuver have to be preserved in order for the vehicle to carry on its tasks. In order to minimize the effect on vehicle buoyancy, the implementation was built mostly with neutrally buoyant high density polyethylene (HDPE) plastic. The use of metal objects was minimal; however toggle bolts were used as latching devices and band clamps were used to physically attach the implementation to the AUV. To keep the implementation neutrally buoyant, additional foam was therefore necessary. Finally, in order to reduce the added drag caused by the implementation, holes were drilled in its frame. Each side of the implementation was also painted with red and greed respectively to easily identify port and starboard. The system described can be seen in fig. 4.

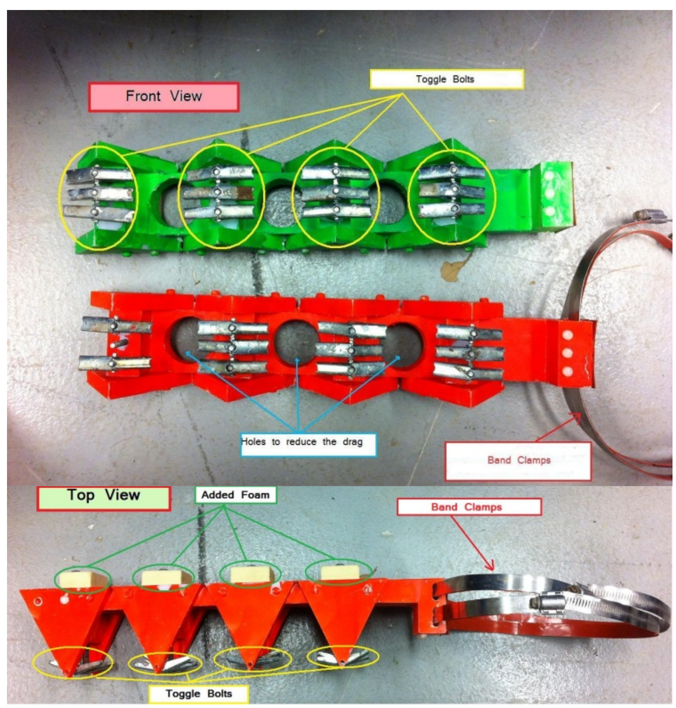


Fig. 4 Front View and Top View of the latching system

To determine if REMUS 100 maintained its maneuverability, the effect of the latching system on the vehicle was tested directly, recording and analyzing motion data to observe the effect on the vehicle hydrodynamics. The initial mission was conducted in calm water. Snyder Park lake in Dania Beach, Florida (fig. 5) provides a suitable location to run this mission, since it meets the described criteria, allowing easy access to the vehicle if needed (unlike during an ocean test). Although running this mission in a lake might affect the USBL and acoustics, navigation data can still be collected for the scope of this mission.

As a safety precaution, a kayaker closely followed the AUV throughout every run to ensure the AUV did not move in an unstable way due to the presence of the latching system (fig. 5).

Finally, a yellow buoy, which served as a reference mark to where REMUS 100 would end its run and was recovered, was put in the water. The yellow buoy was also used to hold the transponder to which the AUV was required to dock underwater (Home in fig. 5).


Fig. 5 Snyder Park Lake and mission set up

By adding the implementation it was expected that the forward velocity would decrease. This is due to the absence of a PID controller, which can account for the added drag on REMUS 100. Adding the latching system does in fact increase the drag on the vehicle dramatically. The final velocity of the modified AUV in the absence of a controller could be estimated from equations 1-4 below. Determining the drag of the vehicle, $D_{AUV}$, (1) and the drag of the latching system, $D_i$, (2) individually, the total drag (D) may be estimated as the sum of the two (3). In the absence of a controller, the AUV will react the same way for different values of drag, therefore D can be set equal to $D_{AUV}$. Finally solving for u', the final velocity of the implemented AUV can be calculated (4).

$$D_{AUV} = \frac{1}{2}\rho(u^2 * A * Cd)_{AUV} \quad (1)$$

$$D_i = \frac{1}{2}\rho(u^2 * A * Cd)_i \quad (2)$$

$$D = D_i + D_{AUV} = \frac{1}{2}\rho * u'^2 * (A_i Cd_i + A_{AUV} Cd_{AUV}) \quad (3)$$

$$u' = \frac{u}{\sqrt{1 + \frac{A_i(Cd_i)}{A_{AUV}(Cd_{AUV})}}} \quad (4)$$

Here u' represents the final velocity of the modified AUV, u is the desired velocity of the AUV (set by the user), $A_i$ and $A_{AUV}$ are the frontal area of the latching system and of the AUV (nose) respectively, $Cd_i$ and $Cd_{AUV}$ are the corresponding drag coefficient for a rectangular shape and bullet (AUV) shape.

The objective for this mission was to collect ADCP and state data of the vehicle performing 8 runs at different speeds and depths, with and without the latching system, as shown in table I. For each run the AUV performed a simple square pattern as shown in Fig. 6

TABLE I – MISSION 1 SET UP

| RUN # | Speed [kt] | Depth [m] | Implementation |
|---|---|---|---|
| 1 | 2 | 0 | NO |
| 2 | 3 | 0 | NO |
| 3 | 4 | 0 | NO |
| 4 | 4 | 2 | NO |
| 5 | 2 | 0 | YES |
| 6 | 3 | 0 | YES |
| 7 | 4 | 0 | YES |
| 8 | 4 | 2 | YES |

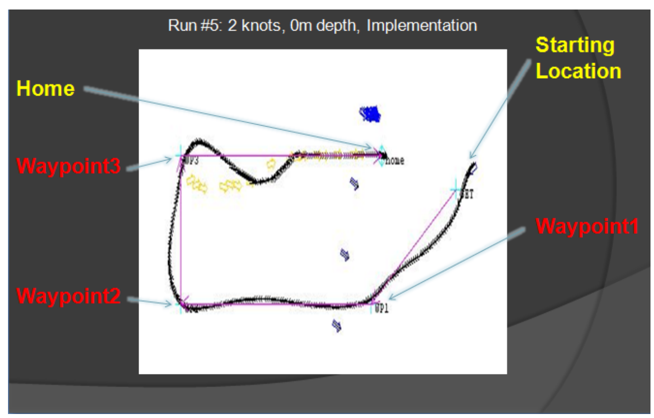


Fig. 6 Run pattern for Snyder Park lake mission

The mission at Snyder Park highlights a few interesting facts:

1. The modified REMUS 100 can still perform all its tasks, including homing
2. The modified REMUS 100 does not reach the desired speed it is programmed for
3. The forward velocity is the only parameter that is considerably affected by the implementation
4. The behavior of the modified REMUS 100 is not affected by depth
5. “Modified REMUS 100” is able to accurately home to the transponder.
6. “Modified REMUS 100” was stable and it was able to navigate through the desired GPS waypoints

Fig. 7 shows forward velocity u vs position (lat, long). Each line represents a specific run. The blue line represents

RUN#1 with the vehicle set to travel at a speed of 2 knots, operating on surface without the implementation. The green line represents RUN#5, which has the same parameters values as RUN#1, with implementation attached. The red line represents the model described in (4).

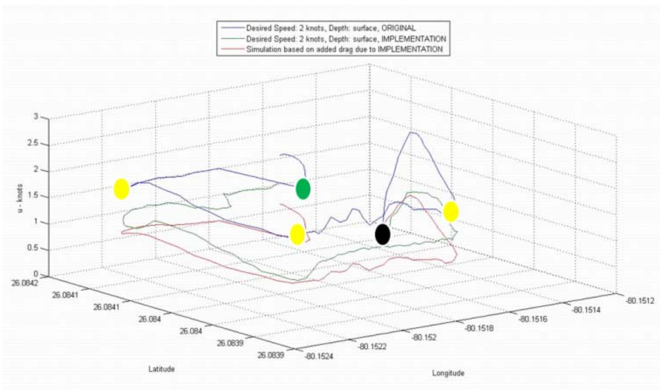


Fig. 7 Effect on forward velocity u due to the modification of the vehicle

Before analysing the graph it is important to notice the shape of the graph, which shows the square path the vehicle followed. The waypoint the vehicle was programmed to follow can also be identified:

- Yellow Dot: Waypoints 1,2,3
- Black Dot: Starting location
- Green Dot: Home (End)

The change in speed from rest to desired velocity can also be identified when the vehicle is at the starting location (black dot). The speed in fact increases very rapidly, within the first few meters from the beginning of the run and then settles to a final value, which corresponds to the desired speed.

The blue line, representing the vehicle with no latching system, shows that the AUV reached its desired speed, and tried to maintain it throughout the entire run. The green line, representing the modified vehicle, shows that the AUV does not reach the desired speed, which it was programmed to achieve**.** The desired speed is therefore never reached when the latching system is implemented. The graph suggests that the AUV maintained a velocity lower than expected (~1.4 knots). From the graph it can also be seen that although the modified AUV does not reach the desired speed, it is still capable of navigating through the desired waypoints and hone in on the end point.

Also, it is interesting to note that the model only slightly underestimated the values of forward velocity. The reason for this is that REMUS 100 is equipped with a basic proportional (P) controller, which allows it to output a higher thrust if the vehicle has difficulties in reaching the desired speed. The P controller, however, can only account for small perturbations and is therefore not suited for the increased drag. As a result, the vehicle is able to navigate a little (~10%) faster than it would with no controller (as shown in the model).

This concept is confirmed in fig. 8, where forward velocity u vs thrust (RPM) are shown. Each set of dots represents a specific run. Once again, the blue dots represent RUN#1 with the vehicle set to travel at a speed of 2 knots, operating on surface without the latching system. The green dots represent RUN#5, which has the same parameters values as RUN#1, but the latching system was included.

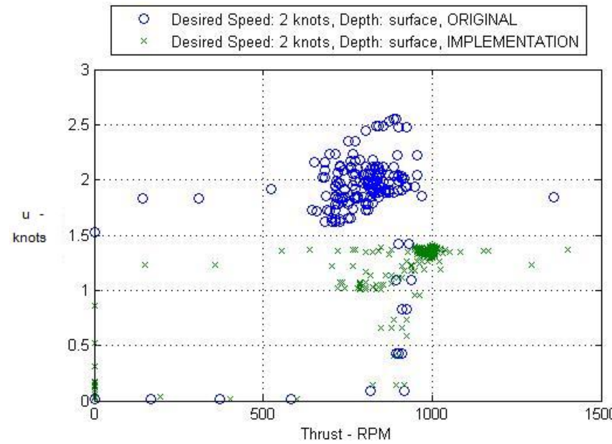


Fig.8 Effect on Thrust due to the implementation

In fig. 8, the cluster of blue and the green circles at around 750 -1000 RPM mark the final operating speeds achieved by the vehicle during each run with and without the implementation of the latching system respectively. The rest of the markers that are not within the vicinity of the clusters, simply represent the vehicle in a phase of acceleration (from the start location) or deceleration (to end location) and are therefore irrelevant. It can clearly be seen that when the latching system is implemented, a higher propeller RPM is required to achieve a speed that is lower than when the arms were absent. The vehicle outputs a certain thrust based on the desired speed it needs to achieve. However, if the desired speed is still not achieved, the AUV tries to output a higher RPM to reach the desired speed. Finally, if the desired speed is still not achieved, the AUV simply ignores that parameter by maintaining a steady thrust. The AUV therefore does not adapt to the increased drag due to the presence of the latching system. The vehicle needs a higher thrust to overcome the added drag and achieve the same speed (as without the latching system).

The results obtained in this first mission allowed us to better understand how REMUS 100 reacts when the latching system is implemented on the vehicle. Also, the data obtained suggests that such an implementation could actually be assembled for the purpose of recovering the AUV. The result of this first mission allowed for further testing of AUV docking to an underwater stationary pole in the open ocean.

Since it was now certain that the implementation of the latching system had a minimal effect on the functionality of the AUV, the safety requirements for this mission regarding weather and sea states were lessened. The maximum allowable sea state for this type of mission was determined to be sea state 4, while any type of weather was considered acceptable as long as no lighting would occur. A second mission was conducted in the open ocean off Ft. Lauderdale. The objective of this second mission was to test the ability of the modified REMUS 100 to latch to a pole in the open ocean. To do so, an anchoring checker-board target was tied to a transponder, a hollow plastic pole and a surface buoy (fig. 9) in this order and dropped at a specific location in the ocean. Two GoPro cameras were also installed: one on the AUV and the other one above the latching pole. These two cameras, together with the grayscale RC camera integrated in the REMUS 100, allowed for a wide field of view throughout the entire run (fig. 9).

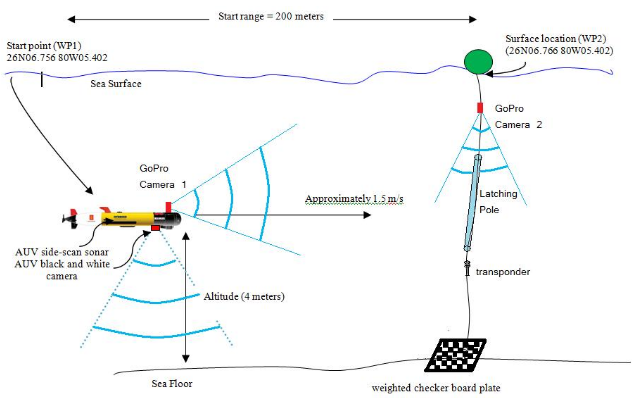


Fig. 9 Mission 2 set up

The purpose of the checker board target (Fig. 10) was to have an object on the seafloor easily identifiable by the RC grey scale camera present on REMUS 100. The positioning of the target within the field of view of the camera would also allow quantifying how close the vehicle approached the transponder (homing error). The pole simply served as a physical object to which the AUV could latch.

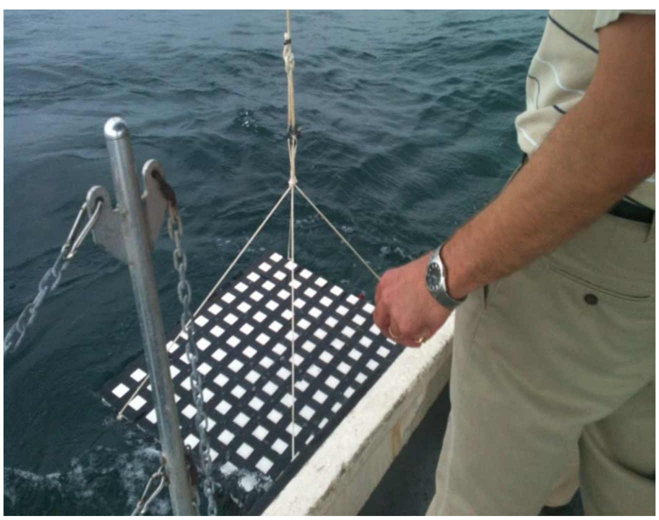

Fig. 10 Checker Board Target deployment

The AUV was then deployed 200 m away from this location so that it would simply navigate directly to the transponder (HOME in fig. 11) and therefore latch to the pole.

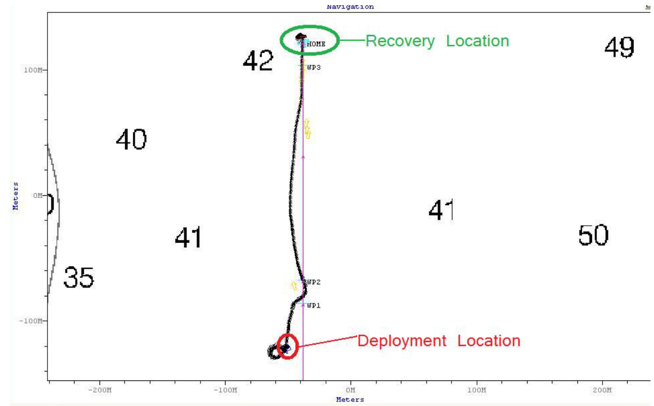


Fig. 11 AUV path

A study of USBL [11], suggested that the homing process be run at a depth of 5 m. This would allow the USBL to work in its optimal conditions, maximizing homing accuracy. Running at this depth also allowed minimizing the effect of natural obstacles such as wind and surface waves.

After deployment in the ocean, the vehicle reacted as expected: the forward velocity was still less than what REMUS 100 was programmed for, but the AUV was still able to accurately navigate and complete the mission by honing in to the transponder and latched to the underwater pole (fig. 12).

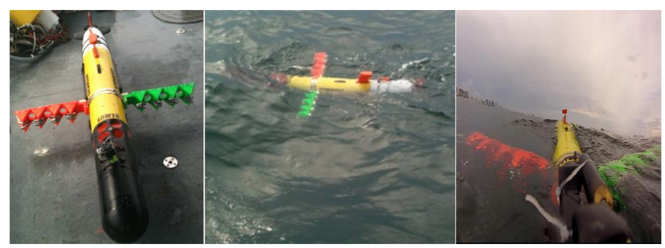

Fig. 12 Implemented REMUS 100

At the end of the run, RUMUS 100 successfully latched to the underwater pole (fig. 13). At this stage of the project, the latching mechanism lacks a method to unlatch it from the pole after successful docking. Therefore, since the mission was successful, the AUV ended physically attached to the underwater pole.

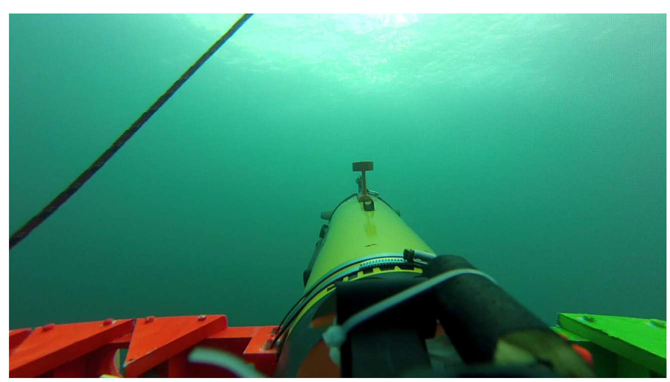

Fig. 13 Docked REMUS 100

As it can be seen in fig. 14, the vehicle finished its run right above the checker-board target, implying that the USBL was able to minimize the homing error. The very good performance of the USBL is partly attributed to the reduced speed of the AUV due to the presence of the latching system. This allowed the USBL to have more time to operate and therefore receive more fixes, increasing its accuracy in docking the vehicle to the transponder.

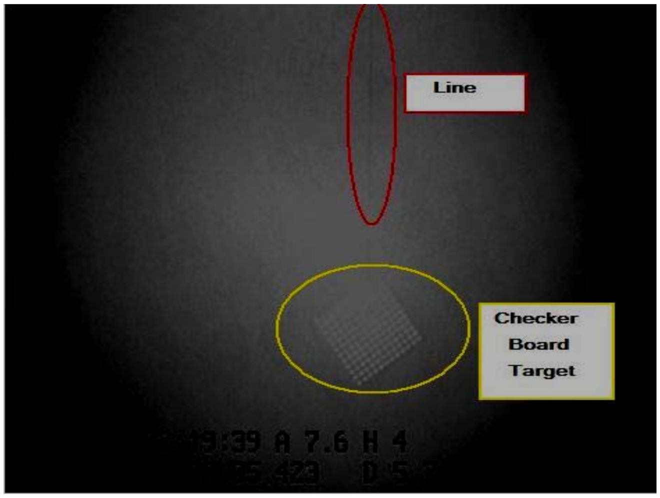


Fig. 14 Target and line seen from REMUS gray scale camera

The goal of this second mission was to have the AUV dock to a relatively stationary pole, although the final purpose of the project is to actually recover REMUS 100 from a moving platform (the USV). The success of this mission confirms that REMUS 100 may be equipped with such a latching device to be recovered. The next stage of the project will involve a new series of tests where the USV will be used to recover the AUV. To do so, the USV will have to be implemented with a new mechanism, such as an extendable telescopic pole to allow physical contact between the two vehicles.

At first the USV will be remotely controlled to stay relatively stationary, then an adaptive controller will be implemented on the USV to allow it to move autonomously during the recovery process.

## IV. Future Work

Further work towards testing and improving the designs of these systems still needs to be carried out to allow REMUS 100 to be precisely retrieved from the water onto the WAM-V USV.

The latching mechanism needs to be modified to allow automated unlatching. Further consideration needs to be given to having the mounting arms of the latching system tucked away along the side of the AUV during normal operation and capable of unfolding during docking to optimize performance. A new set of tests involving direct interaction between the AUV and the USV also needs to take place to finalize a fully functional system.

The stinger system discussed above still needs to be completely built and programmed. Various simulations also need to be finalized. Afterwards a whole new set of tests will take place; this will most likely underline some particular aspects of the system that need to be changed in order for it to work properly.

Finally, another alternative design will be considered that will leverage the lessons learned from the two designs described above. An optimal solution will then be developed.

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