ABSTRACT

With the conclusion of the project, it has been deemed that the most effective and feasible method of recovering an AUV through a torpedo tube would be to use a physical guiding system.

The method chosen is similar to that of a broken cone or flower petals, multiple stage flaps are extended out of the torpedo tubes using a track and pulley system, and the front of them levered open by tensioning of drawstrings. Positioning and guidance transmitters, receivers, or transceivers can be mounted onto the flaps to provide additional data to the AUV for it to more accurately position itself to enter the torpedo tube.

INTRODUCTION

Autonomous Underwater Vehicles (AUVs) have many purposes, they are often used to perform mapping of the ocean floor, search operations, reconnaissance and/or supportive combat roles.

There is a growing need to launch AUVs from submarines for reconnaissance and to support combat roles. The most feasible way, while underwater, is through its torpedo tubes, which is much akin to launching a typical torpedo. The launch and recovery of an AUV underwater is desired to reduce the exposure of the submarine to surface threats. However, as signals cannot effectively transmit data underwater, the process is a challenging one. Numerous problems arise when you need to recover the AUV back into a submerged submarine. A dedicated system built into the submarine would require a redesign of the submarine, and also take up additional space in the already small confines of the vessel. Recovery through the torpedo tube is the more feasible and cost effective method, as it makes use of existing infrastructure however aligning the AUV to the small tube will be a challenge.

Another notable method of Submarine-AUV pairing is the MANTA concept developed by the United States navy, where an AUV is a detachable part of a submarine’s hull. Launch and recovery is easily done by simply leaving and entering the large docking indentations on the hull of the submarine. (See Appendix 1, Figure 1)

Unfortunately such a design would result in a more prominent signature especially when the AUV(s) is/are detached, and also affecting the hydrodynamic shape of the vessel. Such a design like this would mean dedication to this role as an AUV “Mothership” of sorts, and would result in a certain loss of ability to be used for other purposes.

Thus, this project will work to evaluate and innovate to find a feasible solution to retrieve AUV’s back into the submarine through the torpedo tubes which will enhance the operational effectiveness of the submarine and AUV pair.
This report will introduce a series of solutions, electromagnetic docking, an extended resting platform, will be covered briefly and the petal funnel method will be elaborated in greater detail.

**METHODOLOGY AND PROCEDURES**

Exploration and evaluation of alternate methods and proposed method, evaluation based on theory, logic, and previous experience of both the project mentor and student.

To be cost effective, redesign of the submarine should be minimalized. To prevent over dedication to the AUV role, minimal modification should be made to the torpedo tube. The mechanism shall fit the below criteria:

1. Retrofit into the empty spaces of torpedo tube
2. Fully extend and retract back into the tube
3. Mechanism shall also not interfere with conventional use of torpedo tube
5. Withstand the impact of the AUV during recovery.

The rough idea was first fleshed out and molded and theoretically checked to be feasible with knowledge through previous experience of both student and mentor, and similar mechanisms used in a different application. In example, the curling petals are inspired by robotic hands that are clenched by drawstrings, and the funnel shape from an existing static underwater dock-point for AUVs. The extension will penetrate through the bow gap for the pressure doors.

Two models were built, the initial test model to prove and showcase the basic mechanism, and the detailed model built with the actual choice materials as the proof of concept.

A prototype model with easy to work materials (E.g. wood, plastics) was created to prove feasibility, and that the concept worked. Any shortcomings, for example the placement of the hinge point and drawstring based curling system not providing enough force to curl the petal, were worked out, by adjusting the hinge points and location of the winch, and improved in the planning for the final model.

The model with actual selected materials was then made to give the final prototype as live proof of workability and feasibility, and as a live demonstration.

**Description of methods**

Three methods were brainstormed. They are; Electromagnetic Arm Docking Recovery, Rest platform recovery & Petaled Funnel Recovery.

**Electromagnetic Arm Docking Recovery**

An arm is built into the torpedo tube, where upon ferromagnetic rings are installed. Similar ferromagnetic rings are also installed on one end of the AUV. To retrieve the AUV, the arm
is extended out of the torpedo tube into open water when the AUV is in proximity (see Appendix 1, Figure 2)

Current is run through the rings, which generates an attractive magnetic force. The drone then has to align and attempt to get to a close enough distance with the arm to be pulled by the magnetic force. The arm and the AUV then get locked together by the magnetic forces. (See Appendix 1, Figure 3)

After the two attach to each other, the arm retracts back in, powered by a motor behind the door of the tube, pulling the AUV fully into the Torpedo tube, (see Appendix 1, Figure 4) and the hatches close, storing the AUV.

**Rest Platform Recovery**

In the gap between the payload inside the torpedo tube and the actual circumference of the torpedo tube, a set of rails is installed, with the resting platform, measuring 5.5m mounted upon them. The resting platform is extended out of the tube by a hydraulic system behind it. The 5.5 meter long platform bridges the gap between the bow shutter and bow cap (Bow Gap) and extends 4 meters past that to become the actual 4 m rest area for the AUV. (See Appendix 1, Figure 5)

When the AUV is hovering in proximity to the torpedo tube, the bed is extended out of the system, the AUV aligns itself to the bed and lowers upon it. (see Appendix 1, Figure 6) It then retracts with the AUV, fully entering the torpedo tube, where the shutters close and the AUV is stored.

**Petaled Funnel Recovery**

A guidance funnel is made through the extension and folding of metal petals/flaps. The petals are each contained in a plank shaped container which would be spaced and bolted to the circumference of the torpedo tube. (See Appendix 1, Figure 7)

The petals are connected to a belt based pulley system on rails to extend them. Fully extended, the petals extend over the bow gap and extend one meter out of the torpedo tube. (See Appendix 1, Figure 8) After extension, the petal will be curled using a drawstring and winch system on the underside of the petal.

Multiple petals form something similar to a funnel which would help channel and guide the AUV in while protecting the submarine and AUV from colliding and damaging each other. Receivers and transmitters can be attached to the panels to help the AUV/submarine achieve the required alignment. (See Appendix 1, Figure 9) The AUV will with its own power swim into the torpedo tube.

After the successful entrance of the AUV into the tube, the arms will be drawn back and the shutters closed, storing the AUV.

**DISCUSSIONS**

Evaluation was based on a series of criteria, the ease of the alignment of the AUV to the docking system, the ease of Implementation into the existing infrastructure of the torpedo tube, the availability of the torpedo tube for other purposes, and the supposed reliability/feasibility of the concept based on proven techniques. The table that follows documents the condensed comparison between the methods covered.
### Criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Electromagnetic Arm Docking Recovery</th>
<th>Rest Platform Recovery</th>
<th>Petaled Funnel Recovery</th>
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<tbody>
<tr>
<td><strong>Ease of Alignment</strong></td>
<td>No: Small area of coverage of electromagnets means that the AUV has a smaller target to find</td>
<td>No: The narrow rest bed would be hard to align to in the event of unstable conditions, eg underwater currents</td>
<td>Yes: The expanded area due to the petal gives a bigger target for the AUV, and will guide it in.</td>
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<tr>
<td><strong>Ease of Implementation</strong></td>
<td>In-between: The mechanical arm and electromagnetic system is easy to implement and build</td>
<td>Easiest: The extending track system is easy to implement and build</td>
<td>Hardest: There are two mechanical systems, extension of the petal is easy, but the curling of the plank is harder.</td>
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<tr>
<td><strong>Versatility of Modified Torpedo Tube</strong></td>
<td>No: The arm takes up space from the payload area, dedicating the torpedo tube for AUV launch and recovery use, other payloads might not be able to be loaded</td>
<td>Yes: The bed is installed between the space for the payload and the actual outer diameter of the torpedo tube, which allows for other payloads to be loaded</td>
<td>Yes: The petal is installed between the space for the payload and the actual outer diameter of the torpedo tube, which allows for other payloads to be loaded</td>
</tr>
<tr>
<td><strong>Reliability/Feasibility Based on Proven Techniques</strong></td>
<td>Yes: Has been researched and covered by other scientists and engineers before[2]</td>
<td>No: It has not been tested before</td>
<td>Yes: Based on current static cone shaped receptacles used for AUV docking</td>
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Considering the Pros and Cons of the three methods above, the Petaled Funnel Recovery method was selected.

**Further description of Petaled Funnel**

The funnel is made of multiple petals arranged in a circle facing outwards. In each petal of the multi-petal system, there are a few subsystems. They, along with their parts and details are described below. (See appendix 1, Figure 10 – 15)

1. 1 Petal system, consisting of three aluminum planks of dimensions:
   a) 1x 4000mmX75mmX6mm
   b) 2x 500mmX75mmX6mm
2. 1 Toothed Belt based pulley system to extend the entire petal out

3. 1 Winch system to curl the petal’s plank

4. 1 Container to house all the systems into one package.

Taking the working conditions of a submarine, for the recovery system to succeed, a suitable material for the components must be selected which conforms to the below criteria:

1. Non-ferromagnetic

2. Reasonable strength of metal to avoid breakage due to force of incoming AUV

3. Does not corrode in salt water easily

The material thus selected an aluminum alloy, with an average tensile strength of 414,000,000 Pascal.

Calculations

Material Selection
The following calculations are based on the assumption that the AUV to be recovered is the “Saab Group AUV62-MR” [4] model which has a top speed of 20 Knots and a dry weight of 1500 Kg.

Kinetic Energy = \( \frac{1}{2}mv^2 \)

Force = \( \frac{\text{Work Done}}{\text{Distance Travelled}} \)

We assume that the AUV travels 0.01 m before it comes to a complete stop from top speed. (Coasting from top speed) and hits the very tip of the petal (worst case scenario)

\[
\text{Force of AUV} = \frac{1}{2}(1500)(10.29)^2 \times \frac{1}{0.01} = 7941307.5 \text{ N}
\]

The force is applied at a 60 degree angle to the tip of a fully curled petal, which is effectively 0.98m long.

Torsional force applied =

Force of AUV applied perpendicular to the petal \times effective distance from hinge point =

\[ [\sin(30) \times 7941307.5] \times 0.98 = 3970700 \times 0.98 = 3891240.675 \text{ N} \]

Total area of thinnest part of angle limiters and hinges (stress point) = 0.013 m²

\[
\text{Stress} = \frac{\text{Force}}{\text{Area}} = \frac{3891240.675}{0.013} = 299.32 \text{ MPa}
\]

Thus with a safety factor of 1.38 times the tensile strength, the aluminum alloy fits the requirements and is selected for use.
To ensure the cable and motor is capable of curling the petal and handling the weight.

Mass = Volume × Density
0.00045 × 2700 = 1.215 Kg

Force of gravity on petal = 1.215 × 9.81 = 11.91915 N
Torque by gravity = 11.91915 × 0.5 = 5.959575
Torque needed to lift petal = 5.959575 ÷ 1 = 5.959575
(Sin (0.5))² × 5.959575= 683

\[
\text{Stress} = \frac{\text{Force}}{\text{Area}}
\]

Wire's cross sectional area = \(\pi r^2 = \pi 0.001^2 = 0.0000098696\) m²

\[
\frac{683}{0.0000098696} = 69.2 \text{ MPa}
\]

With the tensile strength of woven steel wire at 690 MPa, the safety factor is 9.97 which fits the requirements and is selected for use.

**Motor Selection**

Force needed to initially curl petal = 683 N (from 3.2.1, material selection)
A motor with sufficient torque was selected, with capability of providing 800 N maximum of force.

**CONCLUSION**

In conclusion from this project, a method of recovery of an AUV to a torpedo tube using the petaled funnel method was selected, developed and produced. Dry testing was carried out and the models have proven to work reliably and to specification of the theoretical data.

The mechanism has been found to increase the effective catchment radius of the torpedo tube while protecting the AUV and submarine from collision, preventing unneeded damage in case of misalignment while it is swimming in for recovery. The ability for the mechanism to fit within the gap between the torpedo tube and the payload also enables conventional use of the tube even when the mechanism is installed.

Future areas of improvement and research would be the implementation of a sensor/emitter array to aid in guiding of AUV during recovery.

**ACKNOWLEDGEMENTS**

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REFERENCES


APPENDIX 1 – FIGURES

Figure 1 – MANTA concept

Figure 2 – Initial approach
Figure 3 – Latching of AUV to Arm through electromagnets

Figure 4 – Retraction of Arm and AUV
Figure 5 – Diagram of extended Rest Bed

Figure 6 – Stowage of AUV on Rest Bed
Figure 7 – Condensed diagram of petal

Figure 8 – Diagram of one extended petal
Figure 9 – Diagram of entrance of AUV

Figure 10 – Diagram of petaled planks and hinges
Figure 11 – Picture of hinge

Figure 12 – Diagram of belt extension
Figure 13 – Diagram of winch system to curl petal

Figure 14 – Picture of winch system and petal
Figure 15 – Diagram of container instalment into torpedo tube