

A Feature-Rich and Modular Aft Section for Autonomous Underwater Vehicles: The Trident series of tailcones

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Abstract—This paper presents the Trident series of tailcones, a novel 3-axis aft section design for Autonomous Underwater Vehicles (AUVs), developed through three design iterations and tested on nine assemblies across three different AUV platforms developed by the MIT Marine Autonomy Lab. The design features a modular, field-configurable architecture that supports multiple manufacturing methods and includes innovations such as a pluggable drive module, swappable fins, and comprehensive interfaces for vehicle operations. Key contributions include a feature-rich aft section that simplifies AUV design, A-Size compatibility, and an open-design approach for academic and educational applications. The paper discusses design rationale, manufacturing considerations, and presents a sample of preliminary performance data, highlighting the tailcone’s potential to advance low-cost, modular AUV research and development.

Index Terms—autonomous underwater vehicle design, multi-axis tailcone, field robotics, aft section design, propulsion, Trident tailcone

I. INTRODUCTION

In this work we report a novel 3-axis A-Size ready aft section design for Autonomous Underwater Vehicles (AUVs). This general design approach has undergone three design revisions across three different types of Autonomous Underwater Vehicles (AUVs) developed at MIT’s Marine Autonomy Lab and Sea Grant’s AUV Lab. A total of nine assemblies have been manufactured and fielded for operations across these three revisions. The tailcone design presented has been named the “Trident Tailcone”, and the specific designation presented in this work is the Trident 450 S.E.A. Rev. 2, meaning it is for a 4.5” hull diameter and includes additional re-configurable features for Science Enabled Applications. Further designations will be reserved for when a design is modified to fulfill a specific application.

This series of tailcone designs has been tested on three platforms so far: the Sea Beaver I, four modified EMATTs (Sea Badgers), and four Spurdogs, where the three renditions can be seen in Fig. 1.

The goal for this paper is to present a discussion on the overall design, the features included in the aft section, rationale for design decisions which complement lessons learned from research applications and field operations over the nine months of development across the three generations of designs, while

supporting related research which employ AUVs. Further, additional design decisions have been made outside the scope of the direct need, in order to complement work and interests of collaborators, such as meeting A-Sized mission requirements. Generally, this paper is an overview, and a more thorough review of performance and set of comparative analyses will be reserved for future work, which otherwise would not discuss the design and features. A sample of performance data is included for the standard fins for the vehicle, and is included in this work to provide the reader with perspective on performance.

The design presented will have licensing options available starting March of 2025, with permissive and free licenses available for non-commercial educational applications and research conducted by academic institutions, requested via email inquiry.



Fig. 1. Photo of three Spurdog AUVs on the dock at the MIT Sailing Pavilion, Cambridge, Massachusetts. The vehicle on the left is pictured with a Sonotronics Pinger mounted to the mast, with a miniature hydrophone. The vehicle in the center, is fitted with the A-Sized fins. The vehicle on the right is fitted with large elevators to support with improved pitch control, and a toroidal propeller, which was evaluated in related ongoing research.

II. RELATED WORK

Over the long history of Autonomous Underwater Vehicle development, many novel means of propulsion and control have been developed. The most common being variations on fin-based control, various implementations of vector thrust

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Fig. 2. Four perspective views of the Trident 450 Rev. 1 tailcone, including an optional mast, and the “standard” fins on Spurdog.

control such as [1] and [2], [3], variable buoyancy [4], or moving mass elements [5]. Further, there has been new and innovative research on single blade propulsion presented in [6], however while this method may have advantages, there are practical concerns which may arise from the lack of active roll control or high frequency vibrations due to the asymmetry. Until fairly recently, the applications and utility for smaller AUVs have been limited. To support high-endurance operations and carry payloads, AUVs have typically been larger in diameter and in length. Larger AUVs typically come with more operational complexity in terms of deployment and recovery, however once deployed, are dynamically stable and functionally reliable when in service, such as the larger variants in the REMUS series of AUVs [7] or the Bluefin-21 [8]. In addition to being stable and well engineered vehicles, they also have more room to implement their control schemes with a greater variety of actuators, which are often fin based due to the effective, efficient, and reliable maneuvering.

In recent years, AUVs have tended to become smaller, compact, and aim to be modular, to supplement short to medium range missions for applications in fundamental science or defense related work. For smaller AUV platforms, three-fin control has been popular for many platforms, such as the Bluefin Sandshark [9], the Riptide AUV, and the Yuco AUV to name a few. The main advantages of three-fin aft sections, is that it provides control authority for necessary pitch and yaw, while allowing active roll control. Roll control is less of an issue on larger platforms due to their larger separation distance between the center of gravity and center of buoyancy, however as vehicles get smaller, they are more subject to environmental disturbances, while also rolling due to the torque produced by the motor and propeller. This has been an issue long observed in the community, and it is cited that for the original REMUS AUV had a roll of about 5 degrees due to the reaction torque [10].

While AUVs have gotten smaller, only a handful of these AUVs are truly A-Sized, where with the inclusion of their fins, substantially increase the overall diameter of the profile. An A-Size platform, is one which is motivated by the U.S. Navy’s Sonobuoy launch tube system, which allows common platforms to be stowed, transported, and deployed from a

common payload. Arguably the most ubiquitous A-Sized AUV being the MK-39 EMATT AUV which has been developed by Lockheed Martin since the 1980s, up until recently. The EMATT is designed to be an attritable platform, meaning that the scope of the design and the capabilities of the aft section are low-cost and intentionally single use. Repurposing this platform to take on alternative missions beyond its primary application is challenging, since the primary aft section would quickly succumb to corrosion and need to be replaced. Further, the nominal aft section was designed around nominal vehicle performance specifications, where maneuvering may become compromised, and the passive roll compensation was no longer as effective. Variations on an adaptation for the A-Sized aft section also took place, such as the aft design implemented in the modified EMATT vehicle, Morpheus [11], however waterproofing and maintaining small servos in the flooded aft limited the vehicles depth rating and overall reliability. The challenges succeeded from that work, motivated the transition from the Trident A450 Rev. 0, to the Trident A475 Rev. 1.

III. MOTIVATION

Designs with control surfaces and a single thruster are popular due to their efficiency and compact size. Challenges arise however as the diameter of the hull decreases; mechanical complexity for power transmission increases while the compatible actuators become limited. Further, within the restricted form it becomes more difficult to assemble the aft section in a confined space, and remaining space is limited to include additional features. Some AUV’s which use control surfaces and a single thruster in a similar class of vehicles are those such as the Bluefin Sandshark [9], the Riptide AUV from BAE systems, REMUS AUVs, the IVER 3 from L3 Harris, and more. Specifically within the class of A-Sized AUVs and aft section design, literature is limited.

The design and features included in this aft section are motivated by 1) low-cost and modular attritable AUVs, 2) experiences during field operations, 3) the need to improve control authority on low-cost A-Sized platforms while improving robustness and reliability, and 4) field adjustable performance specifications such as passive and active roll compensation, pitch and turning rates, thrust characteristics. This design presents an aft section which is conducive for

supporting wider ranging research interests and field experiments which is highly modular. Often, AUV's are limited in their capacity to support wide ranging research at a low-cost due to overhead for deployments, lack of modularity, and lack of open interfaces for users. For example, researchers in acoustics and robotics may take no interest in aft section or propulsion design, and may want to reconfigure a platform to be "good-enough" through trial and error, while spending the majority of their effort in achieving their unique research goals. Similarly, for conducting research in autonomy, field demonstrations in heterogeneous multi-agent coordination become more interesting when diverse payloads can be quickly integrated onto an AUV through a plug-and-play interface, and be software configurable in the field.

These needs then raise the following questions:

- How does one design a simple and easy to maintain AUV?
- How does an AUV tailcone complement these goals in the design process?
- Where is there room for innovation on aft section design which complements the communities broader interest?
- How can an A-Sized aft section design meet these goals without hindering overall capabilities and maneuverability, to help translate technology from research to applications where this is a strong need?

Overall, the authors believe this has been achieved by producing a thoughtful and feature-rich design which is compatible with commercially available locking tubes from Blue Robotics, and is specifically designed around the Spurdog AUVs sequential coupling philosophy and paradigm, in order to streamline field operations, however can be readily integrated onto other platforms while lending similar advantages. To achieve simple sequential coupling with low-cost components, we believe it is preferable to avoid modification to a pressure vessel, and reducing dependencies and expectations with what features come beyond the core bottle, or one-off custom mating flanges. To achieve this, all physical interfaces for engaging with the core Spurdog AUV is contained within the aft section shrouded with magnetic cowlings and optional configurations on the aft section itself. These features are discussed throughout this paper along with our implementation details.

IV. CONTRIBUTIONS

We outline the contributions for this design and paper as follows:

- A feature-rich aft section which simplifies AUV design, such as the Spurdog AUV.
- An aft section which is field configurable
- An aft section design which is A-Sized compatible via the hot-swappable fins and an optional mast
- An aft section design and blueprint which will have licensing options free for research conducted by academic institutions and educational applications



Fig. 3. Photos of the Sea Beaver I, a modified EMATT variant which was named the "Sea Badger", and then the Spurdog AUV, each depicted with the associated aft section which was tested on the vehicle.

- A discussion on lessons learned across three aft section designs for three different AUVs designs, and the manufacturing of nine of them.

V. DESIGN PROGRESSION AND KEY FEATURES

A. Overview

The design presented and discussed within paper is limited to the Trident 450 S.E.A. Rev. 1, with four perspective views presented in Fig. 2, which is the third aft section in the Trident series of tailcones. The two preceding aft sections leading up to this design is depicted in Fig. 3. This design when assembled with the A-Sized fins and without a mast, fit within a 4.5" OD profile, which smaller than the A-Sized constraint of 4.875".

B. Design Motivations Across Three Designs

The first design was not designed with a specific project or need in mind, and was pursued out of curiosity, which was done for the Sea Beaver I. This design modified a T200 thruster to simplify and streamline the flow around the mounting structure. Further, it is challenging to maximize the separation between the center of gravity and center of buoyancy and improve the hydrostatic stability. With this, the overall vehicle is sensitive to the torque born from the motor and propeller. This then motivated the need to refactor the shroud to passively counteract roll. Originally this design was undesignated, but may be regarded as the Trident A450 Rev. 0.

The second design was motivated by being able to refactor a stock EMATT and enhance the platform to be more useful and maneuverable beyond their intended applications. While the stock design is very sturdy and can reliably endure high impact loadings, when the vehicle modified beyond its nominal configuration, it becomes challenging to control with the bang-bang control surfaces and is subject to corrosion (as the vehicle is only intended to last a few hours) and thus persist beyond one operation. To refactor the aft, we repurposed the stock lip seal assembly and motor assembly, and plugged this into the

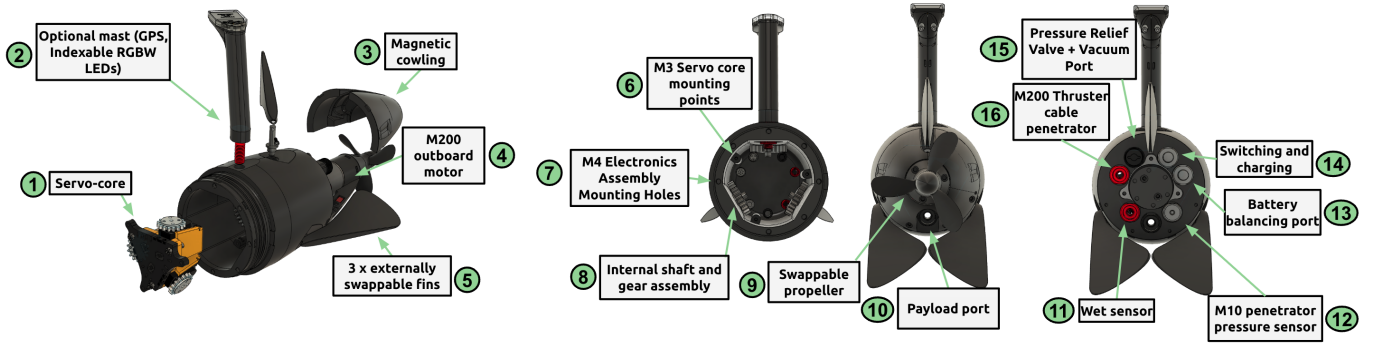


Fig. 4. A diagram outlining the core features on the overall assembly throughout four perspectives. From left to right, we illustrate removable components as fitted into the assembly, the internal assembly with the removable drive module disconnected, the rear of the aft section, and then the interfaces and ports beneath the magnetic cowl.

Trident form. This design was purposed, and was designated as the Trident A475 S.E.A. Rev. 1.

The third design was motivated by the Spurdog AUVs core design paradigm, which revolves around a low-cost AUV design which aims to minimize fabrication time and labor to assemble, simple field configurability of control capabilities, and containing human interfaces for interacting with the core AUV within the aft section. Specifically, physical interfaces for operators are put into the aft section, since if payloads are sequentially coupled in front of the core bottle, payload designers and users should not be constrained with conditions with what features must be included in specific payloads (i.e. a nose-cone). Therefore, beyond basic control, the fundamental interfaces which are included in the aft section include; depth and temperature sensing, vehicle switching and charging, pressure relief and environmental augmentation (i.e. pressure relief, setting a vacuum or positive pressure, gas exchange).

C. Features

Herein we outline features within this aft section.

- There are no high-RPM dynamic seals. All dynamic seals operate below 47 RPM (max-RPM of the servos used). This is to reduce the need for servicing and risk of failure. The RPM is further limited in software to be roughly 15 RPM.
- A flooded outboard motor with swappable propellers, which simplifies manufacturing and post-assembly modifications. This also reduces the threshold for the manufacturing precision required for mating high-RPM dynamic seals (i.e. lip seals) around a tight-tolerance rotary shaft, motor coupling, and dry running motor.
- Swappable magnetic cowlings (bottom) to include shroud and stators with passive roll compensation
- Field swappable fins which may be A-Sized ready, or larger to improve control authority. This is also to aid in the maintenance and assembly of the vehicles.
- A design which supports multiple modes of manufacturing, such as SLA 3D printing, urethane casting, or CNC machining. The presented version of the design has been

optimized for and has fully leveraged SLA 3D printing, where the authors recognize small modifications must be made to support the two latter modes of manufacturing, from what is depicted in this paper.

- A design which includes interfaces for battery charging, vehicle switching (turning on and off), battery cell balancing, and pressure relief / environmental augmentation, all shrouded under magnetic cowl
- A pluggable drive module to simplify assembly within a constrained hull form
- Three general purpose ports for mounting payloads to the vehicle, which may become an optional mast, a port for towing small payloads, or a port for environmental sampling.
- A versatile design which is easy to assemble and refactor to an individual operator's needs.

VI. DESIGN

The authors believe the two most important features which enable the aft section to contain the assortment of features presented, stem from 1) the simple removable drive module, and 2) fins which when assembled are constrained independently from drive module (servo core), within a single main hull. One critical component, the main hull, contains eight static seals, and three dynamic seals in the presented design. Beyond this, all external components are flooded and are not structural. Throughout this section, the authors discuss elements of the design, features, and a variety of considerations concerning the implementations.

A. Pluggable Drive Module

The drive module is a removable component where three servos sit within a snug fit between a plastic mounting plane and Fused Deposition Modeling (FDM) 3D printed servo holder, which is tightly fit to the servos and their form. The independent assembly is depicted in Fig. 5. The plastic panel in implementation is laser cut from a quarter inch acetyl sheet, which includes holes for servo wires and shelves for servo mounting tabs to sit snugly. Between the acetyl panel and the 3D printed servo core, there are complementary features

so a zip-tie can be fed through one hole and routed out another. These zip-tie loops are placed to pull cables from the aft away from the gears during harnessing and assembly, and towards the center in front of the servo core assembly.

We use a commercially available aluminum servo hub which costs roughly \$0.80 USD, where a waterjet steel gear with countersunk features sit below the servo hub. First the gear is mated to the servo hub from below, and then affixed to a servo. This is to optimize space and power transmission. Previously, the gears have previously been 3D printed, however for the implemented assemblies we use a 4130 alloy steel.

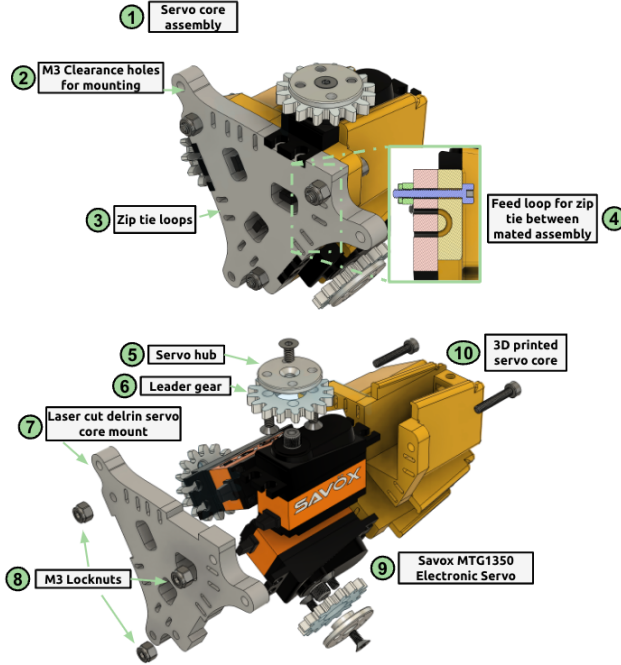


Fig. 5. Diagram depicting the removable drive module and servo core assembly. The removable drive module simplifies assembly of the aft section, and remains compact. It consists of three servos fitted into a 3D printed form, mounted to an acetyl plate which becomes a single component, which is installed within the aft section with three screws.

B. Fin, Follower, and Seal Assembly

The fin, follower, and seal assembly, is intended to minimize space required to effectively transmit torques to drive the control surfaces, while transmitting extraneous forces directly into the hull and away from the o-ring which is currently embedded in the hull. To achieve this, a simple low-cost stainless steel precision pin was machined to contain features for the fin and follower gear to mount to. The mated assembly between the servo core, and the fin, follower, and seal assembly, is depicted in Fig. 6.

An o-ring groove is embedded within the hull, which sits close to and below a acetyl flanged bushing with 1/32" of material which secures the installed o-ring. The flanged bushing is press fit into the hull, and the intention is that the translational forces born from the fin, are transmitted into the hull directly. When the fin is installed, the top flange acts

as a low-friction interface for the fin to slide across. Along the length of the shaft, the teflon washer, the follower gear, and the M3 threaded hole in the shaft, when assembled, is highly planar with the hull with tight tolerances. Altogether, this assembly constrains the shaft in 5-DoF. While the fin has the potential to produce a large moment, it is designed to sit closely to the hull, such that upon any deformation towards the hull (most impacts), there is physical interference with the hull, in order to mitigate further loading on the o-ring or the overall assembly.

The designers admit that originally the reliability of this assembly was questioned when conceived and the hypotheses were difficult to explicitly analyze to predict performance. Because of this, the design was explored via extensive experimentation due to the potential advantages for the intended applications, and has further been put to service across nine assemblies. This assembly and seal design has been physically tested to 60 meters depth off shore (602 kPa), and has been left sealed on a Spurdog AUV for four months with a 40 kPa vacuum (61 kPa absolute) over the course of over 70 field operations and experiments, and there has been zero failures or leaks, across complete vehicle assemblies. Similar performance was observed across the four Sea Badgers throughout their operation, which employed the same design.

For an o-ring, we specifically use an Buna-N rubber X-Profile o-ring as they are typically regarded to have improved performance for dynamic sealing applications over conventional round o-rings. There are various arguments for why this is the case, such as there being four points of contacts and two individual sealing surfaces, the seals requiring less compressive forces to form a seal which imply they have a longer service life, or further they may be more resistant to twisting due to their geometry [12]. The designers specifically prefer these o-rings for dynamic sealing applications since it is easier to observe if an o-ring has been *installed* with a twist which can be corrected before servicing them, and these o-rings can be installed in a gland while holding more grease in the grooves, and under loading, it is speculated by the designers that under deformation this grease moves away from a region of compression and towards the region where a gap may have formed within a control volume, helping support the seal with a high-viscosity high-vacuum grease.

The o-ring dimensions were designed with Parker O-Ring Handbook [13], and adjusted after experimentation to account for shrinking which occurs from most SLA 3D printing.

C. Fin Design

The SLA 3D printed fins consist of a potted standoff embedded within the fin's main form, and are less than \$9 each with minimal labor. Perpendicular to the top of the shaft, a flat machined face mates parallel to the standoff which are fastened with a machine screw. The motivation for using a stand-off over conventional threaded inserts, is so that during assembly large preload can be stored in this joint (screw, shaft, and standoff), while any loading between the stand-off and the fin is distributed via the epoxy interface between the standoff

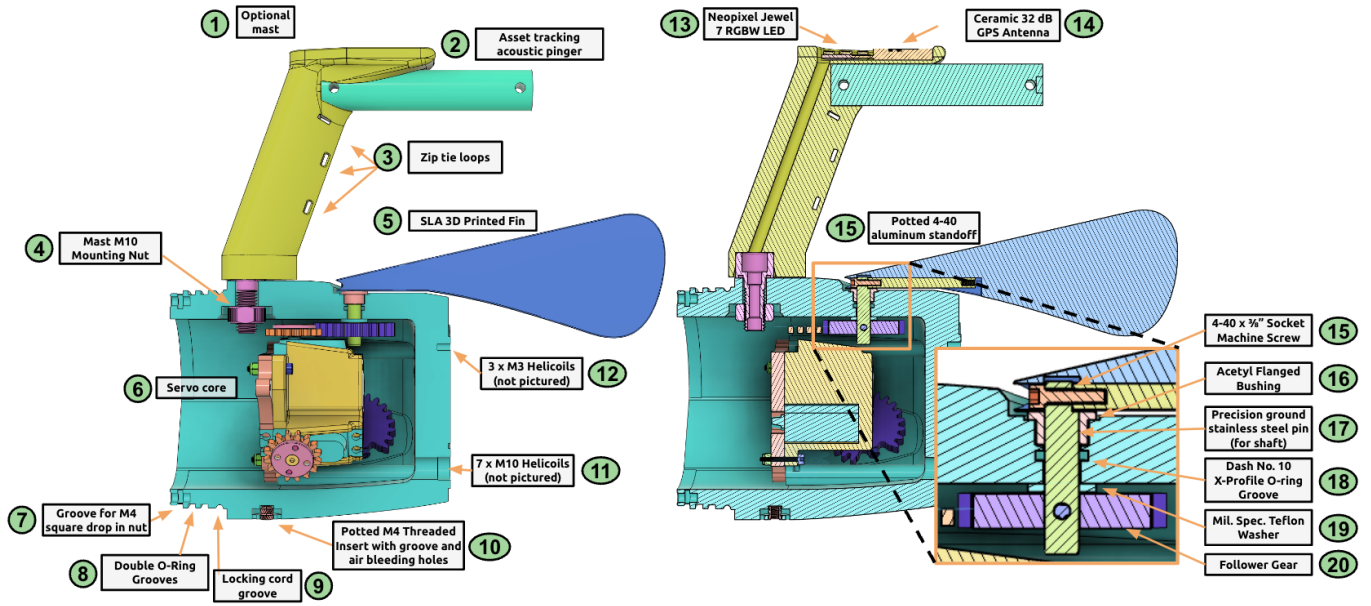


Fig. 6. Split view depicting the overall Trident aft section internal assembly, fin design, and seal design.

and the fin over a large contact area, reducing concentrated forces within the cured photopolymer resin. Further, Loctite can be used during assembly without contacting any plastic components.

D. Torque Transmission

The elements engaged participating in the load path (without the hull, acetyl plate, and 3D printed servo core, to simplify visualization) are highlighted in Fig. 7. From this, we point out that from the servo, torque is transferred from the servo hub, to at least two countersunk M3 screws in shear with the leader gear, and from the leader gear to the follower gear. The follower gear mounts to the shaft with an M3 screw through a tapped hole in the shaft, transmitting torque through friction and shear with the M3 screw. This then controls the fin which is pinned to the shaft through the 4-40 screw, shaft, and 4-40 standoff.

E. Mast Design

A mast is an optional feature which may be integrated via an M10 penetrator. An S.E.A. variant of this aft section contains a general purpose port, rather than dedicated alignment or integration features. For example, in the current design, the design includes a cast 7 element RGBW LED and a ceramic antenna under 1 mm of clear epoxy. Beneath the top of the mast, there is a fitted cap which may be removed to insert an asset tracking acoustic pinger from Sonotronics which may be included before a deployment via dedicated zip tie loops. The placement is motivated by the interest to keep it placed above the AUV, so that in the case of a failure where it may be stuck in sediment, the acoustic pinger is not dampened.

A mast is cast in epoxy, and to an M10 penetrator, where a nut secures it from below. This is so that the mast may be

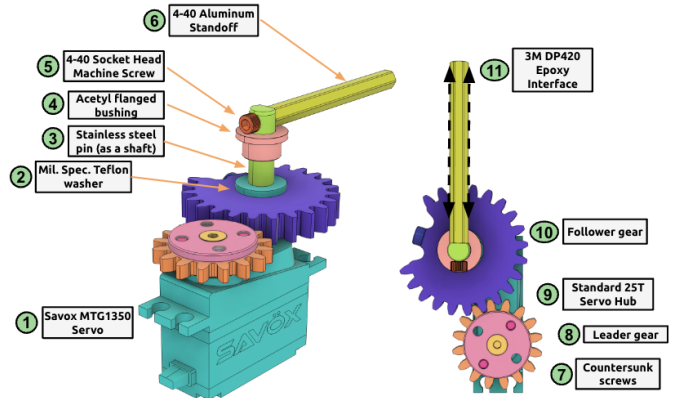


Fig. 7. Isolated view for elements participating in load path, not including the main hull, acetyl servo core mounting plate, or the 3D printed servo core.

aligned during assembly and is only constrained in rotation about the port with significant static friction. Alternatively, there would be challenges to permanently thread this feature due to the need to aligning the thread start so that all masts would be aligned correctly.

F. Manufacturing & Assembly

Assembly of the aft section is fairly simple and straightforward. There are some unique considerations to the SLA printed variant which will be discussed in this section.

1) *Threading*: First, there is a practical challenge for including reliable, strong, and reusable threads in 3D printed parts, with subtle unique challenges when installing them on SLA 3D printed parts. In this design, most permanent threads are M3 and M10, with one M4 thread. Most standard threaded

inserts include heat set inserts, press-fit inserts, and helical inserts, and there are other design modifications which may leverage drop in nuts.

For the SLA printed variant of this design, there are unique one-off features which would not be included in other manufacturing methods. For one, a single M4 heat set insert, is potted with DP-420 epoxy in the bottom of the aft section, for mounting a bracket which holds an 8020 rail on the Spurdog. Melting threaded inserts into SLA components is typically unreliable, so we included a larger gland and employ a brass heat set insert for the exterior channels, which mold with the epoxy in the gland. Elsewhere, such as the three M3 threads used in callout 12 of Fig. 6, Helicoils are used to install fine reusable threads, which secure the M200 motor assembly.

Next, for the M10 penetrators which connect to the aft section, we employ M10 Helicoils. During installation, we install them with a permanent adhesive to prevent them from twisting once installed. Further, we drive them at least 6mm beyond the top face, and at least 1 mm beyond the bottom of the hole. Potted M10 penetrators from Blue Robotics currently have 5 mm of unthreaded length, which are intended for use in clearance holes and secured with a nut. Secondly, when installed 1 mm below the bottom of the hole, the pitch of the thread changes and becomes slightly longer than 1.5mm standard pitch. In practice, since the M10 stainless-steel Helicoils are rather stiff and rigid, this becomes a strong locking feature which is exploited in the installation of the Cobalt Bulkheads and M10 penetrators. These connectors become very hard to remove by hand without leverage, creating a reliable thread locking feature without any permanent adhesives, while these ports frequent operator interaction during deployments. This allows users of the interfaces placed in the aft section to casually interact with the vehicle while reducing the risk of unsettling the compressed o-ring under the bulkhead or penetrator by accident.

At the interface where the Spurdog's electronics assembly mates with the aft section, we use M4 square drop in nuts, for more reliable load bearing performance than Helicoils or heat set inserts, which allows the complete assembly (tailcone and electronics), to be handled by the electronics aluminum and brass chassis or the tailcone section.

2) *Waterjet Gears*: Typically waterjet gears are a cost effective manufacturing method for prototyping, however may introduce backlash, or a poor surface finish along the cutting path of the abrasive garnet. The striations and material along this edge may wear off and introduce particulates into the assembly once serviced. To streamline the manufacturing process without introducing these risks, there were specific procedures introduced to address this. The design includes a deliberate 0.003" interference between the two pitch diameters to allow the waterjet gears to be broken in upon first assembly with a petroleum based cutting fluid and lubricant. Secondly, a high-quality cut was selected in the interface in order to minimize the occurrence of larger striations on the part. Further, elements of the servo core may deform to allow firm contact in the gears to reduce backlash. In practice, this has

resulted in very little (if any) backlash in the assembly, and has rendered satisfactory results and performance.

3) *O-Ring and Shaft Installation*: Originally, the motivation for re-machining a pin is to achieve a low-cost and tight tolerance shaft with a smooth surface finish at the sealing interface. It was thought to simplify machining labor by eliminating the need for a lathe, and instead, only require a simple two-part 3D printed fixture to be used on a mill. In practice, this choice has occasionally resulted in challenges when installing the shaft through the o-ring gland, which will be addressed in future work. Similarly, on the Trident A450 Rev. 0, this seal was produced in an independent SLA 3D printed component which was quality checked before potting it within the hull and allowing misalignments in the assembly to be corrected via potting. The latter became cumbersome and time consuming in practice, where 3D printing the o-ring groove in the hull directly streamlined the process substantially. Overall, while this seal design has been reliable in field operations, it will be adjusted for future work in order to reduce potential risk for shearing or abrading the o-ring, and be more reliable and faster to reproduce with better tooling.

The shaft consists of a stainless steel pin which is made on a mill within an SLA printed jig. It includes a 0.050" flat on the 0.25" diameter shaft (forming a D-Shaft), and a clearance hole for the 4-40 screw, and a tapped M3 hole for mating with the follower gear. The bottom of the shaft and the M3 hole include large chamfers to minimize shearing the o-ring upon installation. The 4-40 and M3 hole along the shaft are offset with a 45-degree rotation, to allow installation of the follower gear on the shaft with a T-handle when a fin is rotated counterclockwise, while the servo always remains on the follower gear teeth within the operating region.

The o-ring is installed in the hull, by first installing lubricant within the groove in the hull, and adding lubricant to the o-ring independently. Thereafter, the acetyl bushing and shaft is installed, before mounting the fin and the follower gear.

G. Costs and Materials

The cost of the aft design presented herein, is a significant portion of the cost for the Spurdog AUV, being up to one third of the total costs. The costs and prices listed are as of August of 2024, and does not include specialized tooling (i.e. M3 Helicoil installation kit, epoxy applicators, etc.) or shipping. Simple amortizable costs have been included for precisely what is used. For example, if six M3 x 14 mm screws are used in an assembly but can only be bought in a bag of 100, then the cost for exactly six screws is included in this estimate. Similarly, for resin materials, 1028 mL of resin is approximated by the PreForm slicer, however resin is sold in increments of 1 liter, however the cost for exactly 1028 milliliters included, where as the costs for post processing (washing in IPA), are difficult to approximate.

With this, the total estimated cost for the aft section design which has been tested and fielded on four Spurdog AUV's, and presented in this paper is \$1,074.82 each. These costs are approximate, and are based on the cost for the authors

to manufacture them in on-campus machine shops. Generally, the implementation discussed can be made from cheaper components and materials, where the implementation discussed is likely one of the more expensive variants which may be produced in this tier (SLA printed). The allocation of cost for this implementation is depicted in Fig. 8.

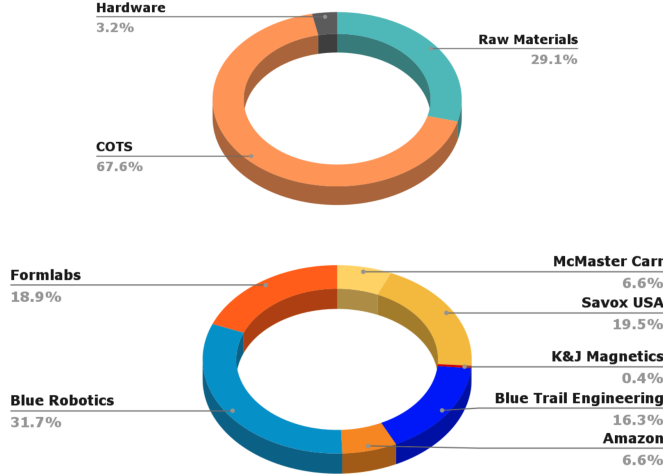


Fig. 8. (Top) Cost breakdown based on commercially available parts, raw materials, and hardware, and (bottom) cost breakdown based on cost allocation based on distributors.

Most of the costs are attributed to Commercial Of The Shelf (COTS) parts at 67.6%, where just under one third of the costs are due to raw materials 29.1%. 19% of the cost is attributed to the premium Tough 2000 resin from Formlabs, while 48% of the costs are attributed to Blue Robotics and Blue Trail Engineering for standard components and connectors, which are subject to educational discounts, which were not included in this breakdown of costs. The only items purchased from Amazon, were for convenience, which include the Hobbywing ERPM sensor, the DP-420 epoxy, and the servo hubs.

VII. CONTROL PERFORMANCE

The following data presents the standard fins for this aft section, which have a planform area of 49 cm², and make the vehicle as observed along the x-axis in a NED frame, have a profile diameter of 177 mm (6.97 "). These results were from preliminary field data for ongoing work on adaptive control, where these results were from a conventional AUV controller which use PID depth control, and only PD control for roll, pitch, and yaw. Further, the vehicle was partially roll compensated with external ballast due to the absence of a shroud and set of stators at the time of testing. These results are to inform readers on the expected performance for this aft section on an AUV which is 96 cm in length, and 11.43 cm in diameter, weighing less than 9 kg.

In these results, we include only PD control for heading control limiting the rudder to roughly 50% the maximum allowable effort. We employ PID control for the depth controller, and pitch control limiting the maximum pitch to ± 12

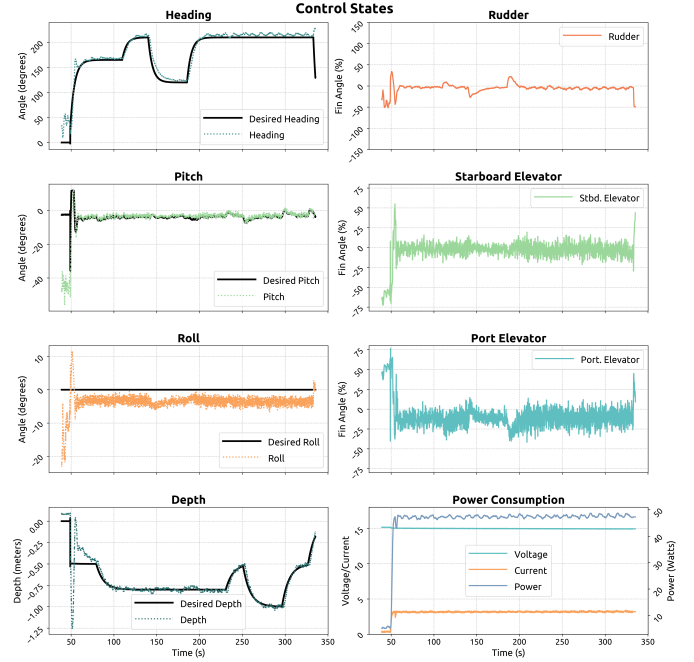


Fig. 9. A sample of field trial results of a for a Trident S.E.A. 450 tailcone equipped to a Spurdog AUV.

degrees, and limiting the pitch elevators 70% the maximum effort. With this, the Spurdog with the aft section, when under the constant disturbance of the tether, succeeds in trajectory tracking control, while counteracting roll actively throughout the mission, and particularly during turns.

VIII. CONCLUSIONS AND FUTURE WORK

Overall this work introduces the Trident series of tailcone designs, with a version which is currently implemented on the Spurdog AUV. This aft section design includes 3-axis control, and is designed to be highly modular and reconfigurable to support high-level and wide ranging research objectives. The aft design includes most physical interfaces required for an AUV, which has been motivated by the sequential coupling system on the Spurdog. This work intends to foster a discussion on specifically the methods and the design of the aft section, with a sample of performance data when tested on the Spurdog.

Throughout development and testing, the importance of a well-designed shroud and set of stators has been further realized. Smaller AUVs, such as A-Size AUVs, typically have poor innate inertial hydrostatic stability due to the small separation between the center of gravity and center of buoyancy. These were included on the variants developed for the Sea Beaver I and the Sea Badgers, however, this feature has been momentarily excluded from the present design explicitly due to ongoing work with experimental propeller characterization. While the torque due to the propeller may be canceled out with the three fin axes, it effectively wastes the allocation of effort in compounded maneuvers such as simultaneously diving, turning, all while canceling out unwanted roll. The

placement and overall fin design, especially in an A-Sized configuration, is intended to have improved heading and pitch control authority over alternative A-Sized fin-based aft section designs, while also being able to actively cancel out roll. It has been observed that this design is effective for heading and pitch control, and reduce unwanted roll. Due to the small separation between the center of pressure of the fins and the x-axis, the aft design is less effective for rejecting large passive disturbances in roll, and is best complemented with a shroud and set of stators in order to maximize control authority throughout compound maneuvers.

The intention is that a shroud and cowling will be included on the bottom fixed magnetic cowling as seen in Fig. 4. Next steps in this design include a design of an optimized cowling and set of stators for the propellers employed on the Spurdogs, and change the dynamic seal paradigm from a female gland to a male gland within a custom shaft fabricated on a lathe while preserving other characteristics in the overall fin, follower, and seal assembly, which will reduce overall risk of damaging the o-ring during installation and simplify the assembly process.

Future research work extending this design includes:

- A comparative study with a variety of fin sizes and shrouds, to better study the relationships between roll, pitch, and yaw control authorities, and passive roll control.
- An extension of the principles included in this design to a four-axis aft section design.
- The impact of propeller walk on asymmetries in A-Size AUV control and its impact on maneuvering.
- Destructive testing and complete characterization of capabilities and performance.
- Spring loaded A-Size fins which deploy more control surface area to improve maneuverability when deployed.

Ongoing work related to this aft section design includes characterization of conventional and toroidal marine propellers, adaptive control and estimation, and the design of small Autonomous Underwater Vehicles.

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