

The Spurdog AUV: A Field Configurable and Optionally A-Sized Low-Cost AUV

Raymond Turrisi^{1,2}, Haojing Huang¹, Filip Strømstad¹, John Morrison^{1,2}, Alan Papalia^{1,2},
John Leonard¹, Michael Benjamin¹

¹Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

²Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA

rturrisi@mit.edu

Abstract—The MIT Spurdog AUV is a low-cost autonomous underwater vehicle (AUV) designed to facilitate research in multi-agent autonomy. The core vehicle costs less than \$3,000 USD and utilizes commercially available or 3D-printed parts to enable easy reproduction and maintenance. Featuring a new Sequential Coupling System for modular payload integration, the Spurdog supports rapid reconfiguration and multiple modes of manufacture. This paper presents the Spurdog’s mechanical, electrical, and software architecture, highlighting its potential to serve as an intermediate platform which bridges the gap between academic research and more advanced field-operable AUVs.

Index Terms—autonomous underwater vehicles, field robotics, modular robotics, marine robotics, heterogeneous autonomy, open-sourced robotics



Fig. 1. One of the four fabricated MIT Spurdogs at the MIT Sailing Pavilion.

I. INTRODUCTION

This work introduces the Spurdog AUV — a cylindrical hull form Autonomous Underwater Vehicle (AUV) with a single thruster and fin-based control, which is A-Size ready through the integration of the MIT Trident 450 S.E.A. tailcone [1]. This platform will lower the barrier for novel multi-agent research and facilitate the transfer of new technology and research to fielded systems in the fundamental sciences and defense applications. The standard Spurdog AUV costs less than \$3,000 USD (as of August 2024) due to a strategic use of commercially available components and low-cost and simple to manufacture custom components. The vehicle design supports multiple manufacturing methods and materials, allowing the core capabilities to scale with mission requirements.

The Spurdog uses a new and open standardized sequential coupling system and software-defined interfaces to permit modular payload integration and hot-swapping of payload modules while in the field. This open architecture intends to streamline payload integration for designers and operators, while reducing risk when fielding new technology. Herein we discuss the underlying philosophy, as well as the unique mechanical and system design approaches, which maintain low per unit cost and encourage the addition of user-developed payloads.

Special thanks to **Saab USA**, for co-funding the development of this work with their generous support with student funds, and the National Defense Science and Engineering Graduate (NDSEG) Fellowship Program.

II. RELATED WORK

The development of low-cost Autonomous Underwater Vehicles (AUVs) has been an active area of research and innovation in recent years. While many different vehicles have been developed, we discuss a handful of related platforms with similar objectives, interests, and contexts, in order to motivate the Spurdog.

There are a number of commercial AUV platforms developed for oceanographic and defense missions which feature a modular payload capability. These generally include AUVs such as the Bluefin Sandshark (discontinued, min. \$20,000 USD), Iver3 series (min. \$50,000 USD) [2], YUCO AUV (min. \$25,000 USD) [3], Jaiabot (min. \$10,000 USD), Riptide AUV (no longer commercially available, min. \$15,000 USD), and lastly, the ecoSUB AUV (min. \$20,000 USD). Further, higher end commercial platforms such as the Gavia AUV include a proprietary modular structure with a limited number of field-changeable modules. While some of these vehicles may address the intended applications of the Spurdog, it becomes prohibitively expensive to procure several of these vehicles for multi-agent experiments, and may not support the same level of reconfigurability as intended with the presented design.

There are also several open-source, low-cost platforms which have been developed for academic research, namely the ALPHA [4] (min. \$13,600 material parts USD), LoCO (approx. \$4,000 material parts USD) [5], and the HippoCam-

pus (min. \$800 material parts USD) [6]. However, each of these platforms is designed to fill a unique experimental niche. For example, ALPHA is a highly maneuverable AUV which uses vectored tunnel thrusters and can carry a wide variety of payloads. LoCO consists of two hulls and three thrusters and was optimized for diver support via human-robot interaction. The HippoCampus is a micro AUV designed to achieve hydrobatic maneuvers, operate within highly confined environments, and support very small localization and vision-based payloads.

Beyond commercial and open-source platforms, the DREW-UV developed by Naval Surface Warfare Center Panama City Division (NSWC PCD) has been developed with similar intentions and motivation as a low-cost experimental AUV with a cylindrical hull form, within a standard Blue Robotics tube. Further, limited publicly available fundamental research has been conducted on the development of A-Sized AUVs, beyond Morpheus, which is a modified Mk 39 EMATT variant [7], which sought to maintain an A-Sized configuration when stowed, but included actuated dorsal fins to improve maneuverability when needed.

III. MOTIVATION

While each of the platforms discussed thus far are innovative with respect to their design methodology and applications, they fail to balance cost, modularity, payload capacity, and ease of reproduction, in the manner required for multi-agent heterogeneous autonomy research. The Spurdog aims to address this gap by offering an open and low-cost platform, which would allow researchers to reduce technical risk in fielding novel technologies, before translating them to more robust platforms.

The Spurdog's design philosophy envisions a standard vehicle which provides a minimal solution for most AUV research applications. Its open architecture and standardized payload interfaces enable the integration of diverse sensor payloads to adapt the vehicle to specific experimental roles. By maintaining the per-unit cost low (under \$3,000 material parts USD), the Spurdog simplifies fleet procurement for researchers and lowers financial barriers to multi-agent testing.

IV. CONTRIBUTIONS

- A low-cost and rapidly re-configurable baseline platform, with free licensing options for academic research and educational programs starting March of 2025
- An open AUV framework to aid in the technical transfer of research to high-value commercial and industrial platforms.
- A feature rich and modular aft section compatible with standard commercially available hardware
- A versatile sequential coupling scheme for both power and communication propagation, and payload extensibility
- An open-architecture platform which permits the development of diverse payloads to support a user's unique needs

- An AUV which supports multiple modes of manufacturing, to allow capabilities to scale with mission needs

V. DESIGN

A. Overview

The standard Spurdog design depicted in Fig. 1 and Fig. 2 contains the minimum equipment required for basic AUV missions. The standard vehicle consists of a three primary sections: the Trident aft section [1] (containing the external user interfaces, select sensing such as depth, thruster and control surfaces), the core bottle (containing the main electronics bay and battery), and the nose-cone (containing a altimeter and auxiliary electronics bay).

The set of electronics selected for the standard vehicle provide safe and effective closed-loop control over the directly observable states of depth, altitude, roll, pitch, and yaw, for maneuvering while submerged. This complements the standard outputs of the autonomy framework provided by MOOS-IvP, which typically outputs desired heading, depth, and speed [8]. It is primarily intended that this framework is sufficient for basic missions and research objectives. Depending on the scope of research or the application, a custom payload will fill in the gaps in state-estimation as needed, and may take over and steer the vehicle along a desired trajectory through standard or user defined interfaces.

The standard vehicle is designed to be readily enhanced by the inclusion of sequentially coupled user-designed payloads, or simple modifications for the standard vehicle. This may be achieved via the Sequential Coupling System (SCS), the inclusion of small payloads with room left within the spare payload region on the standard electrical tray, or refactoring the standard nose-cone as needed. A modified vehicle containing a WHOI Micromodem-2 in the modular payload bay and a Cerulean DVL integrated into the nose-cone is shown in Fig. 3. While rapidly re-configuring an AUV with payloads is of itself not a novel concept [9]–[11], the SCS designed for the Spurdog is a unique approach for a cohesive mechanical, electrical, and software solution for integrating payloads through low-cost custom components and commercially available connectors.

All critical components are designed to support multiple modes of manufacturing so that a common design can be adapted to a range of mission requirements and manufacturer resources. For example, the Trident aft section and sequential coupling flange designs support SLA printing, and with small modifications, high-strength urethane casting, and mill and lathe machining. Furthermore, all modular payloads can utilize either the Blue Robotics cast acrylic tubing or the dimensionally-equivalent aluminum tubing depending on the required depth rating.

B. Technical Specifications

The Spurdog is inherently modular, where we present the recommended minimum configuration standard and specifications, including performance metrics with a propeller op-

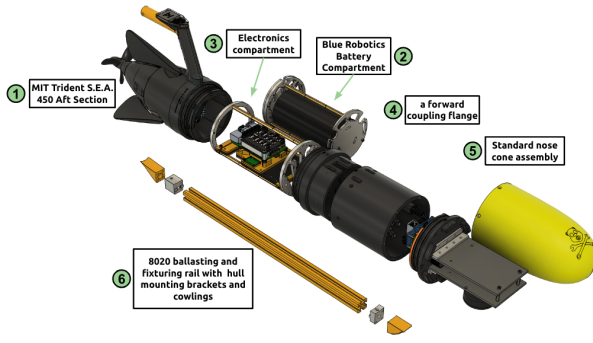


Fig. 2. An exploded view of the standard Spurdog AUV.

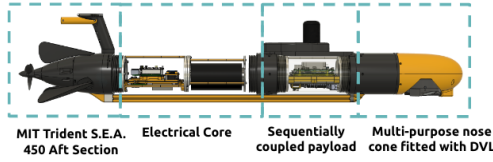


Fig. 3. A diagram depicting an example configuration with different assembly boundaries. This example assembly demonstrates Spurdog with a WHOI Micromodem Payload, and a modified standard nose-cone with a Cerulean DVL.

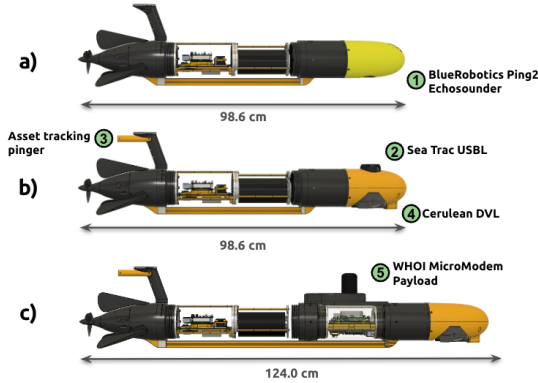


Fig. 4. The Spurdog supporting sequential coupling capabilities and example modifications, beyond the minimum core vehicle. A repurposeable nose-cone is essentially a terminating payload, where more payloads can be placed between the core bottle, and a designated terminating payload.

timized for this vehicle and recently characterized at the MIT Sea Grant Tow Tank [12].

C. Aft Section and Propulsion

The Spurdog uses the Trident S.E.A 450 Rev. 1 tailcone, which succeeds the tailcone design for a sonobuoy-sized AUV such as the Mk 39 EMATT, and upgraded to support this vehicle's sequential coupling architecture. In addition to the thruster and 3-axis control surfaces, which are discussed in greater detail in [1]. The aft section contains all principle physical interfaces for the vehicle, shrouded by a removable hydrodynamic cowling. Through the aft section, an operator can turn the vehicle on and off, charge the primary battery (and balance individual cells), and adjust the atmosphere of

Parameter	Value/Description
Dimensions (min)	11.5 cm ϕ x 1 m
Weight (min)	9 kg
Depth Rating (tested) (min)	60 m
Endurance (max - one battery, idling)	26 hours (265 Wh Battery)
Endurance (Nominal - one battery, approx. 1 m/s)	4 hours
Compute and Processing	Raspberry Pi 4 + Blue Robotics Navigator Flight Controller
Inertial and navigation sensing	1 x ICM-20602 IMU, 1 x MMC5983 Digital Magnetometer, 1 x AK09915 Electronic Compass
Propulsion	Blue Robotics M200 motor with optimized propeller
Software and Operating Framework	moos-ivp, moos-ivp-spurdog
Costs (min)	\$2,500 with \$200 amortizable costs
Max Instantaneous Rated Power Output	340 Watts
Max Empirically Estimated Speed	4 m/s

TABLE I
SPURDOG AUV SPECIFICATIONS AND PERFORMANCE METRICS

the core bottle. By incorporating these connections into the aft section, the design makes no assumptions about the modular payloads supported by the core bottle. Additionally, the aft section includes a wet sensor which allows the vehicle to be armed prior to a mission, then activated once it enters the water (or automatically deactivated if it is pulled from the water prematurely).

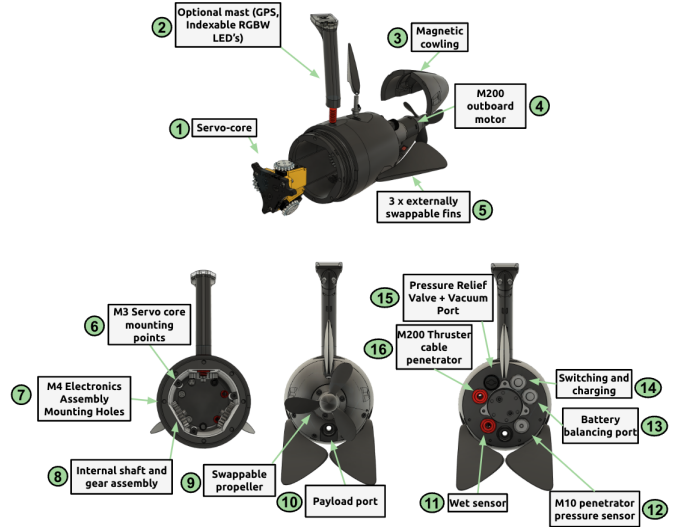


Fig. 5. MIT Trident aft section, specifically MIT Trident S.E.A. 450 Rev. 2.5. This diagram depicts the overall aft section assembly at a high level, with the features contained herein.

D. Core Electronics Assembly

The current electronics core consists of two independent mechanical assemblies: the electronics compartment, and the Blue Robotics battery compartment, structurally suspended by brass standoffs and waterjet aluminum plates. The electronics

compartment includes the standard set of electronics mounted to an acetyl plate which slides into a 3D printed hinging electronics tray. This structure allows additional payloads can be included in spare space region depicted in Fig. 6, or by replacing the entire assembly with a custom electronics stack.

The core assembly attached to the aft section, includes a Raspberry Pi 4 main computer with the Navigator Flight Controller hat, a 5V/15A power supply, a 100A/25.2V Power Sense Module, a Neo-M9N GPS module, a Bar30 sensor, three servos, an ESC with the M200 motor, a Hobbywing ERPM sensor (not depicted), a wireless USB network adapter, and a wet sensor. The Raspberry Pi interfaces with these systems through the Navigator, but can also access the Navigator's onboard sensors such as the onboard IMU, two compasses, and barometer. The overall electrical assemblies for the core vehicle and the standard nose-cone is depicted in Fig. 6. The 5V/15A power supply and a terminal block is positioned on the bottom of the default electronics tray.

The battery compartment suspends the battery under slight compression between two aluminum plates. This is achieved by compressing the battery against a soft adhesive neoprene rubber pad designed with a 2 mm interference, which is sufficient to rigidly secure it within the total assembly. Altogether, this simplifies mechanical assembly and harnessing, while allowing the battery to be easily replaced when necessary.

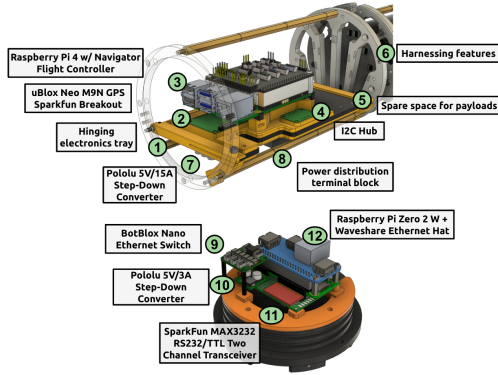


Fig. 6. Standard set of electronics employed in the default electrical stack on the Spurdog, and the standard nose-cone payload.

E. Nose-cone Electronics Assembly

The nose-cone is the default terminating payload consisting of a flooded payload compartment protected by a replaceable cowling and an auxiliary electronics bay which is sequentially coupled to the core bottle. The auxiliary electronics bay includes a Raspberry Pi Zero 2 W with a Waveshare Ethernet HAT, a BotBlox Nano Ethernet switch, and a 5V/5A power supply. This allows for the integration of sensors using either a single Ethernet port, two TTL or RS-232 ports, or the Raspberry Pi 2 W GPIO pins. Access to the flooded portion of the nose-cone is provided through three bulkhead penetrations. Further, if necessary, the standard nose-cone can serve as a template and readily be replaced with another termination payload.

F. Sequential Coupling System

The Sequential Coupling System (SCS) is a key innovation of the Spurdog, enabling modular payload integration with standardized mechanical, electrical, and communication interfaces. The mechanical interface consists of forward and rear coupling flanges that provide a rugged connection between modules, as depicted in Fig. 7. Each module rear flange includes a Pressure Relief Valve (PRV) for independent environment evaluation. Electrically, the SCS uses 3-Pin and 8-Pin Blue Trail Engineering Cobalt connectors for power and data transmission respectively, as depicted in Fig. 8.

The 3-Pin connector provides a power bus, a switched bus with measured voltage and current, and a common ground bus. All batteries, regardless of whether they are installed in the core bottle or a payload module share a common ground (pin 0) and common output (pin 1). A physical switch, when installed shorts pins 1 and 2, to establish a switched bus which delivers power to all core and payload electronics.

The 8-Pin connector accommodates a 100 Base-TX Ethernet bus and a 3.3V I2C bus, allowing for both high-speed data transfer and integration of simple, micro-controller based payloads. Within each module, a standard T-568B Ethernet cable is used to propagate Ethernet and I2C. I2C is physically implemented as twisted pairs with the ground lines connected between the payloads.



Fig. 7. Sequential coupling flanges, labeling features and components. Here we depicted mated flanges which join payloads, in addition to the intermediate flooded section.

G. Modular Payload Integration

The Spurdog design supports the integration of modular payloads between the core bottle containing the battery and main electronics bay and the nose-cone's auxiliary electronics bay. Payloads are required to conform to both the mechanical and electrical interface scheme posed by the sequential coupling system. A payload designer may modify the coupling

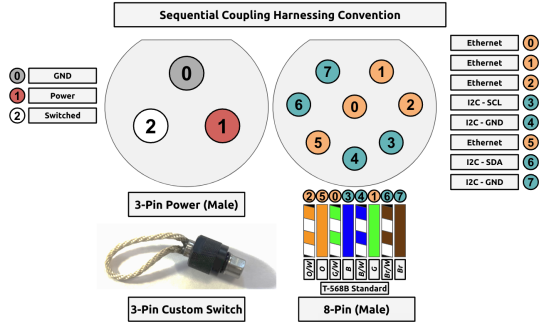


Fig. 8. The SCS’s standard electrical harnessing consists of propagating power and communication among payloads. Here we depict the implemented standard which enables adding batteries in parallel via payloads while switching all payloads simultaneously, in addition to propagating the Ethernet and I2C with a T-568B Ethernet standard via 8-pin Blue Trail Cobalt connectors.

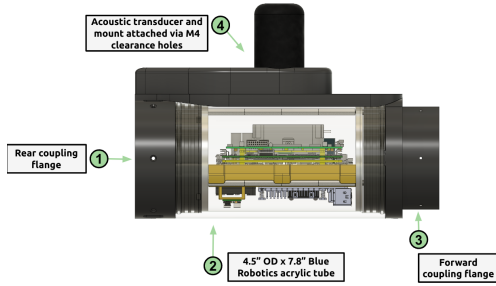


Fig. 9. Example payload which has been developed, which supports a WHOI Micromodem 2 [13].

flanges to meet a payloads needs, such as routing cables outside the bottle.

An example payload which has been developed is depicted in Fig. 9, integrates a WHOI Micromodem-2, Microstrain AHRS, and additional computer for inter-vehicle communication and range-aided localization. Additional payloads include a secondary battery for extended range and a payload autonomy cylinder which provides a separate “backseat” computer.

H. Fabrication and Assembly

Four vehicles have been manufactured and tested to date. These vehicles have used SLA printed parts from Formlabs Tough 2000 Resin, waterjet aluminum plates with tapped holes and harnessing features, and a small number of FDM printed parts for thin-walled fairings or internal semi-structural features like electronics supports. Future work with collaborators aims to develop more robust fabrication methods.

The dominant blocking process in terms of time to manufacture components for the SLA 3D printed variants of the Spurdog which have been fielded and tested, is the SLA printing. We exclusively use Tough 2000 Resin from Formlabs. For the standard assembly presented in Fig. 2, the standard assembly is a minimum of 1956 mL of resin, and little as 77 hours and 28 minutes of continuous printing. On the newer Form 4, it is estimated within PreForm that the same parts can be printed in 23 hours and 48 minutes of continuous printing.

Number of Printers	Form 3	Form 4
1 Printer	77 hours 28 minutes	23 hours 48 minutes
3 Printers	26 hours 42 minutes	8 hours 52 minutes
6 Printers	17 hours 22 minutes	5 hours 39 minutes

TABLE II

FORM 3 VS FORM 4 PRINT TIMES COMPARISON

The other processes involved in the fabrication of components occur concurrently and are comparatively much faster or non-critical, and the precise times depend on systems (waterjets and 3D printers) which vary widely among different systems. For example, all the plates in a single assembly have been observed to be waterjet in under 45 minutes on a reasonably powerful waterjet, while the handful of FDM printed parts which are used in a core assembly, can be printed in less than three hours on a Bambu P1P, while larger individual parts like a nose-cone fairing requires virtually no post processing and print in under 4.5 hours.

VI. SOFTWARE AND SYSTEMS ARCHITECTURE

A. Overview

The overall software and systems architecture is designed around maintaining several vehicles within a working group out of a forked moos-ivp-spurdog repository, and actively using any number of them in a single multi-agent mission. Each Spurdog’s core assembly and Raspberry Pi is configured to host its own DHCP server with a small number of dynamically assigned IP addresses, while it is expected that equivalent payloads use the same static IP address to be plug-and-play. A payload, when developed, sets the same static IP address to its Ethernet network interface, to maintain plug-and-play functionality. The only intended unique features which make up a Spurdog within a working group are 1) the hostname assigned to the Spurdog upon creation (i.e. spurdog-04) for system profile propagation, and 2) the IP address which gets assigned to the USB network driver once connected to a Wi-Fi network.

B. Middleware and Operation

The Spurdog employs a modular software architecture based on the MOOS-IvP middleware and autonomy framework. Key components include:

- MOOSDB for inter-process communication
- pHelmIvP for high-level autonomy
- pTridentCtrl for actuator interfacing and sensing
- pSSPID, a basic AUV controller for local state control (depth, pitch, roll, and yaw)
- pNavigator_DINS, the primary interface for sampling the Navigator’s onboard sensors up to 200 Hz, while sharing this data via shared memory, and providing the basic sensor fusion solution to estimate orientation
- Various state estimation, sensor interface, and MOOS utility processes

The network configuration supports direct access to the vehicle through an access point hosted by the Raspberry Pi, facilitating development and field operations, and through the

network the vehicle is connected to through the USB network driver. The DHCP server and interface bridging allows plug-and-play functionality for payloads, while sharing internet access to connected payloads through the standard vehicles Ethernet network interface.

VII. SAMPLE RESULTS

Herein we present a sample of performance data of a roll-compensated (with ballast) Spurdog under PD control only, without a cowling or stator. Desired state inputs from the IvP Helm are smoothed by a first order low-pass filter, and we observe trajectory tracking and power consumption in Fig. 10.

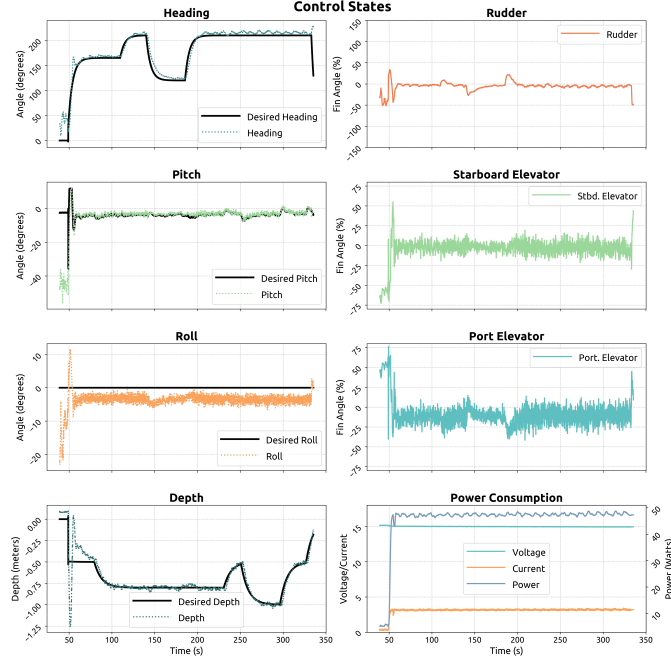


Fig. 10. A sample of field trial results for a Spurdog AUV roll-compensated with ballast (i.e. no shroud or stators).

VIII. CONCLUSIONS AND FUTURE WORK

Herein this paper we introduce the Spurdog AUV; a low-cost and open platform which is designed around a sequential coupling paradigm, with interest in simplifying the manufacturing and assembly processes required to reproduce more platforms. We discuss how this is achieved through commercially available components, a minimal number of electronic components by employing a commercially available flight controller, and a set of designs which can be produced via multiple modes of manufacturing.

While developing the platform, several challenges were realized. For one, the largest challenge has been minimizing roll on the vehicle due to torques induced by the thruster and propeller. For a vehicle of this size, the hydrostatic stability and bandwidth to passively reject disturbances is limited due to its smaller mass and inertia compared with larger vehicles. While a three-axis aft section can actively compensate for roll, compensating for a constant roll disturbance compromises

performance in more sophisticated maneuvers since all control efforts and fins are budgeted. With this, at higher speeds and larger roll angles, the vehicle becomes worse at pitching and turning in yaw due to the active participation in the elevators in counteracting roll. During the initial development, ongoing work with propeller design and optimization was also taking place, where it was not appropriate to design a custom cowling and set of stators for passively counteracting roll. Thus far this has been fixed with ballasting, however developing an optimized shroud and set of stators are the immediate next steps in this work.

Thus far, the platform has supported research on adaptive control, and will continue to support work on cooperative mobile LBL localization with low-cost acoustic modems. Future work which uses the platform will support range-aided navigation and aided diver navigation. Overall, the platform has been designed and is motivated by supporting work in heterogeneous multi-agent autonomy, and designed with constraints and concerns in mind which would otherwise be prohibitive of future use for the platform, such as being A-sized ready, being simple to reproduce with low material and labor costs, and supporting multiple modes of manufacturing.

REFERENCES

- [1] R. Turrissi and M. R. Benjamin, "A feature-rich and modular aft section for autonomous underwater vehicles: The mit trident series of tailcones," in *OCEANS 2024, Halifax*, pp. 1–6, 2024 (Accepted).
- [2] J. Crowell, "Design challenges of a next generation small auv," in *2013 OCEANS - San Diego*, pp. 1–5, 2013.
- [3] Seaber, "Seaber Underwater Drones." <https://seaber.fr/>. Accessed: 2024-08-11.
- [4] M. Zhou, E. C. Gezer, W. McConnell, and C. Yuan, "Acrobatic low-cost portable hybrid auv (alpha): System design and preliminary results," in *OCEANS 2022, Hampton Roads*, pp. 1–5, 2022.
- [5] C. Edge, S. Sakib Enan, M. Fulton, J. Hong, J. Mo, K. Barthelemy, H. Bashaw, B. Kallevig, C. Knutson, K. Orpen, and J. Sattar, "Design and experiments with loco auv: A low cost open-source autonomous underwater vehicle," in *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 1761–1768, 2020.
- [6] D. A. Duecker, N. Bauschmann, T. Hansen, E. Kreuzer, and R. Seifried, "Hippocampusx – a hydrobatic open-source micro auv for confined environments," in *2020 IEEE/OES Autonomous Underwater Vehicles Symposium (AUV)*, pp. 1–6, 2020.
- [7] S. Randeni, E. M. Mellin, M. Sacarny, S. Cheung, M. Benjamin, and M. Triantafyllou, "Bioinspired morphing fins to provide optimal maneuverability, stability, and response to turbulence in rigid hull auvs," *Bioinspiration & Biomimetics*, vol. 17, April 2022.
- [8] M. R. Benjamin, H. Schmidt, P. M. Newman, and J. J. Leonard, "Nested autonomy for unmanned marine vehicles with moos-ivp," *Journal of Field Robotics*, vol. 27, no. 6, pp. 834–875, 2010.
- [9] E. Seeley, T. Paine, J. Snow, L. Harris, J. Ruiz, W. Kempf, A. Roth, and J. Guild, "Field configurable spherical underwater vehicle," Nov. 2022.
- [10] Teledyne Marine, "Teledyne gavia auv (autonomous underwater vehicles)." <https://www.teledynemarine.com/brands/gavia>. Accessed: 2024-05-15.
- [11] K. H. Guðmundsson, "Modular autonomous underwater vehicle system," July 2003.
- [12] D. Fan, G. Jodin, T. R. Consi, L. Bonfiglio, Y. Ma, L. R. Keyes, G. E. Karniadakis, and M. S. Triantafyllou, "A robotic intelligent towing tank for learning complex fluid-structure dynamics," *Science Robotics*, vol. 4, pp. 1–12, November 2019.
- [13] E. Gallimore, J. Partan, I. Vaughn, S. Singh, J. Shusta, and L. Freitag, "The whoi micromodem-2: A scalable system for acoustic communications and networking," in *OCEANS 2010 MTS/IEEE SEATTLE*, pp. 1–7, 2010.