Power-On-and-Go Capabilities for a Low-Cost Modular Autonomous Underwater Vehicle

Chelsey Edge, Sadman Sakib Enan, Michael Fulton, Jungseok Hong, Junaed Sattar
Department of Computer Science and Engineering
University of Minnesota, Twin Cities
Minneapolis, Minnesota 55455, USA
Email: {edge0037,enan0001,fulto081,jungseok,junaed}@umn.edu

***Abstract*—We present LoCO, an autonomous underwater robotic vehicle designed for human-robot collaborative tasks for marine and aquatic environments, and its vision-based human-interface design and systems architecture contributing towards single-user operations. Specifically, we describe the operational characteristics of LoCO in assisting human divers, particularly those engaged in conservation biology, to perform endangered species preservation. LoCO is an open-source, modular platform capable of vision-assisted autonomous behavior and human interaction. We describe how vision-guided autonomy, gesture-based human-to-robot languages, and robot communication via motion have been used in a number of field trials in various water bodies including lakes and open oceans. This paper provides an insight into the system design, computing, intelligent behaviors, and human interaction capabilities of LoCO towards achieving power on and go behavior in underwater human collaborative missions.**

I. INTRODUCTION

Autonomous underwater vehicles (AUVs) have been increasingly used in marine and aquatic environments for both scientific and industrial as well as recreational purposes (*e.g.*, [7], [22], [18], [16]). However, prohibitive costs and deployment difficulties limit their use. Autonomous robots underwater have to overcome a plethora of significant challenges: communication difficulties, poor visibility, turbulent waters, structural risks, health hazards to human operators, and concerns for environmental safety to name a few. In many cases, Remotely Operated Vehicles (ROVs) are instead used, which fail to make use of autonomous capabilities, and also require constant human supervision and control, complicating the operational loop. Across a large variety of application domains, it is essential for the robot to have and provide to human collaborators a clear situational assessment of the operational domain, which ROVs may not be able to provide. With the challenges posed by the underwater domain in sensing, control, locomotion, and thus full autonomous behaviors, human-robot collaborative missions are often the most effective approach to AUV use. If an AUV were available at a lower cost, with less overhead in deployment, and with less constraint on additions and modifications to the platform, this would also significantly reduce the barrier of entry into the theories and practices of autonomous underwater robotics.

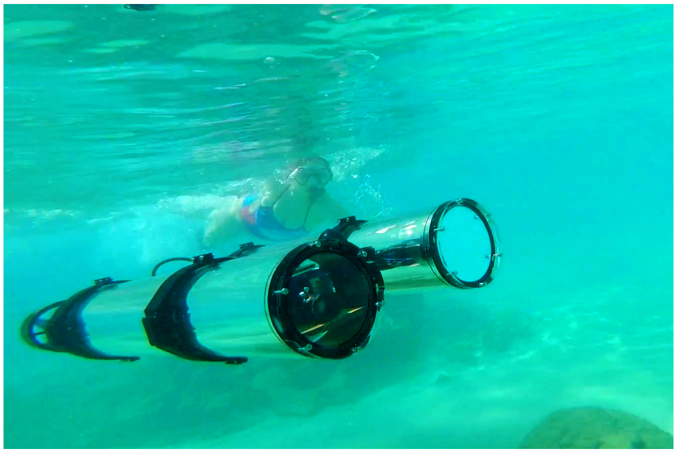

Fig. 1: LoCO in the Caribbean Sea off the coast of Barbados, seen with one human operator swimming alongside.

Towards this goal, we present the LoCO vehicle, a low-cost, open-source, autonomous underwater robot designed for single-person deployment with minimal overhead. LoCO is a power autonomous, visually-guided, lightweight robot, capable of gesture-based bidirectional human-robot communications. We designed the robot to be modular from the ground up, making it possible to accommodate a variety of systems configurations as required by a given mission. However, LoCO's ease-of-use is one of its highlights. It is capable of tetherless (*i.e.*, without a cable) operations up to a depth of 100 meters and from setup to deployment, only a single human operator is needed. LoCO is also capable of remotely-controlled operations, using a lightweight tether and standard game controller from the surface. In this paper, we specifically focus on the systems design, interfaces, and deployment process for LoCO which makes it a true POWER-ON-AND-GO robot.

Related Work

As a large body of work exists in AUV research, the authors primarily highlight works dealing with small and low-cost AUVs, suitable for rapid, low-overhead deployment. The REMUS AUV [2] was developed by Woods Hole Oceanographic Institute, in one of the first attempts to develop a smaller, lower-cost AUV than previous efforts, such as the SPURV vehicles [21, 14]. Later, REMUS 600 [19] improved on the design of REMUS, with a side-looking synthetic aperture sonar and improved endurance and payload flexibility. While traditional torpedo-shaped AUVs and gliders dominate the

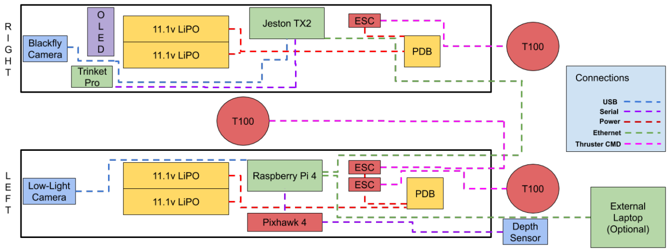

Fig. 2: LoCO systems schematic showing different electrical and mechanical components.

field of AUV development, innovation in the realm of mini-AUVs (mass of $20 - 100$kg) and micro-AUVs (mass of 20kg or less) has begun to spring up, with the flippered Aqua [5] being an example of the variation now existent in the field. Development in the field of micro-AUVs has been particularly interesting of late, *e.g.*, with HippoCampus [10] and SEMBIO [3], micro-AUVs for swarm applications, and AUVs with less typical drive designs, such as a momentum-drive single actuated robot, which rotates its inner body to move the exterior passive flaps and produce swimming motion [9]. Other AUVs such as SHAD [9], HOBALIN [15], and Sparus II [4] have focused hovering motion for seabed inspection and observation tasks, specifically in the context of micro-AUVs. Lastly, the development of general-purpose micro-AUVs is still going strong, with Bluefin's Sandshark [20], a docking AUV [23], and other similar AUVs appearing in the last few years. It is to this class of AUVs that LoCO belongs: small AUVs under 20kg with a general-purpose design, and it is here that we intend to make LoCO an example as an AUV which requires little to no configuration and allows quick and easy small-team deployments.

II. LoCO Design Outline

LoCO is configured as a dual-camera, three-thruster, vision-guided AUV. It is designed in a modular, upgradable fashion, adaptable to a variety of missions, and hence serving as a general-purpose AUV. The following subsections briefly describe the robot's mechanical, electronics, and software; refer to [6] for detailed information.

A. Mechanical

LoCO has two water-tight enclosures [17] with a pitch-control thruster mounted between them and two others mounted behind for controlling horizontal movement. Most control-related electronics are in the left-hand enclosure, while the computational hardware (*e.g.*, for deep-learning inference) is in the right-hand enclosure (as shown in Fig. 2). A laser-cut medium-density fiberboard (MDF), with 3D-printed mounting substructures, mounts the internal components. The space beneath the MDF board is used to attach blocks of stainless-steel-cut ballast, also it fits bags of desiccant which eliminates condensation if the enclosure is sealed in humid air. The flexibility in design allows users to internally mount additional components on the MDF using only screws, and externally mount new sensors between the enclosures.

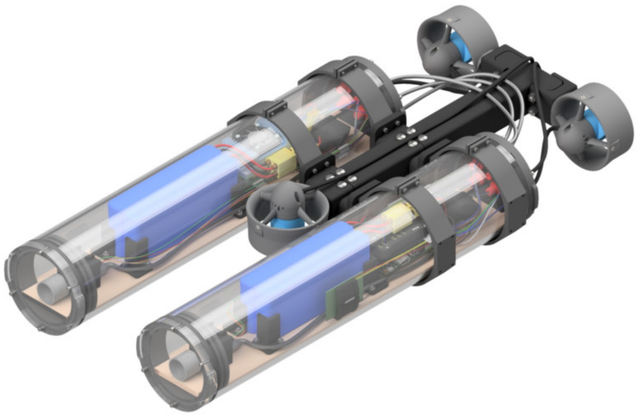

Fig. 3: Isometric view of the LoCO 3D model.

B. Electronics

Four lithium-polymer (11.1V, 8000mAh) batteries, two parallelly connected in each enclosure, are used to power LoCO. Each enclosure has its own power distribution board (PDB) to power the electronics. The entire robot is powered On/Off using a magnetic "key". The three pulse-width modulation (PWM)-controlled thrusters employed for LoCO are T100s [17], each one of which uses a brushless DC motor and a plastic propeller. The thrusters are managed by electronic speed controllers (ESCs) which in turn are controlled by a Pixhawk PX4 [13] autopilot board, employing ArduPilot/ArduSub [1] control software. Furthermore, LoCO has two primary computer systems: an Nvidia Jetson TX2 and a Raspberry Pi 4. The TX2 connects to a powerful FLIR Blackfly$^{\text{TM}}$ S USB3 camera, controls the OLED display, and is responsible for running the deep learning inferences. In contrast, the Pi 4 is used to process images from a low-light USB camera [17] and control the thrusters via serial communication to the Pixhawk, which contains the inertial measurement unit (IMU). The computer systems are connected between enclosures via a Cat 5e Ethernet cable.

C. Software

LoCO is primarily a visually-guided robot. In the basic configuration, the robot comes with two cameras, one in each enclosure, to perform a suite of intelligent behaviors which give it human-interaction and autonomous capabilities. The vision system provides fundamental building blocks for Power-On-and-Go behavior, enabling the robot to carry out object detection, human recognition and following, gesture recognition, and navigation tasks. These are a mixture of deep-learned and analytically designed algorithms, making it possible for the robot to operate in a variety of aquatic and marine conditions without hand-tuning and per-mission parameter optimization. For example, the robot localization subsystem uses the fusion of front cameras and the IMU to perform vision-based navigation. LoCO can accommodate a single-beam sonar altimeter (installation of which has been delayed due to the COVID-19 pandemic) and a depth sensor to find its position in the water column. A Gazebo [12] simulation

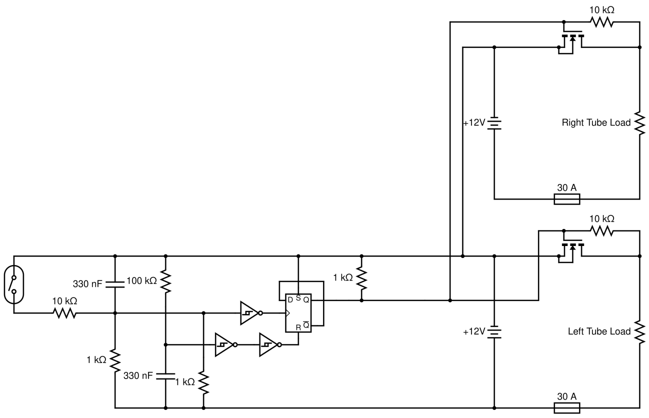

Fig. 4: Schematic for LoCO 's magnetic power switch.

has also been developed to facilitate behavior development. A custom-built model provides stability augmented motion, enabling convenient high-level control of the robot in the 6-degrees-of-freedom underwater environment, shielding users from the complications of low-level controllers. This controller is directly responsible for ensuring stable and predictable motion when operating LoCO tetherless. The tetherless behavior is triggered by a visual gesture recognition system capable of accepting commands (via a visual language called RoboChatGest [11]) delivered through hand gestures or fiducials. These commands are assigned to a variety of adjustable subroutines, which allows for easy creation of new "menus" for different tasks, which are displayed to the user via an onboard OLED screen. This capability is a key contributor to LoCO's Power-On-and-Go behavior.

III. Power-On-and-Go Behavior in LoCO

LoCO is a vehicle designed to be operated easily by a small team (even a single operator), from its power-on sequence and its deployment in field scenarios to the ways in which it can be controlled by human operators. Many aspects of LoCO, from its power switch design, to the use of clear waterproof enclosures, the simple internal structure, or the interactive software suite, contribute to the simple and straightforward deployments this robot is capable of.

A. Physical Power-On-And-Go

LoCO's power switch circuit, seen in Fig. 4, uses a magnetic reed switch situated in the left watertight enclosure of the robot. This allows LoCO to be turned on and off using a magnetic "key", which reduces possible points of failure due to leakage, as well as making emergency power-offs easy. In the event of an emergency, rather than having to grab the robot and try to operate a toggle switch or button, which can be difficult to do underwater, the operator only needs to bring the key to the side of the robot with their magnetic switch, immediately cutting power to all of the robot's systems.

When the robot is powered on by touching the magnetic key to the power switch circuit, the robot enters a sequence of power-on procedures. The clear acrylic chambers allow easy visual inspection of this sequence of procedures. The robot's two computing devices both sport power indicator lights which illuminate immediately upon powering. The microcontroller in the left enclosure also has a status light, which begins by blinking blue, settling to a solid blue once all required software is running and the robot is ready to be operated. This light is large, brightly colored, and pointed towards the top of the robot, making it easy to observe when LoCO is ready for operation. Additionally, the robot's thrusters play tones to indicate their successful startup, which gives audible confirmation that the robot's thrusters are operable almost instantly upon powering the robot. Through this sequence of light and sound, LoCO gives clear indication of its successful startup and preparation for operation, after a single input from the user via the magnetic key.

B. Deployment Procedures

The entire LoCO vehicle is well suited to small-team deployments, even deployment by a single person. In order to prepare it for a deployment, the operator needs to do three things: connect the batteries, seal the enclosure, and ensure water-tightness. After plugging the batteries into the power distribution system, the operator merely slides the robot's internal structure into the two watertight enclosures, pushing them in until the end gaskets are firmly seated at the end of the acrylic enclosure. Once they are, the rear thruster assembly (the 3D printed T-structure) can be attached with its bolts, which are typically tightened/loosened with a power drill and socket wrench for quick attachment or removal. Finally, to ensure that the enclosures remain watertight, the air is pumped out. Once the enclosures have reached a given level of vacuum (typically 10in.Hg), the connectors used to pump the air out are plugged, and the robot is ready for the water. While this process can be sped up with the addition of a second pair of hands, it is easily managed by one operator. Even the process of carrying the robot to the water is easy for a single operator. Weighing in at 27lbs, LoCO is not particularly light, but it is easy to carry by the 3D-printed T-connector to which the rear T100s are mounted (as seen in Figure 5). Particularly when operating in tetherless mode, this makes LoCO easy to carry into the water with oneself to deploy for experiments, such as those described in Section IV.

C. Human Interface Subsystems

LoCO has a full suite of interactive software which makes it operable without a connection to an outside computer. This software includes a virtual "menu" system which enables launching of specific robot behaviors, a fiducial marker recognizer, a hand gestures detection system, an RCVM (robot communication via motion [8]) system for robot-to-humans communication, and a suite to detect and follow divers using LoCO's vision systems. This software comes together to create a straightforward user experience as follows: the operator defines a set of menu options *a priori* before the mission starts, and loads them onto LoCO for use in their next deployment.

Once the menu is loaded, the operator deploys the robot as described in the previous section, powering the robot once in the water. From this point, the operator can trigger menu operations either with a deck of fiducial markers (ARTags) or with hand gestures, starting diver following in order to bring the robot to a new location by following the operator, starting or stopping data recording, or any number of other operations. While multiple operators ease the process, all of these operations are possible for a single diver in the water with the robot. Neither tether nor on-shore partners are required for complex underwater missions.

IV. EXPERIMENTS

LoCO has been deployed during field trials in various locations, including seven times in pools, once in Wayzata Bay, Minnesota, and off the coast of Barbados five times. While many deployments have been tethered for data collection and live debugging purposes, the tetherless deployments have shown promising results that LoCO will be a POWER-ON-AND-GO AUV.

LoCO's tetherless deployments have taken place in the Caribbean Sea. A typical example of one such trial is as follows. Before the arrival at the water, the robot menu and software are updated to prepare for the day's tests. Next, the robot is prepared for deployment as in Section III-B. This process has a typical duration of 20 minutes or less when using a hand vacuum pump. The actual water deployment requires only one team member to carry the robot into the water. Once in the water, a water-tightness check is completed. As the main body is transparent, checking moisture-indicating desiccant packets for any color change and making sure there is no visible water inside the enclosures is simple. With a distributed system and only one routinely used seal per enclosure, the potential for flooding is fairly small; however, we nevertheless visually check for leaks and air-bubbles once the robot is submerged. The robot is then powered on and the operator is able to test the pre-programmed autopilot using the menu system and RoboChatGest. Once finished with the experiments, teardown is also straightforward. The robot is returned to the on-land base, rinsed in fresh water and dried. Once dry, the vacuum seals are released and the thruster assembly removed, followed by pulling out the internal structure and battery disconnects, completing the teardown procedure.

In the majority of these tetherless deployments, a team of 4 people was present, with one operator who interacted with the robot and stayed near to watch for obstacles. The other team members generally took external videos, were the target of an algorithm such as diver following, or swam in the area to ensure operational safety. All team members typically took part in the preparation and teardown for the trial. In one specific trial, however, after a diagnosis of an incorrect cable connection, one team member was able to return the robot to the on-land base, reconfigure the cable, reseal the robot, and return the robot to the water for continued testing within 30 minutes. While more than one operator is currently recommended in the water, as improvements are made to the local motion controller and HRI systems, LoCO should easily be able to be operated by one person in the water as easily as on land.

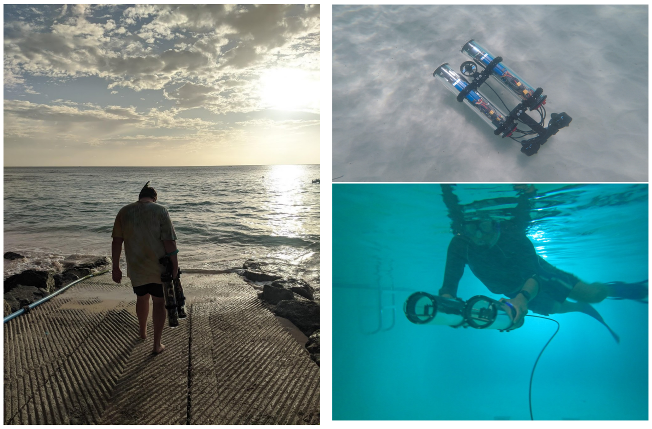
Fig. 5: A sampling of early LoCO deployments in pool and ocean environments.

V. CONCLUSIONS

LoCO is an AUV designed for use by small teams of researchers with little robotics experience and for application to a vast number of underwater tasks (biological observation, distributed sensing, and equipment hauling, to name a few). Because of this, LoCO's capability to POWER-ON-AND-GO–to be easily deployable with minimal configuration and fiddling, is key. It is imperative that scientists who choose LoCO because of its low price point and open design be able to use the AUV for their tasks quickly, easily, and without significant time lost to configuring the robot. LoCO's visually inspectable power-on sequence, simple deployment procedure, and fully featured human interface subsystems make it straightforward to deploy and operate in an underwater environment, even for operators with little robotics experience. While trials of LoCO in its proper place as the tool of such operators to support their scientific work have been delayed by the onset of COVID-19, early pool tests and sea trials in Barbados have been promising. When it is medically advisable, biological science collaborators will be trained in LoCO deployment procedures, after which missions to support their scientific needs will be planned and executed. The authors have spent a great deal of time considering the type of behavior that would make LoCO as easy for non-roboticists as possible, and while much has already proved effective, further collaboration with domain experts will enable even more straightforward deployment procedures. These future iterations of LoCO should continue to expand the robot's POWER-ON-AND-GO capabilities, lowering the barrier to underwater robotics even further by improving the startup experience for people, both familiar and unfamiliar with robots.

REFERENCES

[1] Ardupilot. https://ardupilot.org/. (Accessed on 03/01/2020).
[2] B. Allen, R. Stokey, T. Austin, N. Forrester, R. Goldsborough, M. Purcell, and C. von Alt. REMUS: a small, low cost AUV; system description, field trials and performance results. In

Oceans '97. MTS/IEEE Conference Proceedings, pages 994–1000, October 1997. doi: 10.1109/OCEANS.1997.624126.

[3] A. Amory and E. Maehle. SEMBIO - a small energy-efficient swarm AUV. In *OCEANS 2016 MTS/IEEE Monterey*, pages 1–7, September 2016. doi: 10.1109/OCEANS.2016.7761458.

[4] M. Carreras, J. D. Hernández, E. Vidal, N. Palomeras, D. Ribas, and P. Ridao. Sparus II AUV—A Hovering Vehicle for Seabed Inspection. *IEEE Journal of Oceanic Engineering*, 43(2):344–355, April 2018. ISSN 2373-7786. doi: 10.1109/JOE.2018.2792278.

[5] G. Dudek, P. Giguère, C. Prahacs, S. Saunderson, J. Sattar, L. Torres-Méndez, M. Jenkin, A. German, A. Hogue, A. Ripsman, J. Zacher, E. Milios, H. Liu, P. Zhang, M. Buehler, and C. Georgiades. AQUA: An amphibious autonomous robot. *Computer*, 40:46–53, February 2007. doi: 10.1109/MC.2007.6.

[6] C. Edge, S. S. 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. *arXiv preprint arXiv:2003.09041*, 2020.

[7] B. P. Foley, K. Dellaporta, D. Sakellariou, B. S. Bingham, R. Camilli, R. M. Eustice, D. Evagelistis, V. L. Ferrini, K. Katsaros, D. Kourkoumelis, A. Mallios, P. Micha, D. A. Mindell, C. Roman, H. Singh, D. S. Switzer, and T. Theodoulou. The 2005 Chios Ancient Shipwreck Survey: New Methods for Underwater Archaeology. *Hesperia: The Journal of the American School of Classical Studies at Athens*, 78(2):269–305, 2009. ISSN 0018098X, 15535622.

[8] M. Fulton, C. Edge, and J. Sattar. Robot communication via motion: Closing the underwater human-robot interaction loop. In *2019 International Conference on Robotics and Automation (ICRA)*, pages 4660–4666, May 2019. doi: 10.1109/ICRA.2019.8793491.

[9] C. S. Gonçalves, B. M. Ferreira, and A. C. Matos. Design and development of SHAD - a Small Hovering AUV with Differential actuation. In *OCEANS 2016 MTS/IEEE Monterey*, pages 1–4, September 2016. doi: 10.1109/OCEANS.2016.7761457.

[10] A. Hackbarth, E. Kreuzer, and E. Solowjow. HippoCampus: A micro underwater vehicle for swarm applications. In *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 2258–2263, September 2015. doi: 10.1109/IROS.2015.7353680.

[11] M. J. Islam, M. Ho, and J. Sattar. Dynamic reconfiguration of mission parameters in underwater human-robot collaboration. In *2018 IEEE International Conference on Robotics and Automation (ICRA)*, pages 6212–6219, May 2018. doi: 10.1109/ICRA.2018.8461197.

[12] N. Koenig and A. Howard. Design and use paradigms for gazebo, an open-source multi-robot simulator. In *2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, volume 3, pages 2149–2154, Sep. 2004. doi: 10.1109/IROS.2004.1389727.

[13] L. Meier, D. Honegger, and M. Pollefeys. PX4: A node-based multithreaded open source robotics framework for deeply embedded platforms. In *2015 IEEE International Conference on Robotics and Automation (ICRA)*, pages 6235–6240, May 2015. doi: 10.1109/ICRA.2015.7140074.

[14] W. Nodland, T. Ewart, W. Bendiner, J. Miller, and E. Aagaard. SPURV II-An Unmanned, Free-Swimming Submersible Developed for Oceanographic Research. In *OCEANS 81*, pages 92–98, September 1981. doi: 10.1109/OCEANS.1981.1151607.

[15] A. Okamoto, K. Tamura, M. Sasano, K. Sawada, T. Seta, S. Inaba, T. Ura, Y. Nishida, J. Kojima, and Y. Itoh. Development of hovering-type AUV "HOBALIN" for exploring seafloor hydrothermal deposits. In *OCEANS 2016 MTS/IEEE Monterey*, pages 1–4, September 2016. doi: 10.1109/OCEANS.2016.7761452.

[16] Y. R. Petillot, S. R. Reed, and J. M. Bell. Real time AUV Pipeline Detection and Tracking Using Side Scan Sonar and Multi-Beam Echo-Sounder. In *OCEANS '02 MTS/IEEE*, volume 1, pages 217–222 vol.1, Oct 2002. doi: 10.1109/OCEANS.2002.1193275.

[17] Blue Robotics. Blue robotics online store. https://bluerobotics.com/store/. Accessed June 21, 2020.

[18] S. Sariel, T. Balch, and J. Stack. Distributed Multi-AUV Coordination in Naval Mine Countermeasure Missions. Technical report, Georgia Institute of Technology, 2006.

[19] R. P. Stokey, A. Roup, C. von Alt, B. Allen, N. Forrester, T. Austin, R. Goldsborough, M. Purcell, F. Jaffre, G. Packard, and A. Kukulya. Development of the REMUS 600 autonomous underwater vehicle. In *Proceedings of OCEANS 2005 MTS/IEEE*, pages 1301–1304 Vol. 2, September 2005. doi: 10.1109/OCEANS.2005.1639934.

[20] A. Underwood and C. Murphy. Design of a micro-AUV for autonomy development and multi-vehicle systems. In *OCEANS 2017 - Aberdeen*, pages 1–6, June 2017. doi: 10.1109/OCEANSE.2017.8084807.

[21] H. R. Widditsch. SPURV - The First Decade. Technical report, Defense Technical Information Center, Fort Belvoir, VA, October 1973.

[22] S. B. Williams, O. Pizarro, M. Jakuba, and N. Barrett. AUV Benthic Habitat Mapping in South Eastern Tasmania. In Andrew Howard, Karl Iagnemma, and Alonzo Kelly, editors, *Field and Service Robotics*, pages 275–284, Berlin, Heidelberg, 2010. Springer Berlin Heidelberg. ISBN 978-3-642-13408-1.

[23] J. Wu, S. Peng, T. Xu, R. Hu, S. Wang, M. Pan, and X. Weng. Test Bed AUV for Docking Algorithm Research. In *OCEANS 2018 MTS/IEEE Charleston*, pages 1–6, October 2018. doi: 10.1109/OCEANS.2018.8604893. ISSN: 0197-7385.