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Dana R. Yoerger
Woods Hole Oceanographic Institution

Molly Curran
Woods Hole Oceanographic Institution

Justin Fujii
Woods Hole Oceanographic Institution

Christopher R. German
Woods Hole Oceanographic Institution

Daniel Gomez-Ibanez
Woods Hole Oceanographic Institution

See next page for additional authors

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Authors

Dana R. Yoerger, Molly Curran, Justin Fujii, Christopher R. German, Daniel Gomez-Ibanez, Annette F. Govindarajan, Jonathan C. Howland, Joel K. Llopiz, Peter H. Wiebe, Brett W. Hobson, Kakani Katija, Michael Risi, Bruce H. Robinson, Stephen M. Rock, Cailean J. Wilkinson, and John A. Breier

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Dana R. Yoerger
Molly Curran
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Christopher R. German
Daniel Gomez-Ibanez
Annette F. Govindarajan
Jonathan C. Howland
Joel K. Llopiz
Peter H. Wiebe
Woods Hole Oceanographic Institution
Woods Hole, MA 02543 USA

Brett W. Hobson
Kakani Katija
Michael Risi
Bruce H. Robison
Monterey Bay Aquarium Research Institute,
Moss Landing, CA 95039

Stephen M. Rock
Dept of Aeronautics and Astronautics
Stanford University
Stanford, CA 9430

Cailean J. Wilkinson
University of St Andrews
St Andrews, Fife, United Kingdom

John A. Breier
University of Texas Rio Grande Valley
School of Earth, Environmental, and
Marine Sciences
1 West University Boulevard
Brownsville, Texas, 78520

***Abstract--Mesobot,* a new class of autonomous underwater vehicle, will address specific unmet needs for observing slow-moving targets in the midwater ocean. *Mesobot* will track targets such as zooplankton, fish, and descending particle aggregates using a control system based on stereo cameras and a combination of thrusters and a variable buoyancy system. The vehicle will also be able to collect biogeochemical and environmental DNA (eDNA) samples using a pumped filter sampler.**

Keywords--Underwater robot, midwater oceanography, autonomous tracking, autonomous oceanographic sampling

I. INTRODUCTION

The ocean's midwater realm represents a new frontier for underwater robots. This vast region hosts abundant life and plays a key role in the global carbon cycle, thereby regulating Earth's climate and the biogeochemistry of its oceans. Technological limitations currently constrain our ability to study patterns and processes in this region. Guided by present and future community research priorities, *Mesobot* will be a new robot that will enable unique scientific access to midwater environments, complementing other tools currently available or in development.

The ocean's midwater realm, also called the mesopelagic or "twilight zone," extends from about 200 m depth to approximately 1000 m. These bounds are defined by ambient light levels. The shallow bound corresponds to the depth below which light levels are insufficient to support photosynthetic primary productivity. The lower bound corresponds to the depth where conditions are effectively aphotic [1].

Interest in the twilight zone is growing as the vastness of its biomass and biodiversity become more apparent. While exploration of one of Earth's largest, least understood, and most diverse ecosystems can be motivated by basic scientific interests alone, other more specific considerations are also emerging. According to recent estimates, global midwater fish biomass may be 100 times larger than the total fish biomass harvested globally every year [2], and commercial exploitation is likely inevitable. While midwater fish species differ dramatically from the pelagic fish traditionally exploited for human consumption, midwater animals could find commercial markets in products like fish meal for agriculture and aquaculture as well as other products like "nutraceuticals" such as fish and krill oil. Interest in the midwater is also motivated by understanding how it supports species living in near-surface waters and its role in regulating Earth's climate. Recent observations obtained using tags confirm that many charismatic epipelagic species such as whales, sharks, swordfish, and tuna dive regularly into the Twilight Zone to feed on abundant populations of animals such as squid [3]. Likewise, midwater animals likely play a major role in transferring carbon from near-surface waters to the deep ocean, as part of the "Biological Pump" [4]. These activities may mitigate the effects of rising atmospheric CO2, although the precise mechanisms involved and their global importance are not well-understood.

Many midwater animals undertake diel (daily) vertical migrations, spending daylight hours at hundreds of meters depth (presumably to avoid predation), rising to near-surface waters at night to feed, and then descending to safer, darker waters at daybreak. Some of these animals can be observed from vessel-mounted sonars, forming the "deep scattering layer." This phenomenon occurs between about 60°N and

60°S latitude, circling the globe each day. This daily movement of animals results in the largest migration on Earth. When these animals feed near the surface then defecate after they retreat to deeper water, they physically carry organic carbon from shallow to deep water. But the details of how much carbon is actually sequestered via these biological processes remains uncertain. *Mesobot* has been designed specifically to advance our understanding of the complex daily lives of these animals.

II. MIDWATER EXPLORATION TECHNOLOGY

Much of what we know about midwater biota has been learned by towing nets. A wide variety of nets have been devised, each with specific capabilities [5]. In recent years, these have been supplemented with specialized camera systems to observe midwater biota such as zooplankton [6]–[8], and have been used on towed platforms, powered Autonomous Underwater Vehicles (AUVs), and profiling moorings. Echo sounders, either vessel-mounted, towed, lowered, or moored, also provide data on midwater species. While highly useful, each of these technologies have well-documented biases. For example, many species are able to avoid capture in nets [9]. Likewise, acoustic systems usually emphasize some species over others [10]. Many efforts are underway to make these systems better able to identify species and obtain accurate estimates of biomass and biodiversity [11], [12].

The oceanographic community employs many vessel-deployed and fully autonomous instruments to characterize the midwater ocean, these devices usually characterize the physical environment, geochemical signatures, and microzooplankton communities rather than mesozooplankton and larger biota. CTD profilers (conductivity, temperature, depth) are lowered from research vessels on a cable. Modern CTDs now include a wide variety of other instruments and water sampling [13]. Since 2000, thousands of fully-autonomous profiling Argo floats, actuated by buoyancy engines, have been deployed worldwide. They have provided unprecedented data on a range of topics including ocean circulation, air-sea interaction, and climate change [14]. Gliders carry similar instruments and are powered primarily by buoyancy engines but are actively mobile, using a buoyancy engine, wings that supply lift, and by controlling their attitude by shifting their center-of-gravity [15]. Long-range powered AUVs are also emerging to survey the midwater ocean [16], [17]. The sensor payloads carried by these vehicles have expanded in recent years, and now may include fluorometers, echosounders for bioacoustics, and even mass spectrometers. While these platforms are highly effective for their intended purposes, they do not have the needed maneuverability, sensors, or samplers required for fine-scale continuous observation and sampling of the midwater processes. The *Mesobot* was conceived to fill this gap.

Based on the relevant scientific problems and their survey requirements, the following technical characteristics have been established for *Mesobot*:

- Using stereo cameras, lights, and on-board computing resources, the vehicle will be able to image and follow animals, particulates, aggregates, bubbles, and droplets by extending previous work at Stanford and MBARI [18].
- In addition to the stereo cameras, *Mesobot* will carry a low-light color camera suitable for high-quality scientific imaging capable of recording compressed 4K video and still images.
- The vehicle will carry lights capable of providing both red and white illumination with controllable intensity.
- Like many of its targets, the vehicle will behave “mostly lagrangian”, hovering efficiently and moving with ambient water masses, and maneuvering actively with fine control to follow slow-moving targets using a combination of thrusters and a variable buoyancy system.
- The design will minimize avoidance and disturbance of the imaging volume from a hydrodynamic, acoustic, and optical perspective.
- At the start of a tracking dive, the vehicle will be deployed with a thin, data-only fiber optic tether to support remote control by a human pilot. After acquiring a target, the the tether will be released from the vehicle, after which it will follow targets autonomously.
- The vehicle will have applicability to a range of midwater survey tasks such as exploratory surveys, ground-truthing acoustic surveys, and following features such as isotherms, isopycnals, or neutral surfaces.
- The vehicle will be able to carry a Suspended Particulate Rosette (SUPR) sampler. This device pumps water through filters, thereby concentrating suspended particulates, small plankton, environmental DNA (eDNA), whole water and filtrate [19], [20] from a large volume of seawater (10s of liters typically). *Mesobot’s* SUPR will enable up to twelve samples to be collected and preserved *in situ* using this compact device. Filter contents can later be used for geochemical and biological analyses.
- The vehicle will have a mission duration of over one day to observe diel migration and a duration of approximately four days for the least energetic tasks such as following oceanographic features.
- The vehicle will be able to work to depths of 1000 m, enabling the vehicle to track most diel migrators and putting many important mesopelagic scientific problems within its reach.

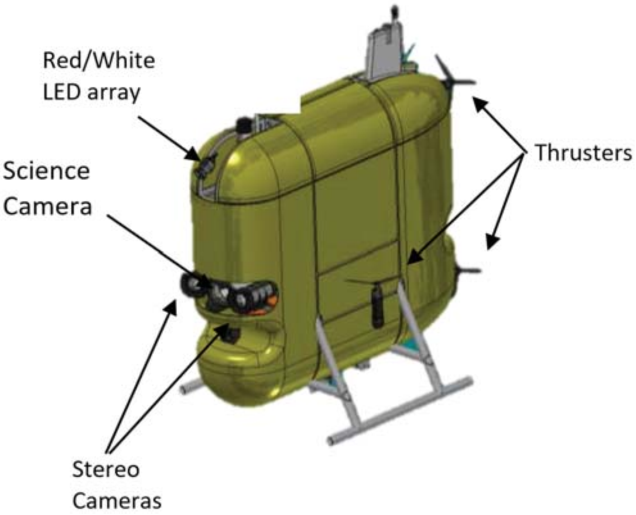

Fig 1. The *Mesobot* will be an autonomous underwater vehicle designed to follow slow-moving midwater targets such as zooplankton, fish, and particle aggregates. The vehicle will carry stereo cameras for target tracking and a high-quality video/still camera for scientific documentation. It will use a combination of thrusters and a variable buoyancy system for maneuvering. The *Mesobot* will be 1.5 meters tall and displace approximately 200 kg.

III. TYPICAL MESOBOT MISSION

While *Mesobot* will be a flexible platform capable of a variety of missions, the most basic dive profile will focus on a mission to track midwater animals over a full diel cycle, including migrating and non-migrating targets. A typical mission is illustrated in Figure 2. The vehicle will be able to take up to a dozen pumped filter samples during a dive.

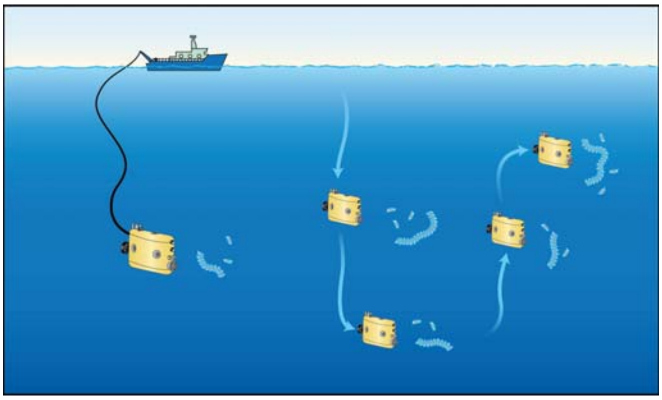

Fig 2. A typical *Mesobot* tracking mission will begin with a teleoperated phase, where the vehicle can be controlled by a human pilot via a tether. After locating a suitable target, the tether will be released and the vehicle will track the target autonomously using its stereo cameras and its control system.

IV. AVOIDANCE AND ATTRACTION

Any robotic platform will disrupt the environment to some extent, causing some animals to flee while attracting other animals to the vehicle. These responses can be evoked due to a large number of factors, including lighting, hydrodynamic disturbances, acoustics, electromagnetic fields, or a vehicle's chemical signature. While all relevant effects cannot be eliminated, they can be minimized. Over decades, midwater animals have been observed successfully from submersibles and ROVs [21], but like all other methods, those observations are often biased.

A substantial literature and significant operational practice exists concerning observation of midwater fish and zooplankton from conventional human-occupied submersibles, remotely-operated vehicles, autonomous vehicles, and human divers. A review of the literature as well as operational practice indicates that simplistic use of any such platforms may result in substantial avoidance or attraction due to the mechanisms listed earlier, although the specifics will vary considerably based on species, the setting, and the characteristics of the vehicle. On the other hand, skillful operation of human-occupied or remotely-operated vehicles can result in excellent close-up observations of even very sensitive animals [22].

In a classic study from 1968, large schools of lanternfish (*Ceratopscopelus maderensis*) were identified at a depth of ~400 m and their abundance estimated by direct observation from the deep-diving human-occupied submersible Alvin [23]. Alvin is a large submersible (displacing about 15 tonnes) and at that time was powered by a relatively noisy hydraulic power unit (HPU) and carried an array of high-powered lights. For the study, the pilot approached the school after observing them by sonar. If approached casually with the lights on, the fish were observed to flee down and away. But when the investigators approached the school carefully with the lights off, they were able to make detailed observation of dense schools of the animals using only dim lighting from flashlights. The animals were observed hanging motionless in random orientations indicating that they had not been disturbed. The acoustic noise and large rigid form of the submersible were likely not a factor.

While avoidance will vary strongly between species and the setting, several important lessons can be drawn from studies like these. A relatively small, acoustically quiet vehicle with controllable dim red and white lights should enable detailed observations while minimizing avoidance or attraction, provided that the control system properly manages the vehicle motions and lights.

V. Mesobot Design

The overall internal layout of *Mesobot* is shown in Figure 3. The design favors hovering behavior and vertical movement over forward transit. It is fully actuated; the thrusters are able to exert forces along and moments about all three body axes. The vehicle is designed for high static pitch and roll stability, with the buoyant elements placed high and the heavy elements placed low. Pitch and roll will not be actively changed, although the controller will generate appropriate pitch and roll moments to counter unintended coupling motions that might degrade the imagery. The main thrusters for the forward/aft and vertical axes will be low-powered (under 60 watts), slow-moving, large diameter thrusters to minimize hydrodynamic disturbances.

In addition to its thrusters, *Mesobot* will carry a variable buoyancy (VB) system to reduce vertical thruster activity while hovering in a “near-lagrangian” manner. Using the thrusters and variable-buoyancy system in complement, *Mesobot* will be able to observe many midwater phenomena with minimal thruster activity. The vehicle’s buoyancy will require adjustment due to any initial ballasting errors as well as changes in the density of seawater and the overall vehicle density as the ambient pressure and temperature vary during a dive. The VB system will use a piezoceramic pump to change the vehicle’s displacement by moving fluid between a rigid housing and a flexible, ambient pressure volume. Currently in development, the system will have a capacity at least 1 liter, allowing it to change the vehicle’s displacement by 1 kg.

For cameras and lights, *Mesobot* will carry a stereo pair of cameras used primarily for tracking, a color 4K video/still camera for scientific imagery, and a pair of LED light arrays. The lights will consist of a pair of COTS LED units (Deep Sea Power and Light) that can emit either red or white light at varying intensity under software control. The placement of those lights are shown in figures 1 and 3.

The stereo camera pair consists of two Allied Vision G-319B monochrome machine vision cameras with Gigabit Ethernet interfaces. These cameras have 1/1.8” CMOS sensors with a global shutter. They have excellent sensitivity especially for red light and 2064 (H) × 1544 (V) resolution. They will operate in COTS housings with domed optics, providing a 62° horizontal field of view. These cameras will be set up for a large depth of field, extending from just past the dome ports to infinity, thereby providing sharp focus without any real time adjustment.

Mesobot’s science camera (Sony UMC-SC3A) will provide high-quality color video (4K) and high-resolution stills (12 MP). The camera features a full-frame 35mm sensor. The camera has outstanding low light capability (0.004 lx /ISO 409,600), compresses and records data to on-board memory, and is configured for remote control and limited viewing through a USB port. Like the stereo cameras, this camera will be placed inside a domed COTS housing.

Mesobot will also carry a suite of oceanographic sensors. These include conductivity, temperature, and depth (CTD), dissolved oxygen (DO), an optical triplet (dual fluorometers and optical backscatter), and Photosynthetically Active Radiation (PAR) sensors. A WHOI-developed radiometer will also be added in the future. In addition to characterizing the environment in which *Mesobot* is operating, the sensor data will be available to the control system in real time, enabling adaptive survey and sampling.

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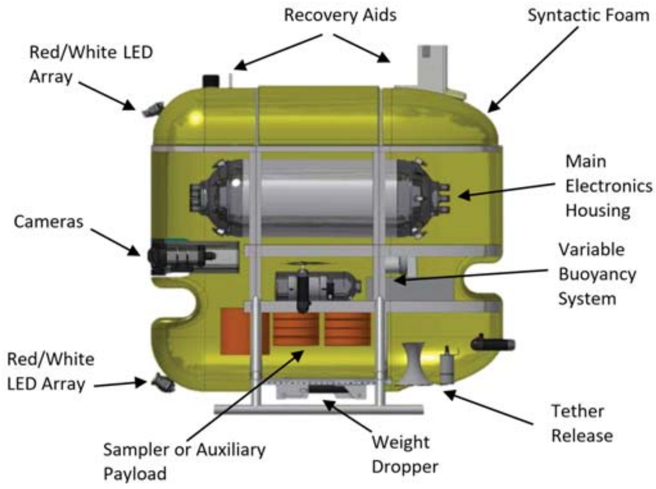

Fig 3. This figure shows a side view of the vehicle with the protective outer skin removed.

Mesobot will have a flexible payload bay, so it can carry a variety of sensors and samplers or be configured with only its core sensors. The first such payload will be a version of the SUPR sampler to obtain geochemical and biological samples, including the collection of filtered particulates and plankton, eDNA, whole water, and filtrate [19], [20]. By moving large quantities of seawater through one or more filters, relatively dilute constituents can be concentrated to levels required for subsequent analysis. SUPR is capable of collecting samples for DNA, RNA, and proteomics work as well as organic carbon and trace metal analysis. Up to 12 samples can be obtained on a given dive. Gathering such samples while following migrating midwater animals will provide unique insights on the environments through which those animals pass based on geochemical and molecular analysis.

VI. COMPUTERS AND SOFTWARE

Mesobot software will enable the vehicle to operate both as a remotely-operated vehicle (ROV) and as a fully autonomous vehicle. *Mesobot* will take advantage of the basic computing infrastructure from MBARI's LRAUV [16], including its main computer (motherboard) and load controller for interfacing and powering all devices on the vehicle. The load controller has facilities for protecting power circuits from overload and unexpected electrical connection to the surrounding seawater (ground faults). The motherboard and its software include redundant emergency control, enabling the vehicle to return to the surface should major faults occur including failure of the main CPU, control software, or battery.

The stereo images will enable real-time target tracking using software developed by the project's Stanford and MBARI collaborators [18]. After initialization, the software will compute the range and bearing to the selected target and generate the force and moment commands to enable the vehicle to track the target. Current issues being addressed include maintaining tracking in the presence of multiple objects and recovery should tracking be lost due to sudden animal movement. While still in development, this software has been demonstrated successfully on MBARI ROVs, most recently using MBARI's Mini ROV with a similar lighting and camera configuration as planned for the *Mesobot*. On the *Mesobot*, the software will run in real-time on an Nvidia TX2.

Mesobot's control system will also include a mission executive driven by a dive-specific script to manage each dive. Unlike many other AUVs, *Mesobot* will often hand off control from the Mission Executive to other systems such as manual pilot operation through the tether and the target-tracking system. To support this, *Mesobo*t will employ a system focused on reacting to changes in the environment and other external events while also capable of direct AUV control when required. The mission executive will have the following functions:

1. Configure the tracking and control system parameters at the start of each dive.
2. Transition the control system, when requested, from teleoperated to autonomous control using either the tracking system or conventional survey motion primitives.
3. Monitor the system for faults, unsafe conditions, or other end-of-mission criteria. These will result in an emergency ascent.
4. Control the operation of the science camera and lights, for example interleaving video and still images through preset sequences, along with appropriate changes in lighting. Early dives will employ preset sequences, but adaptive operation based on the images will be included later.
5. Control the operation of payloads such as the SUPR sampler. On the initial dives, the sampler will be operated in a pre-scheduled sequence. Later dives will sample adaptively based on images, readings from oceanographic sensors, or programmed vehicle motions.
6. Drive the vehicle along preprogrammed survey sequences. For example, the vehicle will be able to make vertical transects or follow constant-depth paths using heading and estimated forward speed. In the future, these capabilities will be expanded to allow the vehicle to follow iso-surfaces or perform other adaptive surveys.

The core mission executive is written in Python using the smach state machine library [24]. Taking advantage of this well-established library enabled creation of a robust state-machine-based system flexible enough for repeated use in a variety of different situations. Despite smach itself being part of the ROS standard library, it can also be used as a standalone module using the LCM system [25] for internal communications between the various systems to interface with existing code.

The mission executive is comprised of six core states, each a nested state machine, covering four distinct stages of *Mesobot* deployment: pre-launch, operation, ascent, and recovery. With the exception of the emergency ascent state, which is hard-coded for reliability, each of these core states is customizable on a per-mission basis. The mission state is responsible for implementing the mission (as defined in the xml) and can be provided with a backup mission to be run as an alternative to aborting should the primary mission fail mid-dive. Meanwhile the safety-loop runs a series of system checks in the background to ensure every component is operating as it should. Either state is able to abort the mission and transition immediately to one of the ascent states at any time.

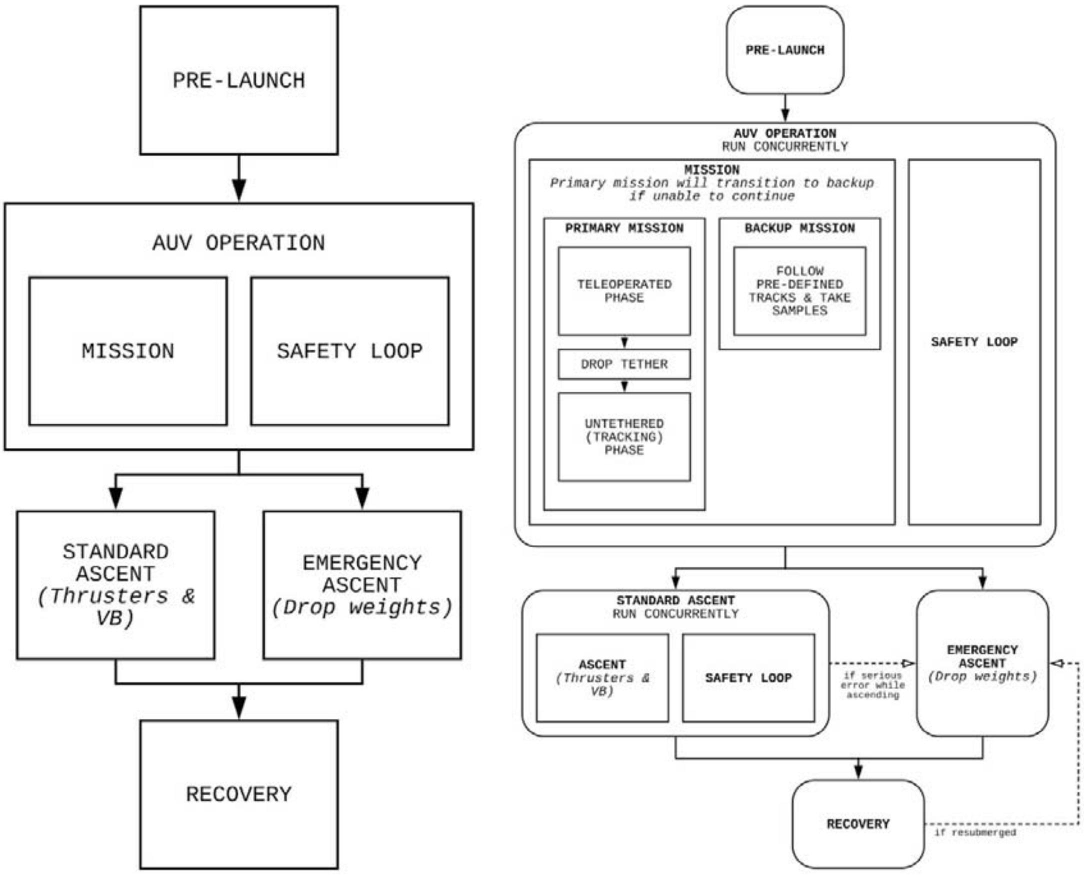

Fig. 4 The mission executive runs as a state machine consisting of 6 per-mission customizable states. Left: The top-level system diagram. During the operation stage, the mission and safety-loop states are run concurrently. Right: An example mission executive setup where the mission is split into teleoperated and animal tracking phases.

The major focus of this development has been a simple xml-like language in which complex missions can be defined without the need for changes to the underlying code. These xml mission-scripts are then interpreted by the system on start-up and used to build the mission executive state-machine, predominantly populated from a predefined library of states of known reliability. This xml-like language supports essential programming features such as looping states and concurrency.

A library of states covering the core features of the *Mesobot* assists in the programming of missions, each configurable to suit the specific mission. The vast majority of *Mesobot* missions can be programmed from this set of states; an advanced user with needs not met by the standard library will be able to write custom states in Python to suit their needs. These states are run in isolation from the core system, and so any such custom states are unable to crash the rest of the mission executive. On a per-state basis, the response to failure of a state or a fatal Python exception can be specified. This allows the end user to implement custom logic as required while always maintaining the guaranteed integrity of the core system.

In addition to specifying a list of states to be run sequentially in each stage, the operator can specify states to be run under certain conditions or when a set event occurs. These states will then be executed every time the conditions are met. For example, a user may define actions to be taken upon an increase in temperature or in response to cues from the animal tracking software such as taking a sample or adjusting the cameras or lighting. This allows the *Mesobot* system to react to the environment independently of how the movement is controlled.

Depending on the scientific goals and operational constraints, missions can be run autonomously or with human supervision through acoustic communications. The AUV can maintain constant two-way acoustic communication with a supervisor on the surface, predominantly to serve status updates in discrete packets. The control system will also react to commands from the supervisor to amend mission parameters mid-dive or to request specific mission data be sent in the following update. If required, the supervisor is also able to request that the AUV end the mission early and return to the surface at any time.

VII. CONCLUSION

Mesobot represents a new class of underwater robots that addresses fundamental issues concerning the biology and chemistry of the ocean's midwaters that currently available systems cannot. Specifically, *Mesobot* will be able to track slow-moving midwater targets including zooplankton, fish, and descending particle aggregates, imaging them with high-quality 4K video and stills. *Mesobot* has been designed to be minimally intrusive to reduce attraction, avoidance, and hydrodynamic disturbance. Specific features in these regards include the use of well-controlled red and white lights, low-light cameras, "near-lagrangian" hydrodynamic behavior, and a quiet acoustic signature. As *Mesobot* follows the targets, it will also be able to take a dozen pumped-filter water samples, providing material for geochemical and eDNA analysis.

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