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TITLE OF PROPOSED PROJECT

Aqua-Gemini: A highly adaptable dual underwater vehicle system coupled by a distributed ocean-sampling sensor-cable

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 406,302	36 months	01/01/2021	

THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW
- ☐ BEGINNING INVESTIGATOR
- ☐ DISCLOSURE OF LOBBYING ACTIVITIES
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- ☐ HISTORIC PLACES
- ☐ VERTEBRATE ANIMALS IACUC App. Date ________
  PHS Animal Welfare Assurance Number ________
- ☒ TYPE OF PROPOSAL Research
- ☐ HUMAN SUBJECTS Human Subjects Assurance Number ________
  Exemption Subsection ________ or IRB App. Date ________
- ☐ FUNDING OF INT'L BRANCH CAMPUS OF U.S. IHE ☐ FUNDING OF FOREIGN ORG
- ☐ INTERNATIONAL ACTIVITIES: COUNTRY/COUNTRIES INVOLVED
- ☒ COLLABORATIVE STATUS Non-Collaborative

PI/PD DEPARTMENT	PI/PD POSTAL ADDRESS
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CO-PI/PD				
CO-PI/PD				

CERTIFICATION PAGE

Certification for Authorized Organizational Representative (or Equivalent) or Individual Applicant

By electronically signing and submitting this proposal, the Authorized Organizational Representative (AOR) or Individual Applicant is: (1) certifying that statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Further, the applicant is hereby providing certifications regarding conflict of interest (when applicable), drug-free workplace, debarment and suspension, lobbying activities (see below), nondiscrimination, flood hazard insurance (when applicable), responsible conduct of research, organizational support, Federal tax obligations, unpaid Federal tax liability, and criminal convictions as set forth in the NSF Proposal & Award Policies & Procedures Guide (PAPPG). Willful provision of false information in this application and its supporting documents or in reports required under an ensuing award is a criminal offense (U.S. Code, Title 18, Section 1001).

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The AOR is required to complete certifications stating that the organization has implemented and is enforcing a written policy on conflicts of interest (COI), consistent with the provisions of PAPPG Chapter IX.A.; that, to the best of his/her knowledge, all financial disclosures required by the conflict of interest policy were made; and that conflicts of interest, if any, were, or prior to the organization's expenditure of any funds under the award, will be, satisfactorily managed, reduced or eliminated in accordance with the organization's conflict of interest policy. Conflicts that cannot be satisfactorily managed, reduced or eliminated and research that proceeds without the imposition of conditions or restrictions when a conflict of interest exists, must be disclosed to NSF via use of the Notifications and Requests Module in FastLane.

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This certification is required for an award of a Federal contract, grant, or cooperative agreement exceeding $100,000 and for an award of a Federal loan or a commitment providing for the United States to insure or guarantee a loan exceeding $150,000.

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The undersigned certifies, to the best of his or her knowledge and belief, that:
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(3) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by section 1352, Title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

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Certification Regarding Flood Hazard Insurance

Two sections of the National Flood Insurance Act of 1968 (42 USC §4012a and §4106) bar Federal agencies from giving financial assistance for acquisition or construction purposes in any area identified by the Federal Emergency Management Agency (FEMA) as having special flood hazards unless the:
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(This certification is not applicable to proposals for conferences, symposia, and workshops.)

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The AOR shall require that the language of this certification be included in any award documents for all subawards at all tiers.

CERTIFICATION PAGE - CONTINUED

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Certification Regarding Federal Tax Obligations

When the proposal exceeds $5,000,000, the Authorized Organizational Representative (or equivalent) is required to complete the following certification regarding Federal tax obligations. By electronically signing the Certification pages, the Authorized Organizational Representative is certifying that, to the best of their knowledge and belief, the proposing organization:
(1) has filed all Federal tax returns required during the three years preceding this certification;
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(3) has not, more than 90 days prior to this certification, been notified of any unpaid Federal tax assessment for which the liability remains unsatisfied, unless the assessment is the subject of an installment agreement or offer in compromise that has been approved by the Internal Revenue Service and is not in default, or the assessment is the subject of a non-frivolous administrative or judicial proceeding.

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AUTHORIZED ORGANIZATIONAL REPRESENTATIVE	SIGNATURE	DATE
NAME Kyle Koza	Electronic Signature	Feb 18 2020 07:01 PM

TELEPHONE NUMBER	EMAIL ADDRESS	FAX NUMBER
	kkoza@hawaii.edu	

Project Summary

Overview

This project encompasses the development of an entirely new approach to oceanographic sensing. Rather than replicating autonomous underwater vehicle (AUV) technology capable of taking single point measurements of various quantities and applying that to a specific measurement application, this project is re-imagining the nature of AUV sensing capabilities. The effort consists of developing a dual AUV system that is coupled through a sensor cable stretching between the two. The cable will consist of an array of distributed sensors, data lines for communication, and reinforcement preventing damage to sensors from tension forces. The system, which we refer to as Aqua-Gemini , will be able to position the sensor cable in multiple configurations thus controlling the virtual aperture of the sensing system, and will also be able to completely reel in the cable and latch vehicles for high speed efficient transit.

Intellectual Merit

The ultimate goal is to dramatically increase the spacial footprint of AUV ocean sampling, by transforming AUV sensing capabilities. Simultaneously, the dynamic positioning of autonomous underwater vehicles (AUVs) will be improved utilizing unsteady jetting technology inspired by squid and jellyfish locomotion. The improved motion control accuracy of the endpoint AUVs will allow Aqua-Gemini to adequately control tension and configuration of the sensor cable. Although the preliminary iterations will focus on sensing quantities like, temperature, local velocity, and salinity, which have obvious applications in oceanography, future iterations can implement distributed acoustic sensing for a variety of vehicle sensing and tracking applications.

Broader Impacts

The technology developed in this project could lead to a new generation of underwater robots that allow for faster mapping of dynamic oceanographic features, and over much larger coverage areas. Those sensing capabilities can in turn lead to better meteorological models and predictions and earlier warnings from both public and military storm warning systems.

The development of the semi-flexible cable embedded with an array of sensors presents a technology area that is fundamentally different from existing robotic sensor integration, which usually involves a rigidly fixed sensor location minimizing possible stresses on that sensor. Procedures to compensate for sensor realignment or external stresses, will not just be useful for this project, but for the entire burgeoning field of soft robotics.

Additionally, the motion control requirements for the endpoint AUVs needed to maintain adequate cable tension and layout represents a capability not seen in current AUVs, but is not a requirement exclusive to the Aqua-Gemini application. AUV propulsion and maneuvering technology which allows nearly instantaneous control forces in all six degrees of freedom, without sacrificing a low drag hull-form, could be utilized by resident AUVs attempting to perform docking, or long range pipeline inspection, or any application where an autonomous robot must travel a long distance before performing some high accuracy manipulation task. The bioinspired jet thruster technology proposed to achieve these motion control requirements is itself still a new technology, which is fundamentally different from current state-of-the-art marine propulsors.

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For font size and page formatting specifications, see PAPPG section II.B.2.

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

Program Solicitation Number: NSF 20-525
Division of Ocean Sciences

Title: Aqua-Gemini: A highly adaptable dual underwater vehicle system coupled by a distributed ocean-sampling sensor-cable

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Project Duration: 01/01/2021 - 12/31/2023 (3 years)
Requested Budget: $391,894 (total)

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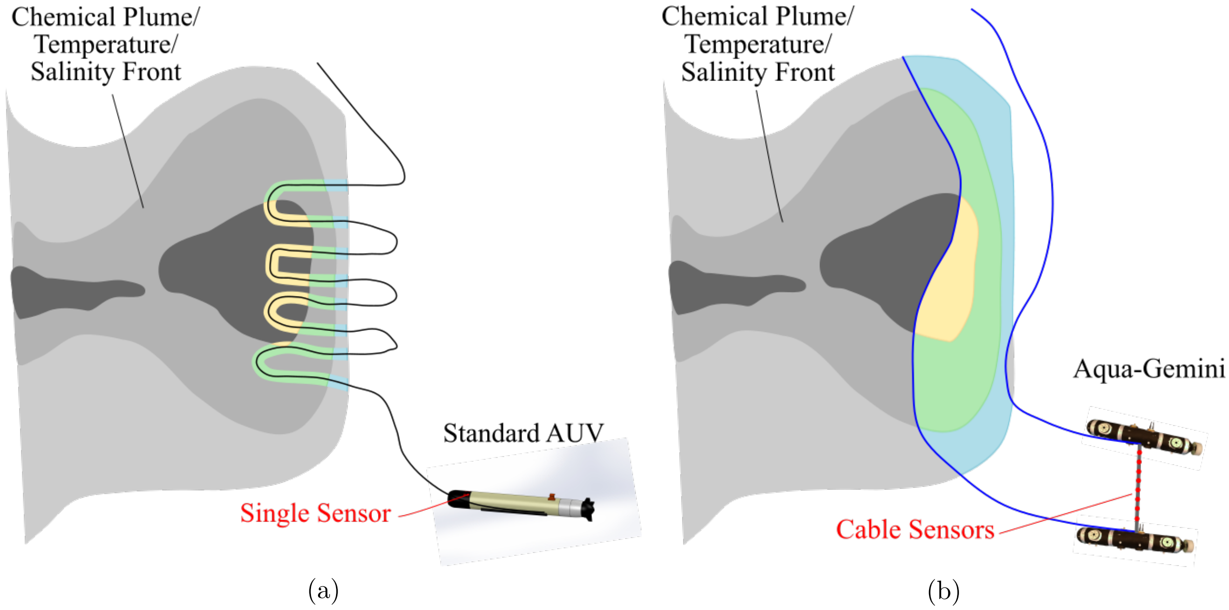

Figure 1: Conceptual diagram of a possible AUV survey mission. (a) The trajectory of a standard AUV which creates a hatch pattern through a dynamic region. (b) The proposed Aqua-Gemini system makes a single sweep through the region of interest.

Project Description

Autonomous underwater vehicles (AUVs) have become an invaluable tool in the field of oceanographic sensing and sampling. While remote sensing data from satellites provide information about temperature, wave height, and a number of other variables near the surface, and vertical profilers take measurements throughout the entire water column at fixed locations, the mobility of AUVs allows them to sample various parameters at remote, dangerous, and dynamically transient locations.

AUV sensing allows the vehicle to take a single point measurement of some quantity at the current location. Therefore, when performing survey missions AUVs must travel in hatching patterns to provide coverage of a region of interest (ROI) and map dynamic features. This standard survey operation is shown in figure 1a. Different styles of AUVs are better suited for resolving different dynamic features. For example, gliders are extremely useful for mapping large scale features with significant vertical gradients, due to their longevity and the inherent oscillation in depth associated with their propulsion. However, small-scale and more transient features require the positioning accuracy of thruster driven AUVs. In this project our goal is to extend the spacial sampling of AUVs at any instant from a point to a line of distributed samples.

Towed acoustic sensing arrays have been used since WWI for underwater surveillance operations. More recently towed arrays have been used in moving ship tomography experiments, whereby acoustic signals emanating from moored sources at known locations are received by an array on a moving ship. Similarly cables with distributed temperature sensors have been towed behind research vessels like NOAA's *Okeanos Explorer* for oceanographic sensing purposes.

This project, which we call Aqua-Gemini , aims to increase sensing coverage of AUV survey missions by creating a cable equipped with distributed sensors which will be suspended between two self propelled AUVs. The cable will be five to ten times the length of the AUV. This configuration offers several advantages to conventional AUV sensing. First and foremost, this will allow the dual AUV system to sample ROIs with a single sweep as shown in figure 1b, thus drastically increasing the total possible sensing coverage in a single mission. The system will also allow more accurate characterization of ROIs with very fast dynamics because the single sweep can be performed much more quickly than a conventional survey pattern (i.e. the "lawn mowing" pattern in figure 1a). Additionally, unlike sensor cables suspended behind research vessels, the dual AUV delivery system affords greater versatility. Aqua-Gemini can be configured in a vertical configuration, horizontal configuration, or combination of the two as required by the ROI characteristic

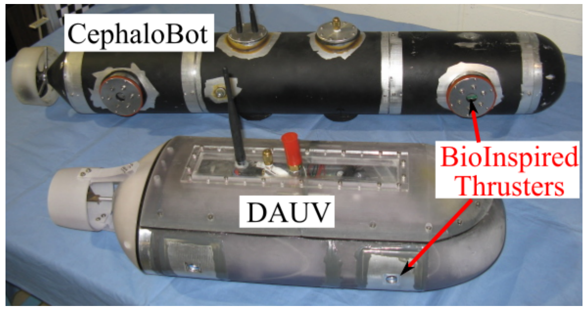

Figure 2: Images of two generations of AUVs, CephaloBot and the daughter AUV (DAUV), utilizing bioinspired jet propulsion, that were developed by the PI while he was working at the University of Florida (Krieg *et al.* MTS Journal, 2011).

layout. Furthermore, the dual AUV system can be utilized in regions like the arctic, which are much more restrictive to research vessels.

The coupling between the two endpoint AUVs also creates multiple other benefits in terms of both navigation and motion control. AUV navigation is a particularly difficult problem, mostly owing to the fact that GPS signals are ineffective in water, resulting in three basic strategies. Classical 'dead-reckoning' navigation is simple to implement, but suffers significant drift errors. Acoustic triangulation via a network of known transponders (i.e. long baseline systems), allows for accurate position measurements but is limited to the few locations where these transponder networks are installed. Therefore, many modern AUVs utilize some form of localization based on either sonar or optical recognition of surrounding seabed topology (whether the topology map is generated simultaneously or *a priori*). Each endpoint AUV will utilize inertial sensors dead-reckoning in the absence of known topology maps, and each will experience drift in estimated position due to local error sources. In order to maintain cable orientation the relative position of endpoint AUVs will be accurately measured using acoustic transponder modules on each hull. The coupled Aqua-Gemini system then filters the random drift error of the two endpoints utilizing the known relative spacing to improve navigation accuracy. More significantly, since the the two AUVs form a known (long) baseline, absolute navigation of Aqua-Gemini can be determined relative to single fixed beacon.

The motion control problem for AUVs often involves overcoming surrounding fluid disturbances that can be both sudden and difficult to resolve using traditional sensing techniques. Similar to the navigation errors, fluid disturbances acting on each endpoint AUV can act to filter each other out through the physical coupling of the cable, assuming that the separation between the endpoints is larger than the characteristic scale of the disturbance flow.

Background Information

For an AUV performing a survey or front tracking mission, typical trajectories often double back on themselves to provide coverage of an ROI. Due to these switchbacks the motion control requirements are essentially forward motion and an adequate turning radius in order to provide desired resolution between passes. In order to maintain proper sensor cable tension and alignment; however, the endpoint AUVs of the Aqua-Gemini system must be capable of generating nearly instantaneous propulsion and maneuvering forces/torques in all six degrees of freedom. This will be accomplished using a propulsion scheme developed by the PI at his previous academic positions.

The propulsion technology is inspired by the locomotion jellyfish, squid, and other cephalopods. The thrusters consist of a deformable cavity internal to the hull of the vehicle connected to an orifice on the hull surface. The cavities expand an collapse driving fluid in and out of the orifice. Since the thruster cavity is internal to the vehicle, they can be used to generate significant maneuvering forces without sacrificing a streamlined hull-form [1]. Such a capability is crucial for the proposed system since it needs to maintain an ability to transit long distances efficiently before reaching a ROI while still being able to maintain cable tension and position while performing sampling in the ROI.

Another benefit of the bioinspired unsteady jet thrusters is that they create maneuvering forces nearly instantaneously [3], as opposed to propeller thrusters, where the time required to reach steady state thrust is

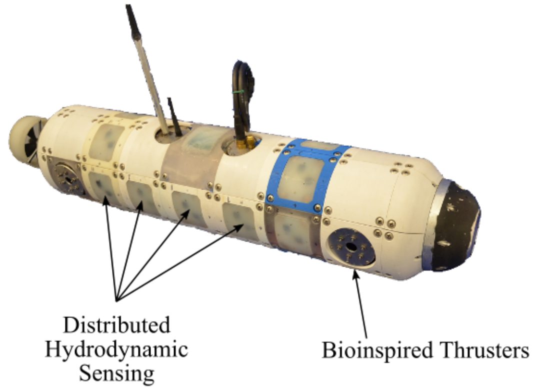

Figure 3: Picture of a prototype AUV developed by the PI with a distributed hydrodynamic sensor shell used to measure disturbance forces for high accuracy motion control [2].

inversely proportional to the level of thrust [4]. The PI has performed extensive work proving the feasibility and optimizing this technology. Thrust dynamics associated with vortex ring formation and nozzle geometry were analyzed in [5], demonstrating how converging radial velocity induced by both significantly enhances impulse transfer. Additionally, a high accuracy internal pressure model was derived in [6] in order to analyze energetics associated with unsteady jetting. This model demonstrated that impulsive jet velocity programs have a higher propulsive efficiency than sinusoidal jet programs because they desynchronize the peaks in internal pressure and cavity boundary velocity.

The PI has also demonstrated an ability to incorporate this propulsion technology into AUV platforms. Maneuvering regimes were defined based on relative scale of a maneuver, where the unsteady jetting is shown to be optimal for small and intermediate scale maneuvers [7]. Multiple generations of AUVs were developed utilizing these maneuvering thrusters [1, 8], two of which are shown in figure 2. Using these platforms the PI demonstrated the benefits of unsteady jetting propulsion for use in high frequency disturbance rejection [9].

The PI also has experiencing developing distributed hydrodynamic sensing systems for AUVs. Inspired by the sensing capabilities of fish lateral line systems, the PI developed a set of custom pressure gradient modules that were patterned on the surface of a prototype AUV as shown in figure 3. Using the distributed sensing system to reconstruct the pressure distribution on the surface of the AUV, total hydrodynamic forces were measured in real time. This allowed the AUV to compensate for disturbances before being displaced by them, improving position tracking by as much as 70-80% over traditional error feedback controllers [2].

Intellectual Merit

Intellectual Merit: Research Direction 1 - Motion Control of the Coupled AUV System

Motion control of the Aqua-Gemini system is a complicated due to the physical coupling of the two endpoint AUVs through the cable. Each vehicle must maintain a desired position, and the coupled system must also maintain the tension in the sensor cable. Therefore the control force allocation for each vehicle cannot be performed independently but as a joined system. Furthermore, the cable interaction forces depend not only on the cable layout, but also the local flow field around it, both of which change dynamically during operation. Fortunately, the local flow field will not need to be modeled, because it will be measured by the sensor cable itself, but it's effect will need to be taken into account in system dynamic modeling.

Aqua-Gemini System Modeling - Not only is it crucial for the system to be able to position itself accurately in a desired location, but the cable configuration must be well defined in order to associate each sensor reading with that sensor's location. There have been multiple studies looking into modeling the

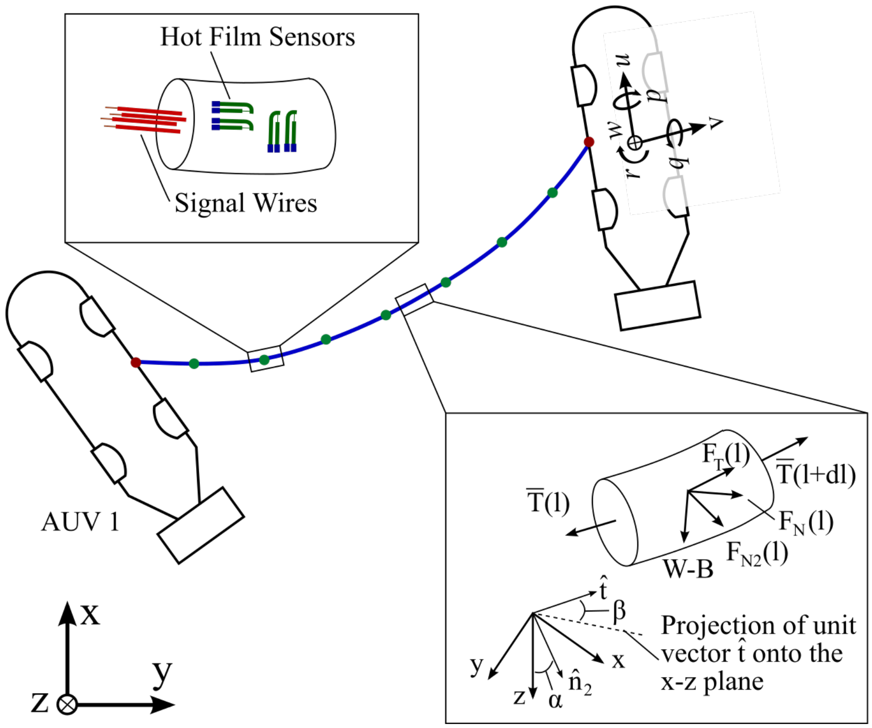

Figure 4: Schematic diagram of the Aqua-Gemini system, showing the characteristic forces on a differential element of the cable, and hot-film sensor layout.

behavior of a towed cable [10, 11]. Dowling derived a model for the tension, $\bar{T}$, and curvature, $\bar{\theta}$, in towed flexible tubes in terms of two differential equations,

$$\begin{aligned} \frac{\partial \bar{T}}{\partial l} &= -\rho_0 (\sigma - 1) \pi a_c^2 g \sin\left(\bar{\theta}\right) - \rho_0 U^2 \pi a_c C_T \cos\left(\bar{\theta}\right) \\ \bar{T}\frac{\partial \bar{\theta}}{\partial l} &= -\rho_0 (\sigma - 1) \pi a_c^2 g \cos\left(\bar{\theta}\right) - \rho_0 U^2 a_c \left[C_D \sin\left(\bar{\theta}\right) + \pi C_N\right] \sin\left(\bar{\theta}\right) \ , \end{aligned} \tag{1}$$

where l is the distance along the cable starting at the root on AUV 1 (see figure 4), ρ_0 is the density of the surrounding water, σ is the specific density of the cable, a_c is the equivalent cable diameter, C_T and C_N are the tangential and normal friction drag coefficients, respectively, C_D is the pressure drag coefficient. It should be noted that this model assumes a uniform surrounding flow, U, which will not be the case in the environments where this system is intended to be used, and that the cable is being towed by one end while the other is free.

Bandyopadhyay *et al.* [12] performed a test where a cable, fixed to a central post on one end and a flapping fin propelled AUV on the other end, was turned about the post by the AUV. They generated a similar model for cable curvature, taking into account the reaction forces being applied at both ends, but ignored any variation in tension along the length of the cable and assumed the surrounding water to be at rest.

The first task of this project will be to create a dynamic model for the Aqua-Gemini system where reaction forces are exerted by AUVs at both ends of the sensor cable, and tension and curvature along the cable take into account local variations in the surrounding flow field. The cable components of this model will be very similar to (1); however, the curvature will need to be defined in multiple dimensions relative to AUV 1 orientation, the fluid velocity will be a function of distance along the cable and have components in all 3 spacial directions, and the boundary conditions will be defined by the AUV components of the model. The AUV modeling will consist of thruster modeling developed by the PI [7, 6] and traditional AUV hydrodynamic modeling [13].

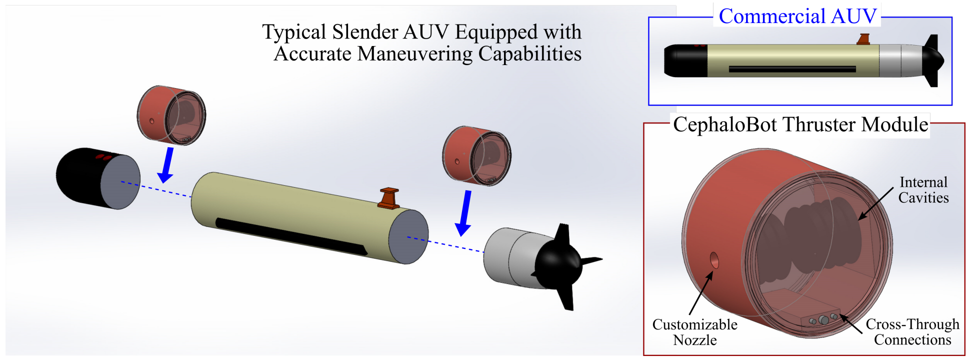

Figure 5: Diagram illustrating custom thruster modules which will be incorporated into commercial AUV platforms. This allows the commercial AUV to independently control sway force and yaw torque from forward force.

Initial validation of the cable component of this new model will be performed for a limited number of surrounding flow structures and boundary conditions (endpoint forcing) within a miniature towing tank in the PI's laboratory (see Facilities section at the end of this document). A cart that traverses along the tank will be outfitted with a customized cable positioning apparatus. Sections of prototype cable will be held by the positioning system which will be able to hold the endpoints stationary, move the endpoints relative to each other, and create spring loaded reaction forces while the cable is being towed through the tank at different orientations. The configuration of the cable during this testing will be recorded with high speed cameras and digitized using standard motion tracking algorithms.

Create Bioinspired Thruster Modules - As was discussed in the section on background information, the PI previously developed a bioinspired thruster technology which allows AUVs to generate lateral maneuvering forces without compromising a streamlined, low-drag hullform. Previously those thrusters were incorporated into prototype AUVs built in house to demonstrate various technologies.

The endpoint AUVs will be standard commercially available vehicles developed for researchers with expandable modular body design and open CPU platform allowing for install of software extensions (either Iver3 Open System AUV or equivalent). They will be purchased using the PI's startup funds if an equipment grant has not been secured by the second year of this project. These AUVs will be utilized for other projects involving research on cooperative control, wake identification, and disturbance rejection, in addition to serving as the endpoint AUVs of the Aqua-Gemini system.

One of the tasks required for this project to be successful will be the development of maneuvering thruster modules that can be integrated with commercial AUVs as depicted in figure 5. These thruster modules will allow the endpoint AUVs to generate the sway forces and yaw torques necessary to maintain adequate tension in the sensor cable, without compromising the streamlined, low-drag shape of the AUV. The thruster modules need to be designed to interface seamlessly with the existing AUV bulkheads. Range of thrust output, which is determined by internal cavity geometry, will be selected based on AUV forces determined through the modeling/simulation discussed in the previous research task.

The thruster modules will also have feed-through lines for data and power connections between other modules fore and aft of the thruster module. Furthermore, the thruster modules will have their own micro-controllers taking in commands from the central CPU in the form of required control force, and then driving the thruster motors correspondingly. The thruster modules will also have motor fault detection, which will be relayed back to the CPU.

Aqua-Gemini Sea basin Validation - Once the tow tank testing has provided initial validation of the system modeling, a fully integrated system will be developed to perform further testing and validation in shallow coastal waters. This research task will also require that the sensor cable integration tasks (Research Direction 2) have been completed before moving on to this step.

Validation of system operation within an adequate ocean environment is a critical step towards eventual deployment for oceanographic sensing missions. As Bandyopadhyay *et al.* said in [12] describing the AUV cable turning experiment, "Further, it is unclear how useful low-speed position, tension, and depth controllers that are developed in the quiescent environment of laboratory tanks would be in the disturbed environment of shallow-water sea basins A basin evaluation of the SPLINE concept would be instructive but would also require an instrumented microtest range."

Fortunately, as described in the corresponding section, the PI's facilities offer unique capabilities for shallow water ocean field testing. The acoustic underwater observatory 'Kilo Nalu' just offshore from the PI's laboratory space in the UH Marine Center is currently being upgraded to serve as a natural laboratory for a number of projects. This station in the Kewalo basin is already equipped with a myriad of acoustic transponders and receivers which will be used to for high-accuracy, real-time tracking of the two endpoint AUVs. There are also receptacles and power hookups for different testing equipment that have yet to be installed. Therefore, Kilo Nalu is the ideal location to perform initial field testing and validation of modeling/controllers before adapting the system for use as a new ocean testing instrument.

We will begin field testing with the simplest case, whereby one end of the sensor cable is fixed to a stationary post that will be installed at Kilo Nalu, and the other end is fixed to one of the endpoint AUVs, and the AUV will perform different 3D turning maneuvers while maintaining appropriate tension in the cable. After the troubleshooting and improvements to control algorithms and cable/vehicle system modeling, the cable will be removed from the stationary post and attached to the second endpoint AUV and a much wider range of maneuvers and cable configurations will be tested.

Intellectual Merit: Research Direction 2 - Sensor Cable Integration

One of the defining capabilities of AUVs leading to their widespread use for oceanographic survey missions is an ability to transit long distances to investigate an ROI, without the need of a support vessel. Aqua-Gemini must maintain this capability to maximize the usefulness of the system. A bioinspired maneuvering/propulsion system (discussed in the previous section) will provide the necessary control authority without compromising forward drag. However, the sensor cable itself will also contribute a significant amount of drag. Therefore, the Aqua-Gemini system will be equipped with a cable management system on one end. During high speed transit the sensor cable will be retracted and the two endpoint AUVs will be latched together as a dual hull over-actuated AUV, but upon arrival at an ROI the two hulls will detach, and the cable will be deployed. Therefore the sensors need to be integrated into the cable in such a way that it can be coiled up without damaging those sensors.

Furthermore, Given the relatively small size of AUVs (relative to research vessels), one of the challenges of this project is going to be designing a low-profile cable, embedded with sensors, that has a small enough diameter to be transported by the coupled AUV system.

Simultaneous Temperature and Shear/Velocity Sensing - This project will begin by embedding a dual use arrangement of hot-film sensors into the cable, to simplify the cable size challenges, but in later years we will investigate including acoustic receivers and fiber-optic bio-chem sensors as well. The hot film sensors will be arranged in pairs, as shown in figure 4, and charged to different voltages so that the sensor pair can be used to simultaneously measure local water temperature and shear stress and hence local relative fluid velocity.

The shear stress, τ, on the surface of the cable is defined as,

$$\tau = \mu \frac{\partial U}{\partial \hat{e}_n}, \tag{2}$$

where $\hat{e}_n$ is the unit vector normal to the cable surface and μ is the fluid viscosity. Hot film sensors involve applying a voltage across a narrow wire in a flow, and the heat loss to the flow is dependent on both the temperature differnce between the wire and fluid ΔT and the shear stress at the sensor location. The equation for the power transfer relates these parameters,

$$P = \frac{V}{R_s} = \Delta T \left[A \left(\rho\tau\right)^{1/3} + B \right] \qquad A \propto \left(\frac{C_p k_T^2}{\mu} \right)^{1/3} \tag{3}$$

where P is power, V is voltage, R_s is the sensor resistance, C_p and k_T are the specific heat and thermal conductivity of the fluid, respectively, and B is the heat loss to the substrate (function of heat conductivity of the cable surface). Since C_p, k_T, and B are all constant for a given sensor configuration and fluid, hot

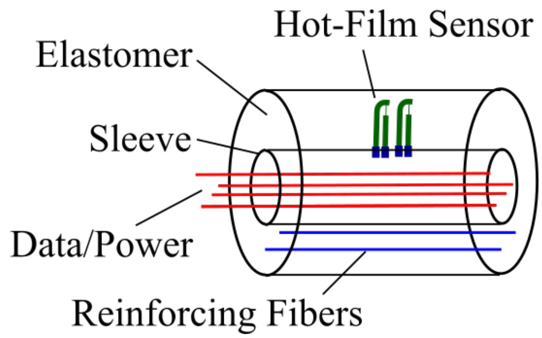

Figure 6: Diagram showing the inner layout of the proposed flexible cable.

film sensors are typically calibrated for a specific fluid temperature and then used to measure shear. The fluid velocity can be related to the shear stress on the surface through boundary layer solutions.

For the sensor cable we will instead use a pair of hot film sensors charged to different voltages and placed close enough together that the fluid temperature and shear stress are equivalent. Thus, the power equations for the two sensors form a system of two equations for two unknowns. Furthermore, by using the identical hot film sensors to measure both temperature and shear stress we greatly reduce the total work that needs to be done integrating the sensor into the cable substrate, and maintain consistent power requirements.

This research task will validate the ability to simultaneously measure temperature and shear/velocity by placing prototype sensor cables in the miniature towing tank described in the Facilities section. The sensor cable will be placed in different orientations as it's dragged through the water at different speeds. The tests will also be performed in water at different temperatures. We will perform a parametric study to determine the optimal sensor charging voltages to yield the greatest sensitivity to the temperature range expected to be encountered in ocean testing.

Cable management System - In order for the Aqua-Gemini system to be effective, it needs to be able to retract the cable and have the two endpoint AUVs latch together to facilitate efficient long range transit to a particular region of interest. As part of this project we will design a compact cable management system consisting of a grooved drum that can articulate forward and backward within the body of the AUV. The cable will enter the hull through an opening outfitted with rollers that provide consistent reaction force but allow the cable to feed inside the body. The drum will simultaneously rotate to coil the cable around itself while either translating forward or backward to maintain that the cable is being pulled in directly behind the opening. Therefore the cable needs to be flexible enough in bending to coil around the cable management system, but maintain the tensile strength in order to withstand the necessary tension forces.

In this research task we will design the driving mechanism to generate simultaneous rotation and axial oscillation of the grooved drum, and create a microcontroller to synchronize those motions and maintain that the cable is continually being pulled in directly behind the opening. This can be done by noting that the cable forms a helical spiral on the surface of the drum with a wavelength equal to the cable diameter, so that for a drum rotational velocity of ω the axial velocity, v_a, should be matched to,

$$v_a = \frac{d_s}{2\pi}\omega \, . \tag{4}$$

We will also design the cable itself to be a flexible elastomer reinforced with high tensile strength reinforcing fibers, and embedded with a central bundle of data and power lines running to the sensors, as shown in figure 6. For this task the PI will draw on his extensive background designing fiber reinforced elastomer systems with passive deformation control [22, 23]. We will select the elastomer material to be just flexible enough to allow it to be coiled onto the drum of the cable management system. The data and power lines running to the sensors will be in a central sleeve that will allow them to slide freely withing the reinforced elastomer to avoid possible damage. Additionally, part of this task will be determining an appropriate method of bonding the hot-film sensors to the surface of the elastomer cable. This embedding process needs to maintain sufficient bonding strength even when the cable becomes bent.

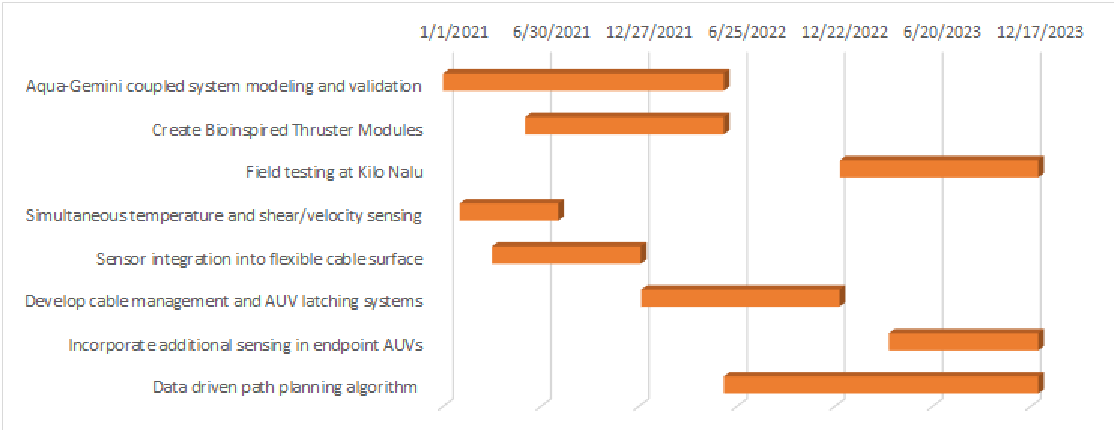

Figure 7: Gantt chart of project research milestones and timeline.

Once the cable and cable management system have been designed and prototypes have been assembled, the entire system will be rigorously tested in the AUV testing pool located outside of the PI's laboratory (see the facilities section for a picture and description), prior to any field testing.

Additional Sensing - There are also complementary sensors which, along with temperature and relative flow velocity, can greatly improve the reconstruction of plume/front features. However, these sensors tend to be bulkier, thus unsuitable for installation on the cable. Therefore, the Aqua-Gemini system will also have sensors like flourometers and optical plankton counters installed on the endpoint AUVs. Overall the sensory system would then consist of two point measurements of several parameters with a gradient of temperature and flow velocity measurements in between.

Develop Path Planning Algorithms to Maximize Information Capture - In the final year of this project, after the validity of the motion control algorithms and sensing techniques have been established, path planning algorithms for the Aqua-Gemini system based on recovered data will be developed. In this scheme, path planning algorithms will drive system trajectories towards high gradients in both temperature and velocity in order to provide direct sampling of the most information rich areas.

Broader Impacts

This project has the potential to have a transformative impact on oceanographic sampling and measurement techniques. Since the sensor cable is suspended between a pair of AUVs it can be delivered to several ocean regions that were considered inaccessible due to either physical barriers or inaccessible safety risks.

For example, the interface between sea ice shelves and the rest of the ocean is typically populated by grease ice or pankake ice. This thin semi-solid ice layer is known to dissipate incoming ocean waves before they reach the solid ice shelves, which has a significant impact on sea ice melting, and thus on sea level rise. However, modeling this process is extremely difficult due to a lack of fluid velocity data underneath the grease ice to validate various models [14]. Surface vessels perform minimal testing because of possible damage due to ice breaking, and those that do venture into this region contaminate the velocity distribution by breaking the ice and introducing wake flows. Permanent observations are similarly impractical in this region because of the seasonal and spacially transient nature of these ice structures. The Aqua-Gemini system would be ideal for measurements intended to record fluid flow structures in these regions.

Furthermore, moving from single point oceanographic sampling to distributed sampling along a moving line, allows measurement of chaotic and transient features that dissipate faster than a mobile sensor can traverse the feature.

By creating a tool for sensing ocean phenomenon previously inaccessible, can lead to significantly improved modeling of sea level rise, climate change, and weather patterns. These improved models in turn allow leaders and legislators to make more informed policy decisions, improving the lives of countless worldwide. Improved weather models in particular can directly save lives by providing earlier warnings to people in the path of catastrophic storms. Additionally, better models of ice breakup and ice loss in the arctic region can lead to improved planning of future shipping routes and therefore increased use economic competitiveness.

Project Timeline

In order to ensure that this project meets its identified goals and objectives, a schedule of milestones has been created for the different research tasks identified in previous sections of this project description. A Gantt chart showing the proposed timeline of this project is provided in figure 7

References

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Biographical Sketch for Michael Krieg

Professional Preparation

- **University of Colorado (Boulder)** Aerospace Engineering Sciences BS 2006
- **University of Colorado (Boulder)** Aerospace Engineering Sciences PhD 2012
- **University of Florida (Gainesville)** Robotics/Controller Design/Fluid Modeling 2012-2016

Appointments

- **University of Hawaii (Manoa)** [2019-2020] Assistant Professor - Ocean and Resources Engineering
- **University of Florida (Gainesville)** [2016-2019] Research Scientist - Mechanical and Aerospace Engineering

Personal Background and Expertise

Prof. Krieg's graduate research was focused on unsteady underwater jet propulsion, inspired by the locomotion of squid and jellyfish. In contrast to continuous fluid jets, pulsed jets (or starting jets) are characterized by the formation of a leading vortex ring, due to roll-up of the unstable free shear layer. The propulsive dynamics and energetics of unsteady jetting are heavily dependent on the state of the primary vortex ring, which is complicated by a process where the ring becomes saturated and separates from the trailing shear flow.

One aspect of the work characterizing the propulsive dynamics of unsteady jets was to take particle image velocimetry (PIV) measurements of jet flows under a multitude of starting conditions and use the velocity field data to validate theoretical modeling [15]. Similarly, Prof. Krieg developed analytical models for evolution of circulation, hydrodynamic impulse, and kinetic energy in the jet [5], models for pressure dynamics both at the jetting source and inside the cavity [6], and identified similarities between affects of nozzle geometry and those induced by the leading vortex ring formation. In coordination with PIV measurements of fluid velocity fields, custom data acquisition hardware was setup to simultaneously measure various forces, pressures, and power consumption [3]. All of which was summarized in a chapter Prof. Krieg wrote [16] for a book on engineering analysis of synthetic jet actuators.

Prof. Krieg also created the first prototype AUVs using unsteady jet thrusters to demonstrate improved maneuvering capabilities. As such, he was one of the main researchers responsible for the design and fabrication of these underwater robots and their control systems [17, 1]. Testing on how the new thrusters alter vehicle dynamics, as well as un-restrained propulsive efficiency testing, require that the vehicle's trajectory be tracked throughout different actions [18]. In order to perform this testing he setup and calibrated an underwater motion capture system, and optimized the camera placement to ensure the best coverage for different tests. Working with complex vehicle systems led to several skills useful for robotics research, such as programming micro-controllers to drive individual systems and communicate with central controllers using standard protocols, and has also lead to extensive fabrication experience. The unsteady nature of the propulsion and non-linear environment are a significant challenge for vehicle autonomy [19, 20]. In order to accommodate these difficulties Prof. Krieg developed custom control algorithms and identified different maneuvering regimes based on relative length scales, each with unique dynamic behavior [7, ?]. Recently, he has also worked to incorporate distributed hydrodynamic sensing, inspired by the fish lateral line, into a novel motion controller. In this technique, fluid interaction forces are measured and compensated directly, improving position tracking accuracy [2].

His graduate research has branched out to the field of soft robotics. Inspired by squid mantle structures, which contain a complex system of reinforcing collagen fibers in order to passively drive jetting-optimal deformations [21], Prof. Krieg developed a theory of using fiber reinforcement to control planar strain relationships of highly deformable soft composites [22, 23]. This research led to creation of a patent (#15/842,065). In the process, he has gained a functional understanding of Cosserat, or micropolar, elasticity, which allows for local rotations of material points as well as displacement; and have gained experience with unsteady curvilinear coordinate systems. He has developed unique procedures for determining body deformation based on distributed pressure sensing [24], and for analyzing body deformations in terms of automatically identified motion primitives [25].

Prof. Krieg's wide range of multidisciplinary skills is showcased by publications in high-ranking journals across a wide range of fields, including the Journal of Fluid Mechanics, Nature: Machine Intelligence, the International Journal of Robotics Research, IEEE Transactions on Robotics, the Journal of Morphology, Bioinspiration and Biomimetics, and Composites: Science and Technology.

Products

Publications which are most related to the project:

1. M. Krieg, K. Nelson and, K. Mohseni, Distributed sensing for fluid disturbance compensation and motion control of intelligent robots, *Nature Machine Intelligence*, **1(5)**, 216-224, **2019**. DOI: 10.1038/s42256-019-0044-1

2. M. Krieg, P. Klein, R. Hodgkinson, and K. Mohseni, A hybrid class underwater vehicle: Bioinspired propulsion, embedded system, and acoustic communication and localization system, *Marine Technology Society Journal*, **45(4)**, 153-164, **2011**

3. M. Krieg, K. Nelson, J. Eisele, K. Mohseni, Bioinspired jet propulsion for disturbance rejection of marine robots, *IEEE RA-Letters*, **3(3)**, 2378-2385, **2018**

4. M. Krieg and K. Mohseni, Comparison of Different Methods for Estimating Energetics Related to Efficiency on a UUV with Cephalopod Inspired Propulsion, *5th Symposium on Marine Propulsors*, Helsinki Finland, June 12-15, **2017**

5. M. Krieg and K. Mohseni, Dynamic modeling and control of biologically inspired vortex ring thrusters for underwater robot locomotion, *IEEE Trans. Rob.*, **26(3)**, 542-554, **2010**

Other significant publications worth noting:

1. M. Krieg, and K. Mohseni, Pressure and work analysis of unsteady, deformable, axisymmetric, jet producing cavity bodies, *J. Fluid Mech.*, **769**, 337-368, **2015**

2. M. Krieg and K. Mohseni, Relative Planar Strain Control and Minimizing Deformation Work in Elastomeric Sheets via Reinforcing Fiber Arrays, *Composites Science and Technology*, **142**, 50-64, **2017**

3. M. Krieg, I. J. Sledge, and K. Mohseni, Design considerations for an underwater soft-robot inspired from marine invertibrates, *Bioinsp. Biomim.*, **10(6)**, 065004, **2015**

4. M. Krieg and K. Mohseni, Modelling circulation, impulse, and kinetic energy of starting jets with non-zero radial velocity, *J. Fluid Mech.*, **719**, 488-526, **2013**

5. M. Krieg and K. Mohseni, Thrust Characterization of a Bio-inspired Vortex Ring Generator for Locomotion of Underwater Robots, *IEEE J. of Oceanic Eng.*, **33(2)**, doi. 10.1109/JOE.2008.920171, **2008**

Synergistic Activities

Hōkūle'a Ship Hull Discretization - In his first semester of teaching a class on hydrostatics and dynamics of floating ships, Prof. Krieg developed a module to simultaneous teach students technical computing methods for ship design and traditional Hawaiian navigation and ship-making. Hōkūle'a is a voyaging canoe built to demonstrate and celebrate Polynesian voyaging. The students were taught about the history of the ship, and Prof. Krieg discretized the hull form to have students calculate stability criteria using modern naval architecture techniques on a traditional native vehicle.

Other Personnel Biographical Information

Data Not Available

SUMMARY PROPOSAL BUDGET

YEAR 1

	FOR NSF USE ONLY		
ORGANIZATION University of Hawaii	PROPOSAL NO. 2023732	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR Michael Krieg	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Michael Krieg - Principal Inv	0.0			0	
2.					
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.0			0	
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	0.0			0	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL SCHOLARS	0.0			0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.0			0	
3. (1) GRADUATE STUDENTS				30,312	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				30,312	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				4,270	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				34,582	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) Hot-Film Sensors (30 at 486) $ 14580 Motion Tracking Software $ 10500 Bioinspired Thruster Modules $ 0					
TOTAL EQUIPMENT				25,080	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				5,000	
2. INTERNATIONAL				0	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				5,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				0	
TOTAL OTHER DIRECT COSTS				5,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				69,662	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) University F&A (Rate: 44.5, Base:59162)					
TOTAL INDIRECT COSTS (F&A)				26,327	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				95,989	
K. FEE				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				95,989	
M. COST SHARING PROPOSED LEVEL $	AGREED LEVEL IF DIFFERENT $				

	FOR NSF USE ONLY		
PI/PD NAME Michael Krieg	INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME* Kyle Koza	Date Checked	Date Of Rate Sheet	Initials - ORG

1 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

SUMMARY PROPOSAL BUDGET

YEAR 2

ORGANIZATION University of Hawaii				FOR NSF USE ONLY PROPOSAL NO. 2023732	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR Michael Krieg				AWARD NO.		
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)	
1. Michael Krieg - Principal Inv	1.0			12,055		
2.						
3.						
4.						
5.						
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.0			0		
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	1.0			12,055		
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)						
1. (0) POST DOCTORAL SCHOLARS	0.0			0		
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.0			0		
3. (2) GRADUATE STUDENTS				42,343		
4. (0) UNDERGRADUATE STUDENTS				0		
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0		
6. (0) OTHER				0		
TOTAL SALARIES AND WAGES (A + B)				54,398		
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				13,501		
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				67,899		
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) Hot-Film Sensors (30 at 486) $ 0 Motion Tracking Software $ 0 Bioinspired Thruster Modules $ 16000						
TOTAL EQUIPMENT				16,000		
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				5,000		
2. INTERNATIONAL				0		
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0						
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0		
G. OTHER DIRECT COSTS						
1. MATERIALS AND SUPPLIES				5,000		
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0		
3. CONSULTANT SERVICES				0		
4. COMPUTER SERVICES				0		
5. SUBAWARDS				0		
6. OTHER				0		
TOTAL OTHER DIRECT COSTS				5,000		
H. TOTAL DIRECT COSTS (A THROUGH G)				93,899		
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) University F&A (Rate: 45.0, Base:77910)						
TOTAL INDIRECT COSTS (F&A)				35,060		
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				128,959		
K. FEE				0		
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				128,959		
M. COST SHARING PROPOSED LEVEL $	AGREED LEVEL IF DIFFERENT $					
PI/PD NAME Michael Krieg	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION					
ORG. REP. NAME* Kyle Koza	Date Checked	Date Of Rate Sheet	Initials - ORG			

2 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

SUMMARY PROPOSAL BUDGET

YEAR 3

ORGANIZATION: University of Hawaii				FOR NSF USE ONLY — PROPOSAL NO. 2023732	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR: Michael Krieg				AWARD NO.		
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)	
1. Michael Krieg - Principal Inv	2.0			24,955		
2.						
3.						
4.						
5.						
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.0			0		
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	2.0			24,955		
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)						
1. (0) POST DOCTORAL SCHOLARS	0.0			0		
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.0			0		
3. (2) GRADUATE STUDENTS				64,942		
4. (0) UNDERGRADUATE STUDENTS				0		
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0		
6. (0) OTHER				0		
TOTAL SALARIES AND WAGES (A + B)				89,897		
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				24,745		
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				114,642		
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)						
Hot-Film Sensors (30 at 486) $ 0						
Motion Tracking Software $ 0						
Bioinspired Thruster Modules $ 0						
TOTAL EQUIPMENT				0		
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				5,000		
2. INTERNATIONAL				0		
F. PARTICIPANT SUPPORT COSTS						
1. STIPENDS $ 0						
2. TRAVEL 0						
3. SUBSISTENCE 0						
4. OTHER 0						
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0		
G. OTHER DIRECT COSTS						
1. MATERIALS AND SUPPLIES				5,000		
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0		
3. CONSULTANT SERVICES				0		
4. COMPUTER SERVICES				0		
5. SUBAWARDS				0		
6. OTHER				0		
TOTAL OTHER DIRECT COSTS				5,000		
H. TOTAL DIRECT COSTS (A THROUGH G)				124,642		
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) University F&A (Rate: 45.5, Base:124642)						
TOTAL INDIRECT COSTS (F&A)				56,712		
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				181,354		
K. FEE				0		
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				181,354		
M. COST SHARING PROPOSED LEVEL $	AGREED LEVEL IF DIFFERENT $					
PI/PD NAME: Michael Krieg				FOR NSF USE ONLY — INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*: Kyle Koza				Date Checked	Date Of Rate Sheet	Initials - ORG

3 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

SUMMARY PROPOSAL BUDGET

Cummulative

ORGANIZATION University of Hawaii			FOR NSF USE ONLY PROPOSAL NO. 2023732	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR Michael Krieg			AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Michael Krieg - Principal Inv	3.0			37,010	
2.					
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)					
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	3.0			37,010	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL SCHOLARS	0.0			0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.0			0	
3. (5) GRADUATE STUDENTS				137,597	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				174,607	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				42,516	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				217,123	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				41,080	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				15,000	
2. INTERNATIONAL				0	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0.0) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				15,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				0	
TOTAL OTHER DIRECT COSTS				15,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				288,203	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS (F&A)				118,099	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				406,302	
K. FEE					
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				406,302	
M. COST SHARING PROPOSED LEVEL $	AGREED LEVEL IF DIFFERENT $				

PI/PD NAME Michael Krieg	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME* Kyle Koza	Date Checked	Date Of Rate Sheet	Initials - ORG

C *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

Budget and Budget Justification

The budget is included as a spreadsheet in the attached documents. Please refer to this attached budget. Below you can find a line by line justification for the different costs included in the budget.

Table 1: Justification for budget allocated to the first period (01/2021-12/2021) of the proposed project.

Category	Item	Justification
Labor	Graduate Assistant 1	The graduate student will be assisting the PI in fabricating the prototype sensor cable, creating the miniature towing tank mounting aparatus for the prototype sensor cable, and performing the parametric study of cable deformation under different loading and operational conditions. The salary level corresponds to the ‘Step 16’ designation within UH graduate assistant pay schedule. Step 16 is the designation for students coming in with an MS.
Materials	Hot-Film Sensors	The commercial hot-film sensors (SenFlex 9311) are manufactured by Tau Systems, to be very low profile sensors for custom installation applications. They will be installed in the prototype sensor cable to be used for simultaneous temperature and shear measurements. The price comes from a quote requested by the PI.
Materials	Raw Materials	This item is a lump sum of low cost materials needed to perform the project, including but not limited to: a computer for the lab workstation, nuts, bolts, mounting hardware, wires, PCBs, and stock material for custom part fabrication.
Equipment	Motion Tracking Software	Parametric studies on cable deformation require that the cable configuration is measured throughout the test. The cable shape will be filmed with a high speed camera (purchased with PI startup for a variety of projects) and this software will be used to recover the dynamic cable shape from the high speed video.
Travel	Annual Review	This travel expense will allow the PI to travel to present a summary of progress on the project at an annual review. Cost is estimated as equivalent to a recent travel expense by the PI to a conference in Seattle.
Travel	Conference	This travel expense will allow the PI to travel to an international peer reviewed conference to promote the project and present the latest findings to the academic community. Cost is estimated as equivalent to a recent travel expense by the PI to a conference in Seattle.

Table 2: Justification for budget allocated to the Second period (01/2022-12/2022) of the proposed project.

Category	Item	Justification
Labor	Prof. Krieg	This item is to cover the PI salary over one month in the summer. The cost is 1/11'th of the PI's salary.
Labor	Graduate Assistant 1	The graduate student will be assisting the PI in fabricating the prototype sensor cable, creating the miniature towing tank mounting apparatus for the prototype sensor cable, and performing the parametric study of cable deformation under different loading and operational conditions. The salary level corresponds to the 'Step 16' designation within UH graduate assistant pay schedule. Step 16 is the designation for students coming in with an MS.
Labor	Graduate Assistant 2	The graduate student will be assisting the PI in fabricating the custom bioinspired sensor modules, integrating them into low cost commercial AUVs, performing field testing at Kilo Nalu, and performing simulations on different motion control algorithms. This student will be picked up in the fall semester of 2022. The salary level corresponds to the 'Step 16' designation within UH graduate assistant pay schedule. Step 16 is the designation for students coming in with an MS.
Materials	Raw Materials	This item is a lump sum of low cost materials needed to perform the project, including but not limited to: a computer for the lab workstation, nuts, bolts, mounting hardware, wires, PCBs, and stock material for custom part fabrication.
Equipment	Thruster Modules	These Bioinspired thruster modules will be built in the lab based on designs the PI developed in previous projects. They will be designed to be integrated into an open platform commercial AUV. The thrusters will give the commercial AUV enhanced maneuvering capabilities needed to maintain cable tension and shape during field testing. This item includes 4 thruster modules (2 for each AUV). The estimated cost comes from the cost of previous thruster modules created by the PI at a previous appointment, and includes motors, microcontrollers, timing belts/pulleys, bearings, linear guides, and fabricated parts.
Travel	Annual Review	This travel expense will allow the PI to travel to present a summary of progress on the project at an annual review. Cost is estimated as equivalent to a recent travel expense by the PI to a conference in Seattle.
Travel	Conference	This travel expense will allow the PI to travel to an international peer reviewed conference to promote the project and present the latest findings to the academic community. Cost is estimated as equivalent to a recent travel expense by the PI to a conference in Seattle.

Table 3: Justification for budget allocated to the third period (01/2023-12/2023) of the proposed project.

Category	Item	Justification
Labor	Prof. Krieg	This item is to cover the PI salary over one month in the summer. The cost is 2/11'ths of the PI's salary.
Labor	Graduate Assistant 1	The graduate student will be assisting the PI in fabricating the prototype sensor cable, creating the miniature towing tank mounting apparatus for the prototype sensor cable, and performing the parametric study of cable deformation under different loading and operational conditions. The salary level corresponds to the 'Step 16' designation within UH graduate assistant pay schedule. Step 16 is the designation for students coming in with an MS.
Labor	Graduate Assistant 2	The graduate student will be assisting the PI in fabricating the custom bioinspired sensor modules, integrating them into low cost commercial AUVs, performing field testing at Kilo Nalu, and performing simulations on different motion control algorithms. This student will be picked up in the fall semester of 2022. The salary level corresponds to the 'Step 16' designation within UH graduate assistant pay schedule. Step 16 is the designation for students coming in with an MS.
Materials	Raw Materials	This item is a lump sum of low cost materials needed to perform the project, including but not limited to: a computer for the lab workstation, nuts, bolts, mounting hardware, wires, PCBs, and stock material for custom part fabrication.
Travel	Annual Review	This travel expense will allow the PI to travel to present a summary of progress on the project at an annual review. Cost is estimated as equivalent to a recent travel expense by the PI to a conference in Seattle.
Travel	Conference	This travel expense will allow the PI to travel to an international peer reviewed conference to promote the project and present the latest findings to the academic community. Cost is estimated as equivalent to a recent travel expense by the PI to a conference in Seattle.

Current and Pending Support

The PI does not currently have any support (1st year as professor).

If this project gets funded, it would constitute the pending support of the PI.

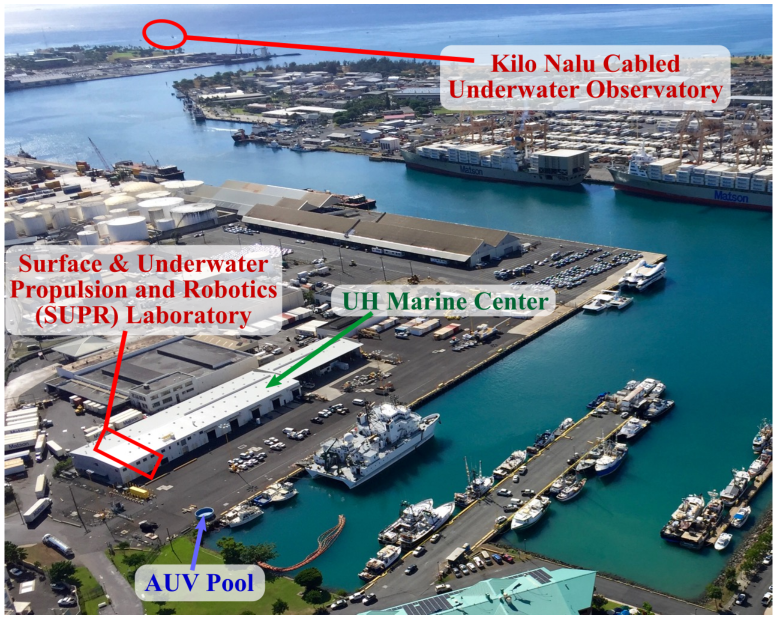
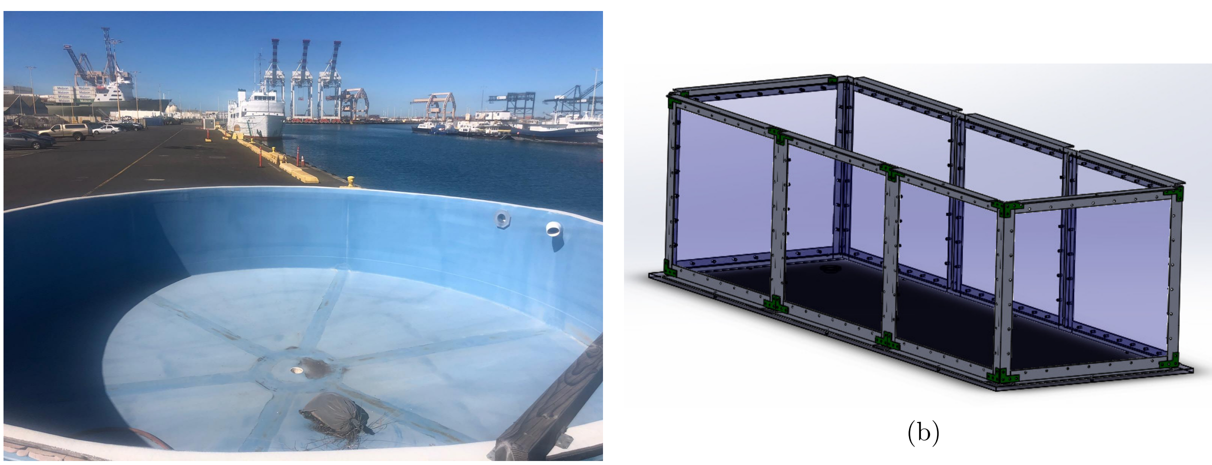


Figure 8: Aerial image of the University of Hawaii Marine Center indicating the location of Prof. Krieg's laboratory and the Kilo Nalu Observatory.

Facilities

The PI's new appointment at the University of Hawaii provides several unique opportunities that will contribute to the success of the proposed project. This appointment comes with a laboratory space ($\approx 800 ft^2$) at the University of Hawaii Marine Center, which is located at pier 35 in Honolulu harbor. An aerial view of this facility is shown in figure 8 illustrating the unique ease of access to the ocean.



(a) (b)

Figure 9: Experimental testing facilities. (a) Image of the AUV pool used for testing integrated vehicles (b) CAD image of the sub-system testing tank.

A flow visualization and measurement tank, shown in figure 9b, is currently being constructed in this lab, which will allow accurate isolated testing of propulsion/maneuvering subsystems using PIV techniques. The 12'x4'x4' tank is constructed of a steel frame with acrylic panels allowing visual access from all sides, making it ideal for PIV measurements of novel propulsors. The flow visualization tank will also be equipped with a top rail to perform towing tests of small scale sensor cable mock ups. Just outside this lab space the marine center has a large AUV pool, shown in figure 9a, which will be utilized for preliminary testing of fully integrated vehicle prototypes.

In addition to this lab space the PI is collaborating with other researchers to retrofit the Kilo Nalu Observatory to make it an optimal site for underwater robotics field testing. Kilo Nalu (see figure 8) is a permanent cabled underwater observatory providing acoustic and oceanographic measurements of Honolulu coastal conditions. This observatory, which has continuous power supplied through a cable running back to the shore, will be retrofitted with acoustic modems and acoustic baseline systems in order to allow communication and tracking of underwater robots during testing in actual ocean conditions.

These facilities will be optimal to provide a seamless transition from purely academic concepts to fully developed technology. Concepts are validated and characterized in the controlled laboratory environment. Fully integrated robotic systems will be tested to troubleshoot bugs in the system in a 20 ft diameter AUV pool located at the Marine Center, and finally the performance of ocean-ready systems will be examined at the Kilo Nalu testing site.

Data management plan

This project does not have a data management plan. This is because the project involves development of a technology to be used for oceanographic surveys, but does not involve any surveys where data will be collected. Likewise, there are no sample collections associated with this project. Any development on the technology will be reported in journal/conference publications.

Postdoctoral Mentoring Plan

Data Not Available

Other Supplementary Documents

Data Not Available