Project Number: 901809

Project Start: Jan. 1, 2021 **Project Duration (in years): Year 1 of 5**

Please indicate if proposal includes requests for any of the following (mark all that apply).

[x] **Ship Time**	[x] **ROV**	[x] **AUV**	[x] **Wave Glider**	[x] **Mini ROV**

Please indicate what type of project is being proposed (mark only one).

[ ] **Feasibility/Scoping** [Less than 100 days effort]	[x] **Development**[1]	[x] **Research**	[ ] **Infrastructure**[2]	[ ] **Education**	[ ] **Time Series**	[ ] **Institute Initiative**

Project Manager[2]: Joost Daniels

Principal Investigator: Kakani Katija

Lead Scientist: [Enter name here]

Lead Engineer: [Enter name here]

Project Title: Bioinspiration Lab

Please indicate which category best describes the project theme (mark only one).

[ ] **Ocean biogeochemistry**	[ ] **Ecosystem dynamics**	[x] **Ocean visualization**	[ ] **Exploration & discovery**

Please indicate percentage of effort on this project anticipated for 2021 toward these three highest institutional goals (percentage total should equal 100%).

Goal	Developing/adapting innovative technologies	Utilizing developments to explore and understand ocean systems	Technology/knowledge transfer[3]
Percentage	40%	30%	30%

1 Development and infrastructure projects must complete the risk matrix (see end of the proposal form).

2 Not all projects will require all four titles to be filled in. Please indicate individuals only for those titles that are appropriate for your project.

3 This category includes transfer of hardware, know-how, publications, presentations, etc.

1) ABSTRACT (if submitted during abstract phase)

The overarching themes of the Bioinspiration Lab's efforts are to develop technologies that enable observations of biology at temporal and spatial scales that are not currently achievable in the ocean. Since observations of biology are multi-faceted, our efforts will employ novel imaging modalities, utilize statistical methods (e.g., machine learning) for data synthesis and image-based control algorithms, and engage non-traditional partners to participate in oceanographic research. These approaches have and will continue to be applied to novel instrument and vehicle developments. These efforts will facilitate a number of activities that include, but are not limited to, targeted studies of organismal ecomechanics in the deep sea, rapid surveys of midwater and benthic regions to quantify and assess biological communities, and broader engagement of a user community for our development efforts both within MBARI and beyond. Building on successful deployments of in-situ developments as part of the Bioinspiration Lab's activities (i.e., DeepPIV, EyeRIS, Mesobot, ML-Tracking) as well as laboratory imaging tools (i.e., PIV, telecentric, lightfield, 3DR), we will continue to develop and apply these instruments to new studies, as well as use our existing data to publish in scientific literature. While our interests primarily lie at the intersection of elucidating biological-physical interactions, our goal is to develop systems that can be broadly used to realize innovative science in the ocean.

The Bioinspiration Lab seeks support for 5 years, with specific science and engineering priorities that include engineering developments, instrument deployments and maintenance, and collaboration with internal and external scientists and engineers. In each year, we will request one 7-day summer *Western Flyer* cruise and multiple *Rachel Carson* ship days spread throughout the year.

2) PROPOSAL

a) All Projects

Statement of the challenge, why it is important

Developing technology to instrument and explore the oceans is a challenging prospect because of the vast three-dimensional space being sampled, corrosive underwater conditions that are characterized by high pressures and variable temperatures, and the finite resources available (e.g., power and light) to conduct these missions. Marine organisms across all size ranges survive these challenging marine conditions, and they have evolved a variety of successful solutions for locomotion, feeding, predation avoidance, and reproduction as a way to cope with limited resources (e.g., energy, nutrients, and oxygen). By studying these strategies for survival, which can be used to inform bio-inspired design, we can develop technologies and instrumentation to explore and observe the oceans more effectively. The Bioinspiration Lab ultimately hopes to apply these lessons learned to technology that advances MBARI's and the ocean science community's research and engineering missions. However, engineering developments that

enable scalable observations of these cryptic animals in their natural, deep sea environments are needed, and are largely the focus of the Lab in this proposal.

Relevance

How does it relate/contribute to MBARI's mission and strategic plan?

The Bioinspiration Lab's goals are directly in line with MBARI's, where we seek to develop new tools and techniques to address questions that inform our understanding of how the oceans function, and by either directly using or collaborating with researchers to utilize these technological developments, we can transfer the knowledge, tools, and methods to the wider oceanographic community. The activities and developments by members of the Bioinspiration Lab (e.g., EyeRIS, Mesobot, FathomNet) will contribute to all of MBARI's research themes.

Does it relate to the Technology Roadmap? If so, please describe how. (See http://mww.mbari.org/oed/TechnologyRoadmap.pdf.)

- *Taking the laboratory into the ocean*: Developing EyeRIS (Remote Imaging System) will enable high temporal and spatial resolution measurements of three-dimensional fluid motion as well as static or deforming biological surfaces using state-of-the-art plenoptic imaging technology. This effort (800139 EyeRIS) is supported by the Gordon and Betty Moore Foundation. In addition, as part of 902000 Multi-Spectral StealthCam effort, we hope to deduce whether specific lighting wavelengths and intensities will alter or elicit behaviors of animals we are hoping to target, with application to selecting illumination systems for EyeRIS and other future imaging systems. Leveraging what we've learned as part of EyeRIS, we hope to begin development of a multi-camera lightfield imaging system for integration on MBARI's ROVs to enable high spatiotemporal 3D reconstructions of 5-30 cm animals, and collaborating with partners at CVisionAI and Digital Life 3D to develop workflows for these data products. Finally, DeepPIV has been requested for deployments on numerous research cruises to investigate various deep sea systems (e.g., 901220 Midwater Ecology, 901007 Benthic Ecology, Deep Sea Coral Observatory, 901101 Ocean Imaging, 901023 Continental Margins, 800145 Deep Sea 3D), and our Lab will continue to support these efforts.
- *Enabling targeted sampling*: Research and development activities in last year's 701136 Mesobot project, where the vehicle requires human-in-the-loop input to initiate tracking missions, has highlighted the importance of fully automating the acquisition of targets for tracking missions. Given our efforts to spin up *FathomNet* (902002) and recent developments in supervised machine learning, we will continue to pursue integrating machine learning into mission planning to enable autonomous, targeted sampling of midwater animals (proposed here) and 701139 ML Tracking will capture these efforts.
- *Advancing a persistent presence*: In collaboration with 902002 FathomNet, 701139 ML Tracking, and 600034 Precision Control, we will be pursuing efforts to use machine learning to develop more robust algorithms for long-term visual tracking of targets in midwater. To test these algorithms and enable rapid iterative improvements, we will utilize ROV MiniROV and Mesobot (pending vehicle availability) both in MBARI's Test Tank and on RV Rachel

Carson. Supervised autonomy, which will enable human-in-the-loop verification of autonomous tracking missions (effort captured here) will also contribute to this theme.

How does it relate/contribute to the Packard Foundation's Ocean Grantmaking Program? (See https://www.packard.org/what-we-fund/ocean/ and documents therein.)

This project will be involved in research and development projects that will lead to improving our understanding of the ocean and how marine ecosystems function.

Overall approach to the challenge: Over the complete term of the project, what is needed to address the challenge (e.g., sensors, platforms, marine operations, de novo R & D, etc.)

Research

The Bioinspiration Lab's research efforts are ultimately to study marine organismal ecomechanics with application to bio-inspired ocean exploration technologies. To achieve this, we seek to develop solutions to overcome challenges associated with studying animal behavior, structure, and function in the deep sea. The solutions we develop are cross-cutting, and can be applied to a diverse range of problems in Oceanography from biogeochemical cycling and carbon flux, to feeding ecology and vertical migration behavior. The 901506 DeepPIV project is an excellent example of this: the instrument is currently being used to study filtration rates and energetics of deep sea sponges and the feeding strategies of coral in high-flow seamount environments; later in 2020, DeepPIV will be used to conduct in situ 3D scans of gelatinous organisms for taxonomic referencing in the South Pacific (800145 Deep Sea 3D); validate volumetric particle field imaging systems like 800139 EyeRIS; and will continue to be used in midwater and benthic ROV dives in collaboration with 901220 Midwater Ecology, 901007 Benthic Biology and Ecology, 901101 Ocean Imaging, 901023 Continental Margins, and external collaborators and members of the Deep Ocean Inspiration Group (DOIG). We anticipate that current and future development projects for the Bioinspiration Lab (e.g., Mesobot, 800139 EyeRIS, and 902002 FathomNet) will have the same impact.

As existing technology developments mature, the Bioinspiration Lab has begun to evaluate available and desired observational tools and platforms to persistently study organismal behavior in the deep sea. A widespread behavior that is shared with billions of organisms in the twilight zone is vertical migration. Vertical migrations in the ocean are the largest mass movement of animals on our planet, and our understanding of these dynamics are very limited due to the challenges of conducting observations in the twilight zone. By studying animals that vertically migrate, on temporal scales equivalent to the migration duration or longer, these observations may yield insights for bio-inspired design, including energetically efficient propulsion mechanisms for underwater vehicles. Based on collective interest of studying this topic from the 2018 MBARI Ideation Workshop, we anticipate proposing an institution-wide initiative on Vertical Migration in the near future based on smaller scale experiments we are conducting now and have proposed in 2021 that use multiple vehicles (e.g., WaveGlider, LRAUVs, and MiniROV/Mesobot) working in tandem while tracking an

individual vertical migrator. In close collaboration with a variety of research groups (e.g., 901220 Midwater Ecology, 901700 Acoustical Ocean Ecology, etc.) and development projects (e.g., 901906 MultiSpectral StealthCam, 901800 LRAUV Payloads, 901911 ROVVR, etc.), the Bioinspiration Lab will be contributing to research and technology development efforts involving underwater imaging and autonomy in preparation for this and other related initiatives.

Engineering/Technology Development

Due to MBARI's marine operations resources (e.g., ROVs, AUVs, floats, wavegliders), access to these environments can be achieved. However, what are the tools that we need to simultaneously quantify marine organism behavior and function and physical processes in their natural environment? What platforms can be used or needed to enable long-term (or persistent) observations of marine organisms to quantify behavioral optimizations? How can we use these tools to inform how systems function, and extend these solutions to bio-inspired design? To address these questions, we will use an integrated design and engineering approach:

- *Bringing the laboratory into the ocean*: Developing platforms and tools to address marine organismal function in their natural environment. These platforms and tools include (1) 800139 EyeRIS - plenoptic imaging solution to measure 3D particle distributions and motion as well as reconstructing deformable biological surfaces and (2) the multi-camera lightfield array (proposed here) - large-scale temporally variable surface reconstructions. EyeRIS will be deployed from both ROV and AUV assets at the completion of the project, and the multi-camera lightfield array will first be deployed from MiniROV.
- *Advancing a persistent presence for observing population-scale behavior*: Developing nimble instruments and capability to sample organismal group behavior in response to environmental cues. These platforms and tools include: 901906 Multi-Spectral StealthCam - low-light camera system deployable from R/V Paragon that will have variable intensity and wavelength of illumination. Combined with acoustics (901700 Acoustical Ocean Ecology), we can deduce organismal behavior in response to light cues, and inform illumination design criteria for future imaging developments.
- *Advancing a persistent presence for observing individual-scale behavior*: Developing platforms and incorporating machine learning tracking algorithms to robustly acquire and track organismal targets for longer than 24 hours. These developments include: 902002 FathomNet - developing image training set for machine learning classification by mining MBARI's VARS database; supervised autonomy (captured here) to seek user input to verify long-term tracking operations; and automated acquisition and tracking of underwater targets using machine learning (701139 ML-Tracking). These efforts will be conducted in close collaboration with Dr. Steve Rock (600034 Precision Control). Additionally, designing a new class of tracking autonomous underwater vehicles (902105 TAUV) will significantly contribute to this theme.

Marine Operations/Field Programs

As part of this project, we are requesting one 7-day cruise on R/V Western Flyer, three 2-day cruises on the R/V Rachel Carson using ROV MiniROV and Mesobot, and two 5-day cruises on R/V Paragon with LRAUV (in the late Spring and late Fall). These coordinated LRAUV and Wave Glider requests will contribute to data collection using the EyeRIS instrument for our lab's incoming postdoctoral fellow Eric Orenstein. Ideally, the Carson days will be scheduled back-to-back with 600034 Precision Control, 708141 Minions, and 901220 Midwater Ecology project's ship time requests with the Paragon/LRAUV deployments in parallel. Research activities will commence during the Flyer cruise and one 2-day cruise on the Carson; development activities will commence on the remaining ship days. In addition to ROV Doc Ricketts, we will be requesting MiniROV dives on the Flyer and Carson (with Dale Graves) to conduct shallow dives and run machine-learning tracking and acquisition algorithms for long durations.

Data

What data products will be generated?

We will be generating image data from our cruises, tests, and lab work. These image data will be used to generate velocity fields, surface reconstructions, 3D models of particle fields, and moving biological surfaces.

How will the data products be managed?

Annotation of data products will be managed by the Video Lab, and hours for Video Lab technicians have been requested to cover this effort. Once annotations are made, the data are organized by date, named by measurement technique or platform, and graded depending on the measurement data quality. These annotations will be made available in a summary document that collaborators and Bioinspiration Lab members can reference for data synthesis and publications.

Describe data availability outside of the project team.

Data will be made available to members outside of the project team to collaborators (e.g., members of DOIG) and others by written request.

Describe data storage requirements.

We will be requesting 20 TB of storage space on Atlas for the Bioinspiration Lab.

Anticipated Impact

Who are the consumers of the instruments, methods, systems, and data that will be generated?

Consumers of data will include members of the Bioinspiration Lab, DOIG, and external collaborators by request. Instruments, methods, and systems will be used by the Bioinspiration Lab and external collaborators (e.g., WHOI, URI, Harvard, Stanford, Scripps, etc.).

Anticipated Outreach

What outreach assets might you need to better reach the audience/consumers you are targeting? Specify how you might like to reach your audience (published paper, seminar, conference, social media, etc.) and what type of assets (graphic, animation, video, etc.) you might need ITD to help generate.

We anticipate needing to create outreach assets, including video, animations, and graphics, to help disseminate our efforts to potential science users, industry partners, funding agencies, and the general public through popular press, media organizations, and social media.

Intellectual Property (IP) Considerations

Do you anticipate a need for a cooperative research and development agreement or licensing arrangement with an external entity?

Yes, we anticipate needing to set up cooperative research and development agreements with DOIG members as well as external partners CVision AI and Digital Life 3D.

Will novel IP be created, and how might it be disseminated (e.g., open-source, royalty-free license, commercial license agreement)?

We anticipate that novel IP will be created, and we are planning on making our efforts all open-source.

Will the work potentially result in a patentable product or service?

We don't anticipate that the work will result in a patentable product. However, all code developed as part of our effort will be made publicly available on our Bitbucket account.

For additional guidance please review MBARI's intellectual property internal web page: https://mww.mbari.org/itd/ip/.

b) Continuing Projects

If the proposed project includes multiple individual projects, please list each of these projects as a subheading in the proposal. For each subheading, please address the following:

Current status of project and results to date

	2020 Project Milestones	Milestone Progress
1.	Ecomechanics of marine invertebrates - midwater and benthic animals	*Larvacean-inspired internal cilia arrangements for novel flow generation.* Collaborators Drs. Janna Nawroth (Univ. of Hawaii) and Eva Kanso (Univ. Southern Calif.) are finalizing a manuscript that describes our findings during a series of research cruises in 2018. *Tomopterid swimming mechanics.* Along with collaborator Dr. Karen Osborn (Smithsonian), we are finalizing analysis of lab-swimming *Tomopterids* for a publication. *Siphonophore swimming mechanics.* We are collaborating with Drs. Jack Costello (Providence Coll.) and Sean Colin (RWU) to study siphonophore ecology using ML-Tracking. *Sponge and coral ecology.* Dr. Amanda Kahn is currently analyzing DeepPIV data with Joost Daniels to quantify feeding fluxes of sponges at MBNMS site Sur Ridge.
2.	DeepPIV flow measurements in physical flows (e.g., cold seeps)	*Flows emanating from cold seeps.* Due to COVID-19, these activities have been postponed until 2021 pending the proposal process.
3.	DeepPIV support tasks	*In progress*. DeepPIV v4.0 is nearing completion after fiber cable setbacks in 2019. Acquisition of spare parts and refinement of instrument documentation are on schedule for completion at the end of 2020.
4.	Productionize DeepPIV and Mesobot pipelines	*In progress.* Mesobot-related tasks will be conducted in Fall of 2020. DeepPIV footage is now recorded directly by VARS when on MBARI ships, and is transported and archived to M3RS along with the main science camera video. Pre-2019 data is being ported over to the same system, and this process is ongoing. Camera and laser metadata is now being logged, and we are developing a pipeline to include this with existing dive data in the fall of 2020.
5.	Smart algorithms	*In progress.* Collaborating with CVision AI, we have trained, integrated, and deployed various versions of ML algorithms with vehicle control algorithms on MiniROV in the test tank and at sea. We have demonstrated more robust tracking with ML integration, and hope to demonstrate robust automated target acquisition by 2021.
6.	Publications and conference presentations of methods and collaborative efforts	*In progress.* In 2020, two papers have been submitted (NeurIPS/ArXiV and *Science Robotics*), one paper has been published in *Nature* (DeepPIV 3D reconstructions), five manuscripts in progress (Mesobot, ciliary geometries, tomopteris biomechanics, EyeRIS development, and 3DR larvacean house build), and 19 conference presentations. See list of project activities below for more details.

What percentage of labor and budget have been used through the 1st half of year?

We have used 40% of our labor and 47% of our expense budget in the 1st half of the year.

Will you complete the current year's scheduled work?

Due to COVID-19 several deployments have been postponed until next year. We should have time to test DeepPIV v4 at sea during the upcoming Flyer cruise. Continuing work on productionizing DeepPIV and Mesobot pipelines, as well as smart algorithms, are on track.

If you are at less than 50% resource usage, what is the plan to complete, or what work won't be done this year?

We will be on target for our resource usage for the rest of the year.

Significant changes from previous project proposal

We did not experience many significant changes to our project proposal beyond delays due to COVID-19. Despite the pandemic, most of our proposed efforts will be completed by 2021.

Over the past two years, what peer-reviewed publications, education and/or outreach activities have resulted directly from this project? Please be brief.

Publications (underline - mentee, bold - Bioinspiration Lab member):

Boulais O, Woodward B, Lundsten L, **Barnard K**, Schlining B, Bell KC, **Katija K** (2020). *FathomNet*: An underwater image training database for ocean exploration and discovery. Submitted to *Neural Information Processing Systems*.

Masmitja I, Navarro J, Gomariz S, Aguzzi J, Kieft B, O'Reilly T, **Katija K**, Bouvet PJ, **Fannjiang C**, Vigo M, Puig P, Alcocer A, Vallicrosa G, Palomeras N, Carreras M, Del-Rio J, Company JB (2020). Mobile robotic platforms for the acoustic tracking of deep-sea demersal fishery resources. Submitted to *Science Robotics.*

Katija K, Troni G, **Daniels J**, Lance K, Sherlock RE, Sherman AD, Robison BH (2020). "Revealing enigmatic mucus structures in the deep sea using DeepPIV." *Nature* 583 78-82.

Gonzalez BC, Martínez A, Olesen J, Truskey SB, Ballou L, Allentoft-Larsen M, **Daniels J**, Heinerth P, Parrish M, Manco N, Ward J, Iliffe TM, Osborn KJ, Worsaae K (2020). "Anchialine biodiversity in the Turks and Caicos Islands: New discoveries and current faunal composition." *Intl. J. of Speleology, 49: 71-86*.

Fannjiang C, Mooney TA, Shorter KA, Mann D, **Katija K** (2019). "Augmenting biologging with supervised machine learning to study in situ behavior of the medusa *Chrysaora fuscescens*." *J. Exp. Biol. 222.*

Flaspohler G, Mooney TA, **Katija K**, Fontes J, Afonso P, Shorter KA (2019). "Quantifying the swimming gaits of veined squid (*Loligo forbesii*) using bio-logging tags. *J. Exp. Biol*., 222: jeb198226.

Choy CA, Robison BH, Gagne TO, Erwin B, Firl E, Halden RU, Hamilton JA, **Katija K**, Lisin SE, Rolsky C, Van Houtan KS (2019). The vertical distribution and biological transport of marine microplastics across the epipelagic and mesopelagic water column. *Nature Sci. Rep*, 9:7843.

Conferences (* - invited talk, underline - mentee, bold - Bioinspiration Lab member):

ASLO Ocean Sciences Meeting, February 16-21, San Diego, CA.

- **Daniels J**, Kahn AS, Lord J, **Katija K**, Barry JP (2020). "Characterizing animal-fluid interactions in the deep sea benthos using combined *DeepPIV* and respiration measurements."
- Yoerger D, Curran M, Fujii J, Gomez-Ibanez D, Govindarajan A, Howland J, Llopiz J, Wiebe PH, Hobson B, **Katija K**, Risi M, Robison BH, Rock S, Brier JA, Wilkinson CJ (2020). "At-sea testing of the *Mesobot* midwater robot."
- **Roberts P**, Erickson J, **Klimov D**, Henthorn R, **Sherman AD**, Ruhl H, **Katija K** (2020). "In situ, three-dimensional imaging of centimeter-scale biophysical interactions and particle distributions with the deep-sea plenoptic camera *EyeRIS*."
- Cones S, **Katija K**, Shorter KA, Jensen F, Mann D, Afonso P, Fontes J, Wang AZ, Mooney TA (2020). "Diel vertical migrations and climb-and-glide ascents in veined squid (*Loligo forbesi*)."
- Litvin SY, Barry JP, Lovera C, Boch CA, Burton EJ, DeVogelaere AP, Graves D, Guilderson TP, Kahn AS, **Katija K**, Kecy CD, King C, Kuhnz L, McGill P, **Sherman AD** (2020). "The Deep-Sea Coral Observatory (DiSCO) project."
- Sugar JT, Omand M, Adams A, **Katija K**, Wang AZ, Buesseler K, Yoerger D, Cetinic I, Rossby HT (2020). "MINIONS: Small, cheap, Lagrangian floats for measurement of the biological carbon pump."
- **Sherman A**, **Katija K**, Risi M, Rock S, **Roberts P**, Graves D (2020). "The *MiniROV*: A multidisciplinary research and development tool for deep-sea exploration."
- **Katija K**, Woodward B, Schlining B, Lundsten L, **Barnard K**, Bell KLC (2020). "Towards an open, underwater image repository (*FathomNet*) for automated detection and classification of midwater and benthic targets using machine learning."

Society of Integrative and Comparative Biology Annual Meeting, January 3-7, Austin, TX.

- **Daniels J**, Osborn K, Aoki N, Havassy J, Mushegian N, **Katija K** (2020). "A midwater polychaete on the move: Swimming of *Tomopteris*."
- Hoover AP, **Katija K** (2020). "Manse and Tail: Flow structures and morphological constraints of the filtration feeding mechanisms by giant larvaceans."
- **Katija K**, Govindarajan A, Llopiz J, Wiebe P, Breier J, Hobson B, Risi M, Robison B, Rock S, Yoerger D (2020). "Mesobot: Toward autonomous observations of organismal behavior in the ocean's midwaters."
- Li D, **Katija K**, Gilly WF (2020). "Hydrodynamic constraints on jet propulsion in squid paralarvae at intermediate Reynolds numbers."

Daniels J, Osborn K, Aoki N, Havassy J, Mushegian N, **Katija K** (2019). "Swimming of the midwater polychaete *Tomopteris*." *13th International Polychaete Conference*, August 8, 2019, Long Beach, CA.

3rd Marine Imaging Workshop, June 24-28, Victoria BC, Canada.

- **Daniels J**, **Sherman AD**, Graves D, Kecy CD, **Klimov D**, Erickson E, Robison BH, **Katija K** (2019). "In situ 2D flow measurements and scanned 3D reconstructions in midwater and benthic environments using *DeepPIV*."
- **Katija K**, Woodward B, Schlining B, Lundsten L, **Barnard K**, Bell KLC (2019). "*FathomNet*: An open, underwater image repository for automated detection and classification of midwater and benthic targets using machine learning."
- **Roberts PLD**, **Katija K**, **Sherman AD**, Erickson J, Ruhl HE (2019). "A three-dimensional, high-resolution, in situ particle and flow imaging instrument (*EyeRIS*)."

Litvin SY, Barry J, Lovera C, Boch CA, Burton EJ, DeVogelaere AP, Graves D, Guilderson TP, Kahn AS, **Katija K**, Kecy C, King C, Kuhnz LA, McGill P, **Sherman AD** (2019). "The Deep-Sea Coral Observatory (DiSCO) Project." *7th International Symposium on Deep-Sea Corals*, July 29-August 2, Cartagena, Colombia.

IEEE/MTS OCEANS Meeting, June 17-20, Marseille, France.

- Masmitja I, Gomariz S, Del Rio J, Kieft B, O'Reilly TO, Aguzzi J, Bouvet PJ, **Fannjiang C**, **Katija K** (2019). "Area-only method for underwater object tracking using autonomous surface vehicles."
- D Yoerger, Curran M, Fujii J, German CR, Gomez-Ibanez D, Govindarajan AF, Howland JC, Llopiz JK, Wiebe PH, Hobson BW, **Katija K**, Risi M, Robison BH, Wilkinson CJ, Breier JA (2019). "*Mesobot*: An

autonomous underwater vehicle for tracking and sampling midwater targets."

Omand M, Sugar J, Buesseler K, Durkin C, Estapa M, Cetinic I, D'Asaro E, Lee C, Rossby HT, Wang A, Adams A, **Katija K**, Michel A, Yoerger D, Felderman E (2019). "Upcoming EXPORTS technology: Trap cameras, Snocam, and Minions." *NASA EXPORTS Science Meeting*, May 6-8, Williamsburg, VA.

Society of Integrative and Comparative Biology Annual Meeting, January 3-7, Tampa, FL.

- Kahn AS, Lord JP, **Katija K**, Barry JP (2019). "Respiration and water processing by glass sponges in Sur Ridge, a dense, deep-water coral and sponge habitat."
- **Fannjiang C**, **Katija K** (2019). "Using machine learning to deduce fine-scale behavior of jellyfish (*Chrysaora fuscescens*) in Monterey Bay."
- **Katija K**, Aoki N, Harned A, Mushegian N, **Daniels J**, Osborn K (2019). "Locomotion in tomopterids: How do these gelatinous holopelagic worms swim?"

15th Deep Sea Biology Symposium, September 13, Monterey, CA.

- **Katija K**, **Sherman A**, Sherlock R, Robison B (2018). "New technology reveals the structure and function of deep-sea, giant larvacean mucus houses."
- Robison B, Reisenbichler K, Sherlock R, Choy A, **Katija K**, Osborn K, Hoving HJ (2018). "Are giant larvaceans a missing link in deep-sea food webs?"
- Havassy J, **Katija K**, Aoki N, Harned A, Mushigian N, Murthy S, Osborn K (2018). "The kinematics of Tomopteris swimming: differences between power and recovery strokes."
- Aoki N, **Katija K**, Harned A, Havassy J, Mushigian N, Murthy S, Osborn K (2018). "A biomechanical description of tomopterid polychaetes using high-speed video analysis."
- **Katija K**, Govindarajan A, Llopiz J, Wiebe P, Risi M, Hobson B, Breier J, Robison BH, Rock S, Yoerger D (2018). "Mesobot: A new autonomous underwater vehicle for tracking and sampling animals and particles in midwater."

Presentations:

"Designed by Nature." *National Geographic Live!* January-April, 2019.

- Mesa Arts Center, February 19-20, 2020, Mesa, AZ.
- Hammer Theatre Center, February 12-13, 2020, San Jose, CA.
- Benaroya Hall, February 9-11, 2020, Seattle, WA.
- Overture Center for the Arts, January 14, 2020, Madison, WI.

"Technological challenges and potential solutions for exploring the ocean's midwaters."

- *Aeronautics and Astronautics Chair's Distinguished Seminar Series,* University of Washington, February 10, 2020. Seattle, WA.
- *National Science Foundation*, June 13, 2019. Alexandria, VA.

"New laser-imaging technology (DeepPIV) informs ecomechanics of deep sea, giant larvaceans."

- *Biology Department Seminar Series, Western Washington University, February 7, 2020. Bellingham, WA.*
- *Moss Landing Marine Laboratories*, April 9, 2019. Moss Landing, CA.
- *Biomechanics seminar in Ecology and Evolutionary Biology, University of California, Irvine*, April 5, 2019. Irvine, CA.
- *Biomechanics seminar in Ecology and Evolutionary Biology, University of California, Los Angeles*, April 3, 2019. Los Angeles, CA.
- *Ecology seminar in Biological Oceanography, Scripps Institution of Oceanography, University of California, San Diego*, April 25, 2018. La Jolla, CA.

"Bioinspiration Lab: Developing solutions to access the ocean's midwaters." Virtual Workshop: Emerging Technologies for the Blue Economy, Inter-American Development Bank. December 4, 2019.

"Exploring Earth's final frontier, the Ocean Twilight Zone." Friends of Hopkins Seminar Series, November 12, 2019. Pacific Grove, CA.

"Finding inspiration in the Ocean Twilight Zone." Festival of Curiosity, July 20, 2019. Dublin, Ireland.

"Finding inspiration in a deep, dark world." *TEDx, Catalina High School,* April 30th, 2019. Monterey, CA.

"From outer to inner space: How exploration leads to inspiration." *Explorers Festival, National Geographic Society*, June 14th, 2018. Washington, DC.

"Machine learning in oceanography: How algorithms and recent developments in underwater imaging will change the way we explore the ocean." *Computer Science Departmental Seminar, University of California, Santa Cruz*, May 3rd, 2018. Santa Cruz, CA.

"New laser-imaging technology elucidates form, function, and ecological impact of deep sea, giant larvacean mucus houses."

- *Ocean, Earth, and Atmospheric Sciences Seminar, Old Dominion University*, April 12th, 2018. Norfolk, VA.
- *Fluid Dynamics Seminar, Brown University*, April 10th, 2018. Providence, RI.
- *Programs in Atmospheres, Oceans, and Climate Colloquium, Massachusetts Institute of Technology*, April 9th, 2018. Cambridge, MA.

"New technology reveals mysterious inhabitants of the deep sea." *Ocean Luminaries: Making Waves, American Museum of Natural History*, March 2nd, 2018. New York, NY.

"New laser technology illuminates deep sea animals in novel ways." *Here Be Dragons, MIT Media Lab*, February 26th, 2018. Cambridge, MA.

"From outer to inner space: How exploration leads to inspiration." *Stanford Women's Perspectives Seminar, Stanford University*, January 25th, 2018. Palo Alto, CA.

Education:

Undergraduate Research Mentoring	
Jill Alexander, Mechanical Engineering, Boise State University	2020
Brooke Pauken, Mechanical Engineering, Univ. of Calif., San Diego	2020
Aaron Ray, Computer Engineering, Brown University	2019
Kevin Barnard, Computer Science, Colorado School of Mines	2018-2019
Richard Rodriguez, Electrical Engineering, Univ. of Calif., Santa Barbara	2018
Karla Haiat Sasson, Mechanical Engineering, University of Rhode Island	2018
Graduate Research Mentoring	
Clara Fannjiang, Computer Science, Univ. of Calif., Berkeley	2018-present
Diana Li, Biology, Stanford University	2015-2019
Guest Lecturer	
Biologging, Hopkins Marine Station, Stanford University	Professor: J Goldbogen
TED Talks for Marine Conservation, Calif. State Univ. Monterey Bay	Professor: KJ Nickols
Biol. and Phys. Oceanography, Calif. State Univ. Monterey Bay	Professor: KJ Nickols
Explorer Host	
National Geographic's GeoChallenge: *Tackling Plastics!*	2018-2019
Workshop Convener/Organizer	
Big Ocean, Big Data (FathomNet), MBARI	2018

To date has any novel intellectual property been developed and/or disseminated?

As part of the activities in the Lab, we have developed DeepPIV (4 iterations), EyeRIS (1 built, 1 designed), lab-based 3D reconstructions, the FathomNet database, ML-tracking algorithms, and a number of other assets. We have disseminated most of our developments through either publications, conference proceedings, invited seminars and talks, as well as social media.

All Projects: Specific Plans for 2021

Research Activities (* - Deep Ocean Inspiration Group collaboration)

i. Ecomechanics of marine invertebrates
- Microscale flow linkages with cilia arrangement with Drs. Janna Nawroth (imaging; UH) and Eva Kanso (modeling; USC)*
- Tomopterid and scale worm swimming mechanics with Dr. Karen Osborn (ecology; Smithsonian Inst.), Alex Hoover (modeling; Univ. Toledo), Daisuke Takagi (modeling; Univ. Hawaii), Michael Tolley (robotics; UCSD), Nicholas Battista (modeling; Coll. New Jersey), and Katrine Worsae (biology, Univ. Copenhagen)*
- Swimming mechanics of gelata including siphonophores and ctenophores with Drs. Jack Costello (Providence), Sean Colin (RWU), Vivek Prakash (Univ. Miami), and Brad Gemmell (Univ. South Florida)*

ii. Use cases for DeepPIV
- Midwater organism ecomechanics with Robison and DOIG using DeepPIV and dye injector (in situ), benchtop 3DR, and focal following setup (in the laboratory)*
- Filtration feeding impacts of glass sponges and coral polyp feeding on Sur Ridge with Drs. Jim Barry, Steven Litvin, and Amanda Kahn (MLML)
- Benchtop 3DR measurements and in situ 3DR using DeepPIV with Drs. Rob Wood (Harvard Univ.) and Brennan Phillips (URI) on SOI's R/V *Falkor* (800145 Deep Sea 3D)
- Collaborate with Drs. Charlie Paull and David Caress (901101 Ocean Imaging and 901023 Continental Margins) to combine LIDAR, photogrammetry, and DeepPIV measurements of benthic fluid fluxes.

iii. Use cases for EyeRIS
- Collaborate with Francisco Chavez, et al. as part of the 901009 CANON project. EyeRIS would be integrated into the LRAUV nose cone and would conduct midwater transects to document particle and animal distributions.
- Deployments using a modified LRAUV-based EyeRIS on Doc Ricketts at Station M with Ken Smith and Henry Ruhl.
- Quantify classification performance improvements using multiview and/or superresolution from camera array images using the LRAUV-based EyeRIS instrument. This and the previous effort will be the focus of our incoming postdoctoral fellow, Eric Orenstein.
- Quantifying background turbulence rates with Peter Franks (Scripps).*
- Quantifying predator-prey interactions with Brad Gemmell (USF) using the ROV-based EyeRIS instrument.*

iv. Use cases for ML-Tracking (using MiniROV) or Mesobot (pending availability)
- Collaborate with Drs. Bruce Robison and Kelly Benoit-Bird (901220 Midwater Ecology, 901700 Acoustical Ocean Ecology) to autonomously track a midwater target (e.g., giant larvacean, siphonophores) for 24 hrs. The Mesobot is equipped with a Benthos modem that can be tracked from the surface by a WaveGlider (reporting the approximate GPS position of the vehicle) and subsea by LRAUVs equipped with different payloads (e.g., imaging/EyeRIS, acoustics, etc.). Given the depth limitations

of the LRAUV, we will target animals shallower than 300 m, however a deeper-rated LRAUV (see pending proposal 902010 Deep LRAUV) would contribute significantly to this experiment. As part of this 2021 experiment, we hope to document the vertical migration behavior of an individual midwater animal (with replicates), and we have requested time on the Carson (to deploy and recover the Mesobot) and Paragon (to deploy and recover the WaveGlider and LRAUVs).

- Conduct multi-hour observations of midwater gelata feeding and swimming behaviors.*

Engineering/technology development

i. Productionize MiniROV/ML-tracking data pipelines
   - integrate ML-tracking LCM data with STOQS (with M. McCann)
   - automate ML-tracking LCM images and video registration within VARS (with B. Schlining)

ii. Productionize DeepPIV and EyeRIS data pipelines
   - contracting with Digital Life 3D to process 3D data products from DeepPIV scans and EyeRIS imagery

iii. Instrumentation service and upgrades (with A. Sherman, D. Klimov, J. Erickson, J. Daniels)
   - general maintenance and service of DeepPIV and EyeRIS

iv. Multi-camera array
   - design and build multi-camera array to be deployed in parallel with EyeRIS for higher baseline (e.g., larger target) visualizations from an ROV

v. Smart algorithms
   - ML integration on embedded system (with B. Raanan)
   - Automating acquisition and tracking missions with ML (with M. Risi and S. Rock)
   - Testing of algorithms in Test Tank and on Carson using MiniROV (with D. Graves, F. Flores, M. Risi)
   - Implementation and testing of supervised autonomy (with B. Raanan) between MiniROV and WaveGlider

vi. Lab-based imaging setups
   - Maintenance of existing lab setups for shore- and ship-based studies
   - Upgrades of lab imaging setups, e.g. vertical and high-magnification telecentric imaging, multi-spectral diagnostics, improved animal containment and handling equipment

Further engineering/technology development activities of members in the Bioinspiration Lab are captured in externally and internally funded projects 701139 ML Tracking, 902002 FathomNet, 708141 Minions, 800139 EyeRIS, 901911 ROVVR, 902105 TAUV, and 902000 Multi-Spectral StealthCam.

Will novel intellectual property be developed and/or disseminated?
Dissemination includes patenting, licensing, and collaboration agreements.

Yes, we anticipate that novel intellectual property will be developed and disseminated through open source channels, collaborator's agreements, and conferences and publications.

Field programs (detail ship requirements/deployments/diver requirements)
In addition to describing anticipated field programs, please be sure to include requirements for specific platforms and equipment (Dorado AUVs, LRAUVs, Wave Glider, mini ROV, etc.) for each proposed field program so that expectations are clear. Requests must also be entered in the budget entry system.

# of Days	Ship	Vehicle needs	Requested dates	Deployment objectives
2	R/V Rachel Carson	ROV MiniROV	March	Use MiniROV to test ML-integrated tracking and acquisition algorithms, EyeRIS tests, collect animals
2	R/V Rachel Carson	MiniROV + Mesobot	Late May/Early June	Deploy and recover Mesobot over multi-day cruise; pending performance, use MiniROV to collect animals and test ML-integrated tracking and acquisition algorithms.
5	R/V Paragon	LRAUV + WaveGlider	Late May/Early June	Deploy LRAUVs and WaveGlider to track Mesobot; deploy EyeRIS-integrated LRAUV as part of this or CANON effort
7	R/V Western Flyer	ROV Doc Ricketts + MiniROV	Late August	Utilize DeepPIV/EyeRIS hardware, JellyTrack algorithms, ROVVR, and other experiments with DOIG collaborators.
5	R/V Paragon	LRAUV + WaveGlider	October/November	Deploy LRAUVs and WaveGlider to track Mesobot; deploy EyeRIS-LRAUV as part of this or CANON effort
2	R/V Rachel Carson	ROV Ventana	October/November	Deploy and recover Mesobot over multi-day cruise; pending performance, use MiniROV to collect animals and test ML-integrated tracking and acquisition algorithms

For all sea days on the Western Flyer and Rachel Carson, we will need telepresence to enable participation for Lab members and external collaborators.

Isotope Usage
Project teams must provide details regarding any planned isotope use on shore, on ships, in the Sanctuary, etc. Please review the guidance on isotope usage at http://www.mbari.org/at-sea/cruise-planning/hazardous-materials/ and policy at

http://mww.mbari.org/safety/SafetyManual/Isotope_Use_Policy.pdf, and then provide details on plans below.

Not applicable.

Safety Disposal Needs
So the Safety office can plan and budget accordingly, please respond to the questions below regarding any anticipated safety disposal needs for the coming year. Budget for cost of such removal will be captured by the safety office based on responses received.

Will this project generate more than 1 gallon (4 liters) of battery waste per year?

No.

If yes, please indicate the type of batteries (alkaline, NiCad, NiMH, lithium ion or lithium metal) and the approximate amount of each to be generated.

Not applicable.

Will this project generate more than 15 gallons (60 liters) of hazardous liquid waste per year?

No.

If yes, please indicate the composition of the waste(s) and the quantity of each to be generated.

Not applicable.

Specific deliverables

Milestone 1: Productionize ML-Tracking pipelines
Milestone 2: Instrumentation service and upgrades, multi-camera array built
Milestone 3: Smart Algorithms: ML-tracking and automated acquisition, supervised autonomy algorithms
Milestone 4: Instrument and vehicle deployments (e.g., DeepPIV, EyeRIS, ML-Tracking/MiniROV, and Mesobot) and data analysis
Milestone 5: Dissemination of research through publications, presentations, and outreach.

Milestones and required personnel (see personnel classification list for staff classifications)

The milestones below correspond to the specific deliverables above.

2021 Project Start Date: MM/DD/2020	**Milestone 1**	**Milestone 2**	**Milestone 3**	**Milestone 4**	**Milestone 5**	**Total Resources[4] (in hours)** for each resource category for all milestones listed here
Milestone Date	May 2020	September 2020	December 2020	December 2020	December 2020	
Milestone Description	See above deliverables list for a description					
Electrical Engineer		400	200			600
Software Eng-Embedded			535			535
Software Eng-Info Eng	280					280
Mechanical Engineer		200				200
Mechanical Eng-Division						
Mechanical Eng-Mfg			160	140		300
Associate Engineer						
Electrical Tech		220				220
Mechanical Tech		120	160	140		420
Machinist		60				60
Divers						
Science Comm & Video Lab					350	350
DMO Marine Ops Tech		60				60

Budget justification

4 This number should be the same number you entered on the resource requests for this particular resource.

2021 budget below:

DeepPIV (v.3 and v. 4) Service and Upgrades		**General Lab Items**	
laser optics	$ 2,000	camera optics	$ 1,400
fiber cable	$ 1,200	imaging containers	$ 3,000
electronics components	$ 5,500	small portable lasers	$ 7,500
external recorder	$ 1,700	particles	$ 500
bulkhead replacements / caps	$ 4,000	laser safety items	$ 1,200
service / maintenance	$ 5,000	advanced laptop for shipboard computing	$ 5,000
Smart Algorithms		laser optics	$ 1,500
embedded hardware	$ 850	illumination	$ 1,000
ML compute hardware	$ 8,000	imaging diagnostics tools	$ 2,200
Instrument and Vehicle Deployments		external hard drives	$ 500
Travel cases	$ 2,000	supplies	$ 2,500
Multi-camera system development		SICB conference (2)	$ 4,500
Cameras	$ 8,000	**Telepresence (7 days WF)**	$ 5,903
Housings	$ 20,000	**External contracts**	
Subsea cables & connectors	$ 2,000	Science illustrations	$ 5,000
Other mechanical	$ 1,000	Digital Life 3D	$ 15,000
Outsourced computing & consulting	$ 15,000	**TOTAL**	**$ 132,953**

Project team

Principal Investigator: Kakani Katija (2080 hrs); Research Technician: Joost Daniels (2080 hrs); Electrical engineers: Alana Sherman (300 hrs), Denis Klimov (300 hrs); Mechanical engineers: Dale Graves (300 hrs), Jon Erickson (200 hrs); Software engineers: Ben Raanan (375 hrs), Mike McCann (120 hrs), Brian Schlining (160 hrs), Mike Risi (160 hrs); EE Technicians: Jose Rosal (100 hrs), other EE Tech (120 hrs); ME Technicians: Frank Flores (300 hrs), other ME Tech (120 hrs); Machine shop: (60 hrs); DMO Marine Ops Technician: Mike Conway (60 hrs); Video Lab: Lonny Lundsten (100 hrs), Kyra Schlining (100 hrs), Susan von Thun (150 hrs).

Project lab and office space requirements
In addition to any changes to current space usage, please also include anticipated office and lab needs for students, postdocs, collaborators, etc.

We do not anticipate needing any additional lab and office space for this project.

R/V *Paragon* Requests
If the project team will be requesting time for the R/V Paragon, please specify the operators in the group and provide estimates of their availability to operate the vessel. DMO staff have extremely limited availability to be operators and only with advanced budgeting and planning.

We will be requesting the Paragon to launch and recover LRAUVs with LRAUV operators.

Risk matrix (development and infrastructure projects only)

	Technical Risk	Organizational Risk	Tech Transfer Risk	Labor Estimate Risk
High				
Medium	x			x
Low		x	x	

c) Compliance Considerations

Export Regulation
Does the project team anticipate any foreign collaborations or international travel? If so, please identify collaborators by name, institution, and country.

We do not anticipate any international travel or foreign collaborations.

Does the project team plan or anticipate export-controlled purchases, shipments, or transfers of items (e.g., research instruments, proprietary data, hand-carried tools or samples) outside the U.S. temporarily or permanently? If yes, please identify country or countries and indicate whether these items will remain under MBARI control while abroad or controlled by others. Will the items be exported to more than one country? Please include foreign collaborator information as described above.

We do not anticipate having export-controlled purchases, shipments, or transfers of items outside the U.S. in 2020.

Monterey Bay National Marine Sanctuary (MBNMS)

General Permit
Projects teams need to indicate if any work will be performed that is either: (1) currently authorized under our general permit; or (2) will require that we obtain authorization. The current permit can be viewed at https://mww.mbari.org/pco/permits/mbnms-2020-006_exp28feb2025.pdf. Please see Mandy Allen for questions.

Is a permit with MBNMS required for your work?

Yes, our research activities are currently covered under MBARI's existing permit.

SESAs (General map)
Projects will need to indicate whether or not work will be conducted within one of the Monterey Bay National Marine Sanctuary's Ecologically Significant Areas (SESAs). If your work will be conducted in one of these areas, please indicate which area by number or name.

We have plans to conduct measurements using DeepPIV in the Monterey Bay National Marine Sanctuary SESA, specifically on Sur Ridge (SESA site 11), in collaboration with Jim Barry in 2021 based on our previous research efforts. We hope to further address small-scale biological-fluid interactions, including (1) how coral polyps are able to select and attain food particles in high-current deep-sea ridge environments and (2) the magnitude of filtration rates achieved by benthic filter feeders.

Anchors
For activities conducted under MBARI's permit for the Monterey Bay National Marine Sanctuary, Paragraph 16, we are required to recover anchors weighing less than 500 pounds. Project proposals, which involve anchors weighing less than 500 pounds, shall specifically indicate cruise time allocated to anchor recovery. Lack of cruise time is not an acceptable reason for deeming an anchor less than 500 pounds "unrecoverable" under Paragraph 17 of MBNMS permit. Also under Paragraph 17, ***ALL*** *anchors not recovered during the year must be reported detailing location, description of anchor, and reason not recovered. (Mandy Allen will collect this information from project teams to submit as part of the annual report to the Sanctuary.) Each ship will be tracking anchors deployed, duration of attempted anchor recovery, and anchors abandoned on the seafloor with the intent that they be recovered in the future as per MBNMS permit requirements.*

Will you be deploying equipment that will require anchoring? If so, please indicate approximate weight of anchors to be used and recovery plans.

No.

California Department of Fish & Wildlife
A Scientific Collecting Permit will be required for biological and geological sample collections offshore California (even in Federal waters and beyond), and for many activities in State Marine Protected Areas (MPAs). Please see Mandy Allen for questions.

Will you be collecting samples that require a permit?

Yes.

Will you be working in a State Marine Protected Area?(See link above for Statewide MPAs or this link for Central California MPAs.)

No.

United States Coast Guard
If your project will deploy or maintain moorings, the project team must ensure proper compliance and notification of these activities to the US Coast Guard. DMO does not automatically do these notifications on behalf of projects. Two common types of permits and notifications that may apply to your project are Private Aid to Navigation (PATON) authorizations (required for buoys deployed for six (6) months or longer) and Notice to Mariners, which must be submitted for temporary PATONs (less than 6-month deployments). Other science operations may submit a request for a Local Notice to Mariners and are useful for missions or deployments with risk of 3rd Party Liability such as the Wave Glider.

Will your project require a PATON?

No.

If yes, have you obtained a PATON? (Please provide a copy to Mandy Allen.)

Not applicable.

Will your project require submission of a Local Notice to Mariners?

No.

If yes, please indicate who will be submitting request and provide a copy of the submission to Mandy Allen.

Not applicable.

Authorizations/Permits from other Agencies or Organizations
Is the project team aware of any other permits or authorizations that will be necessary to perform the proposed work? If so, please list below along with status of authorizations (obtained, pending, need to apply, etc.). Please see Mandy Allen if you have questions.

We are not aware of any other permits or authorizations needed to perform our proposed work.

Active Acoustics
We are keeping an inventory of acoustic instrumentation. The current list is posted here: https://mww.mbari.org/resources/2021_Proposal_Process/mbari_acoustic_instruments_updated_may_13_2020_ver_13.xlsx. If you have or plan to use equipment that is not already on this list, please be sure to include that information here.

Not applicable.