Velella Sensor

Final Performance Report

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The Johns Hopkins University Applied Physics Laboratory
11100 Johns Hopkins Road, Laurel, MD 20723-6099

To: Dr. Reginald Beach
Office of Naval Research

From: Dr. Morgan Trexler, Program Manager
Dr. Leslie Hamilton, Project Manager, Assistant Program Manager
Science of Extreme and Multifunctional Materials

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6. AUTHOR(S)
Hamilton, Leslie H., Dr.

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14. ABSTRACT
The goal of this project was to develop a novel, low-cost velella-inspired sensing platform. With a unique form factor, soft materials, and low-cost electronics, this sensing platform has been designed to float on the surface of the ocean, collect pertinent environmental information (temperature, position and salinity), and relay data over satellite for analysis. To achieve this vision, we executed against four major objectives (1) Design and synthesis of a biodegradable, bio-benign encapsulation material; (2) Novel sensor development, (3) System level design, and (4) System Deployment.

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PREVIOUS EDITION IS OBSOLETE.

I. Project Overview

The goal of this project was to develop a novel, low-cost velella-inspired sensing platform. With a unique form factor, soft materials, and low-cost electronics, this sensing platform has been designed to float on the surface of the ocean, collect pertinent environmental information (temperature, position and salinity), and relay data over satellite for analysis. In this project, we have executed against four primary objectives:

- *Objective (1) Design and synthesis of a biodegradable, bio-benign encapsulation material.* We developed and characterized a novel biodegradable elastomeric encapsulation material. Combined with novel coatings, the material is designed to resist biofouling and degrade over appropriate timespans into benign byproducts.
- *Objective (2): Novel sensor development.* We developed and characterized a novel salinity sensor that leverages the electrical properties of submerged soft materials. We worked with an external vendor, Innovative Sensor Technology (IST), to procure, characterize, and integrate state-of-the-art miniaturized salinity sensors.
- *Objective (3): System level design.* Inspired by the velella shape, we designed a form factor with robust buoyancy and a protruding sail to promote movement with the wind to house controlling and communication electronics, capable of long-term deployment and remote data retrieval.
- *Objective (4): Deployment demonstration.* We deployed versions of the sensor in the Atlantic and Pacific Oceans.

The multidisciplinary team, consisting of materials scientists, electrical engineers and oceanographers at Johns Hopkins Applied Physics Laboratory (APL), BlackSky Aerospace LLC, and The Naval Postgraduate School (NPS), was inspired by the velella because of its sail. The majority of observational buoys sit beneath the surface and their movements are dictated by the slow, near-surface ocean currents. By mimicking the velella's shape, we have a naturally-propelled sailing buoy that can travel faster and farther across the ocean because it utilizes forces from surface winds. In the current effort, the team focused on designing, fabricating and testing the initial prototypes. In future phases, we could expand the effort to deploy a collection of velella sensors that resemble their natural school structure and are capable of providing large sets of critical oceanic data (Figure 1).

Figure 1: Project vision: a school of velella sensors collecting and communicating critical oceanic data

II. Technical Accomplishments

The goal of this project was to develop a novel, low-cost velella-inspired sensing platform with a unique form factor, novel materials and sensors, and low-cost electronics. To achieve this vision, we executed against four major objectives *(1) Design and synthesis of a biodegradable, bio-benign encapsulation material; (2) Novel sensor development, (3) System level design, and (4) System Deployment.* These objectives are discussed below.

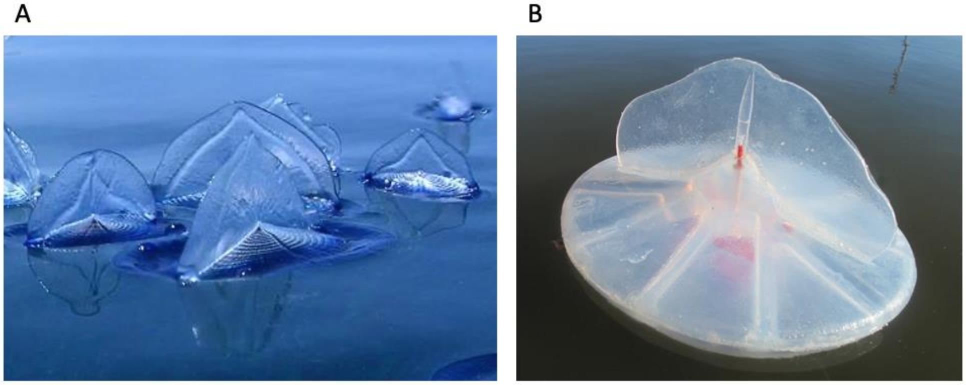

Figure 2: (A) A group of velellas float on the surface of the ocean and (B) An early velella prototype floating in a pond on JHU/APL's campus.

A. Objective 1: Design and synthesis of biodegradable, bio-benign encapsulation material

Summary: The team investigated multiple strategies for soft, biodegradable encapsulation materials, including hydrogels and elastomers. Ultimately, we found the degradable elastomer to be the most promising as an encapsulating material. We performed initial scale-up of this material.

Background: The encapsulation of electronic devices for ocean-sensing applications is challenging due to the strict requirements for material properties. For our intended application, an appropriate encapsulation system must 1) prevent water from coming into contact with electrically active materials, 2) be robust enough to maintain structural integrity against ocean currents, waves, and solar irradiation, 3) be pliable to impart toughness and mimic oceanic organisms, 4) have an innocuous or clear color, and 5) degrade after an appropriate amount of time. We investigated multiple materials systems with these overarching requirements in mind.

Degradable Hydrogel Development and Characterization

In initial efforts, the team explored development of hydrogels with tailorable degradation rates and mechanical properties. First, the team built poly(β-thioester) polymers synthesized by a one-pot, two-step method. By using only two monomers, poly(ethylene glycol) diacrylate (PEGDA) and 2,2’-(ethylenedioxy)diethanethiol (EDDT), we created oligomer chains of varying length and end group functionality by controlling the monomer ratio, see Figure 3. The functionality of the oligomer end group is determined by the monomer in excess. After oligomerization, acrylate-capped oligomers were crosslinked by acrylate-acrylate radical reaction and thiol-capped oligomers by thiol-ene radical reaction with the addition of a tri-ene crosslinker. Details such as molecular weight and crosslinking strategies affect polymer properties. Because of the ester groups in the backbone of these networks, these hydrogels undergo hydrolysis in the presence of water, which is a useful degradation mechanism.

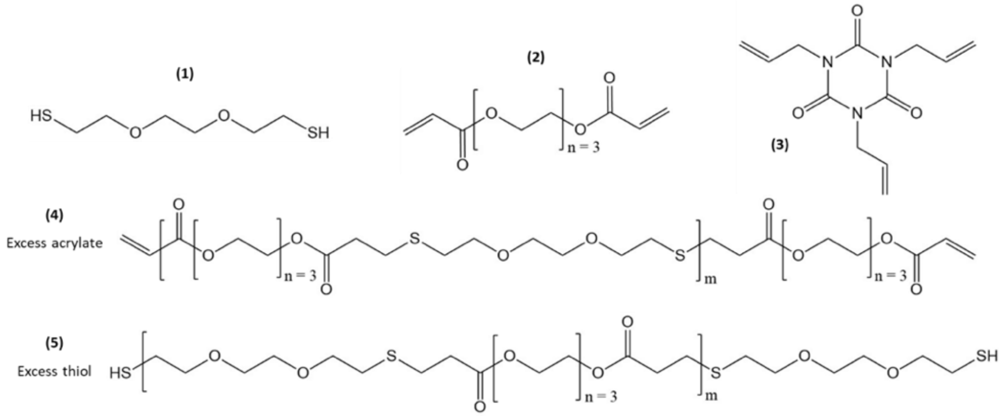

Figure 3: Chemical structures of the monomers and oligomers. EDDT (1) and PEGDA (2) were reacted in varying ratios to produce an acrylate-capped oligomer (4) or a thiol-capped oligomer. Chemical structures of the monomers and oligomers. EDDT (1) and PEGDA (2) were reacted in varying ratios to produce an acrylate-capped oligomer (4) or a thiol-capped oligomer (5). The oligomers were crosslinked by either an acrylate reaction (4) or a thiol-ene reaction using the crosslinker TATATO (5+3).

The team also investigated a second hydrogel synthesis strategy, utilizing the functionality of ortho-nitro benzyl (oNB) groups attached to the cross-linking network of an acrylamide-based hydrogel(Figure 4).

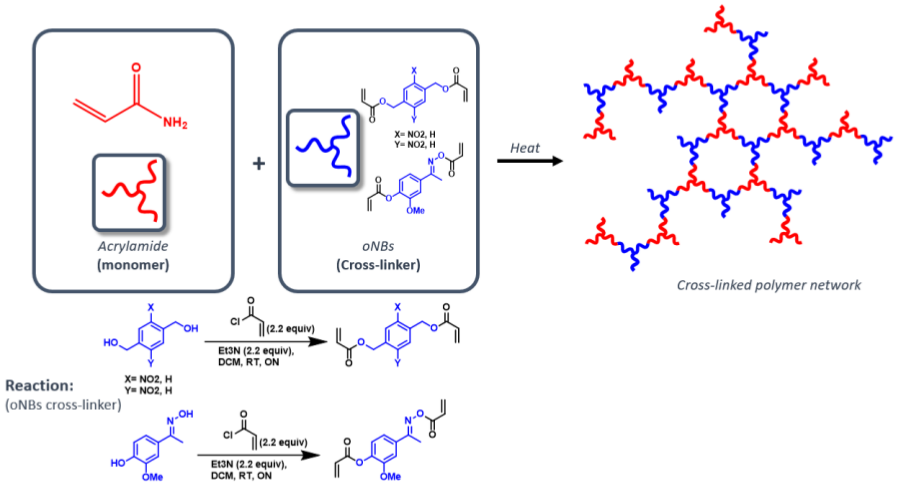

Figure 4: Synthesis strategy of biodegradable hydrogels made with photo-degradable ortho-nitro benzyl (oNB) groups attached to the cross-linking network of the acrylamide-based hydrogel. Three different hydrogels with increasing oNB functionality were prepared.

In the context of the requirements for soft, degradable encapsulation materials, these hydrogels were clear in color and were shown to have tunable degradation. While robust enough to handle in small quantities, the hydrogels were too brittle to pursue velella fabrication. Moreover, they were inherently incapable of preventing water from accessing electronics. In light of these observations, the team shifted to studying, developing, and prototyping an encapsulation platform consisting of a degradable elastomer designed from natural materials.

<u>Degradable elastomer development, characterization and scale-up</u>

Many biodegradable materials are polyester-based, often resulting in high degrees of crystallinity and brittle mechanical properties. Additionally, crystalline materials are often opaque, limiting our ability to control the optical properties of the material. In order to overcome this, we designed a polyester system with a high degree of monomer randomness, which prevents crystallization. By installing acrylate groups on one or both ends of the polyester, these materials can be easily polymerized and crosslinked to form a biodegradable, soft elastomer. After exploring multiple variations of soft polyester elastomers, polymerization of bulk D,L lactide (LA) and caprolactone (CL) with tin octoate ($Sn(Oct)_2$) using HEA as the initiator was found to produce clean pre-network polymers with a high degree of acrylate substitution. The HEA-functionalized polyester (HEA-PE) is a highly viscous oil prior to free-radical polymerization of the HEA group. In order to optimize material robustness, the team included hardeners and optimized crosslinking functionality and density. The resulting elastomer was both elastic and crack/fracture resistant. The ultimate formulation selected consisted of 70% HEA-PE, 25% methyl methacrylate, and 5% polyethylene glycol diacrylate by volume. In addition, a thermal or photoinitiatior equal to 1% of the total sample mass was added to catalyze polymerization. Figure 5 shows the synthetic scheme of elastomer formation. Figure 6 shows images of the ultimate formulation, which can be UV-cured with the addition of Irgacure 819 as a photoinitiator (left), or thermally cured with the addition of azobisisobutyronitrile (AIBN) as a thermal initiator (right.) Both systems crosslinked cleanly, and yielded tough, free-standing elastomers.

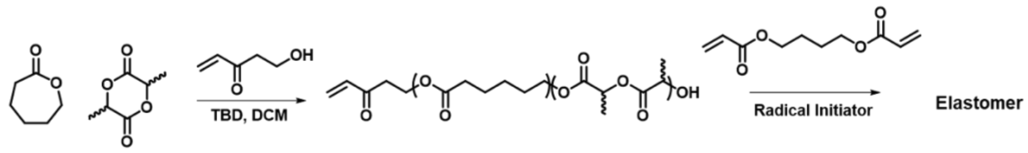

Figure 5: Synthetic scheme for degradable elastomer formulation

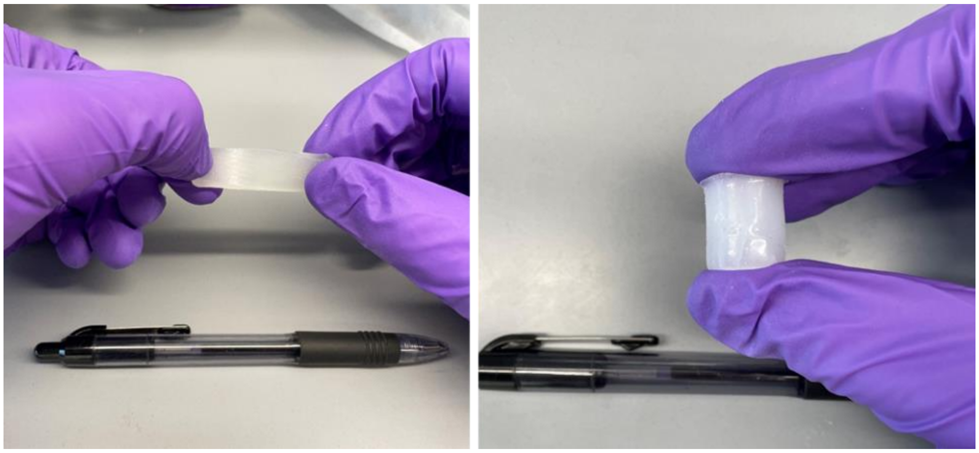

Figure 6: UV-cured (left) and thermally cured (right) final elastomer formulation.

Degradation of the material was characterized. Ultraviolet (UV) degradation was performed using a QUV accelerated weather tester, which simulates solar exposure. Samples were exposed continuously over 60 days to simulate a six-month period of exposure. Samples that were exposed to UV light showed substantial darkening, developing a brown-orange skin on the side exposed to UV. Several samples pulled from the QUV demonstrated mass loss of about 10% total. Further mass loss was limited, which is likely due to the observed skin that stabilized the material and prevented persistent UV penetration. Subsequent Fourier-transform infrared spectroscopy (FTIR) analysis indicated cleavage of ester groups and formation of acid groups, a by-product of degradation.

We scaled-up elastomer synthesis to 100s of grams, allowing us to mold crosslinked material in various shapes, including a miniature velella (Figure 7). The material was easy to mold and robust to handling, showing promise as a candidate material for acting as an encapsulant and structural material for the full-size velella platform in the future.

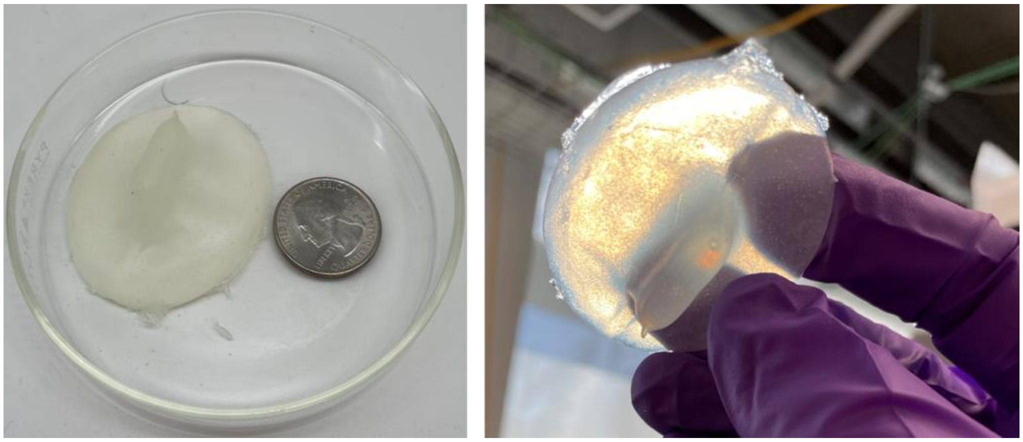

Figure 7. A miniature velella with quarter as a size comparison (left) and held in the light to demonstrate translucency (right).

Throughout this effort, we designed, developed, formulated, and characterized novel hydrogel and soft elastomeric materials. The elastomer materials specifically were generated from renewable materials (including lactide) with degradable ester groups as crosslinking nodes. This system has been shown to be scalable and degrade under a variety of relevant conditions for envisioned missions. With further development, the elastomer material presented here could serve as an ocean-borne sensor platform that leaves a minimal environmental footprint.

B. Objective 2: Novel sensor development

Summary: We developed and characterized a novel salinity sensor designed to leverage the electrical properties of submerged soft materials. Despite initial promise, we ultimately discontinued this effort due to inherent challenges with reproducibility. In turn, we worked with an external vendor, Innovative Sensor Technology (IST), to procure, characterize, and integrate state-of-the-art miniaturized conductivity sensors into our velella sensing platform to monitor changes in salinity.

Background: Ocean salinity sensing is an important yet challenging part of oceanography. First, as opposed to temperature and wind, salinity cannot be sensed from space. Second, accurate sensing is challenging due to how little salinity varies throughout the ocean. There exists multiple salinity sensing strategies, including conductive, inductive and capacitive. For the latter, a set of narrowly spaced, parallel plates coated with an insulator and submerged in water forms a capacitor with a seawater dielectric, the permittivity of the seawater, and hence the capacitance of the parallel plates, is salinity-dependent. The presence of salt ions reduces the permittivity of seawater, and consequently reduces the capacitance of submerged parallel plates. The biggest drawback of capacitive salinity measurement is that seawater's permittivity changes only very slightly in response to changes in salinity, making this a very difficult sensing mode to deploy. In practice, the sensitivity limitations of capacitive salinity sensor are so great that they are not used extensively. Our team attempted to overcome these challenges by incorporating a salinity-sensitive hydrogel between the parallel plates to amplify seawater's salinity-induced permittivity. We measured the output frequency of the salinity-dependent oscillator with a two-clock salinity design, which compared the salinity-dependent oscillator to a non-salinity dependent reference oscillator.

Novel two-clock salinity sensor

Leveraging the salinity-dependent properties of conductive hydrogels and a novel electrical setup, we developed and patented a low-power ocean salinity sensor based on capacitance. The design compares two carefully tuned astable multivibrator oscillators to measure small frequency shifts in the sensing oscillator induced by changes in salt concentration. Comparing the difference in the number of oscillator cycles during a measurement time interval enables the calculation of a frequency shift from which a corresponding salinity change is fitted. Additional theory behind the salinity measurement is discussed in our publication.[1] Figure 8 shows a schematic of device design.

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[1] DOI: 10.23919/OCEANS44145.2021.9705686

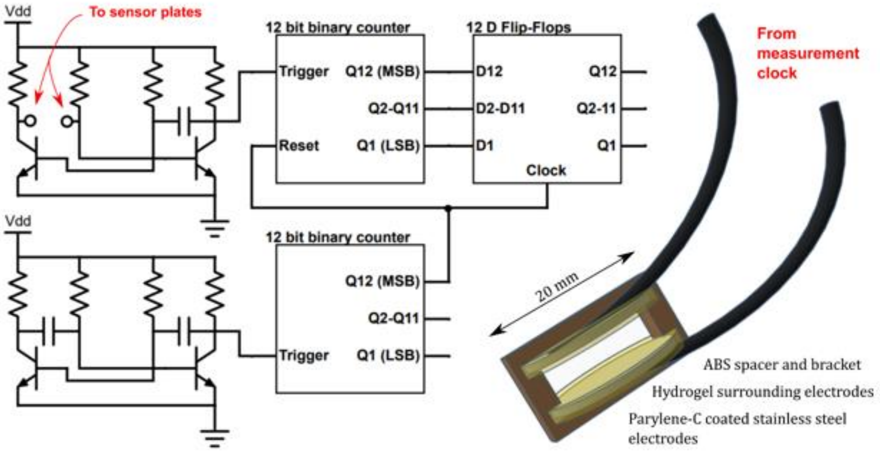

Figure 8: JHU/APL's novel two clock salinity sensing circuit diagram and design.

The device consists of two parallel plates which contain stainless steel disks 15.6 mm in diameter and acted as the capacitor. Constant separation was maintained using a 3D-printed holder. We conformally coated each electrode with a layer of parylene-C to electrically isolate the electrodes during submersion. Between the electrodes was a conductive hydrogel consisting of an acrylamide (AM) backbone with an N,N'-Methylenebisacrylamide (BIS) cross-linker, and carbon nanotubes (CNT). The uncoated and coated parallel plates are shown in Figure 9.

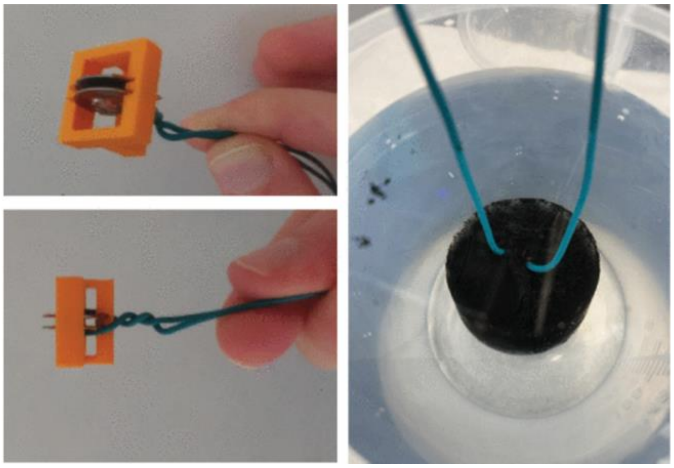

Figure 9: Parylene-C coated parallel plates are shown in a 3D printed fixture with and without the conductive hydrogel coating (left). A sensor, with the conductive hydrogel, is submerged into a saline bath (right.)

The gel-coated parallel plates were assembled into an astable multivibrator. A 1 MΩ resistor paired with the gel-coated parallel plates produced a time constant of approximately 500 as. When paired with the 100 kΩ, 10 nF RC network produced an oscillator output frequency of approximately 4.3 kHz, close to the salinity-sensitive range of the gel. A reference oscillator was built to have a similar oscillation frequency and utilized a 10 kΩ, 100 nF RC network with a 30 kΩ, 100 nF RC network for a frequency of 3.1 kHz.

Each of the two astable multivibrator circuits were connected to the clock pin of a separate binary counter. The binary counters were Texas Instruments CMOS Ripple-Carry Binary Counters (CD4040BE). The 12 output channels from the measurement oscillator's binary counter were connected to a pair of Texas Instruments Octal D-Type Flip-Flops (SN74273). When the reference oscillator's binary counter's most significant bit output (Q12) transitions from low to high, the latches store the current count of the measurement oscillator's binary counter as a 12-bit binary number. Therefore, the output of the latches provides a stable measure of the most recent count differential between the two oscillators. The latches update every 4,096 clock cycles of the reference clock, which occurs approximately every second.

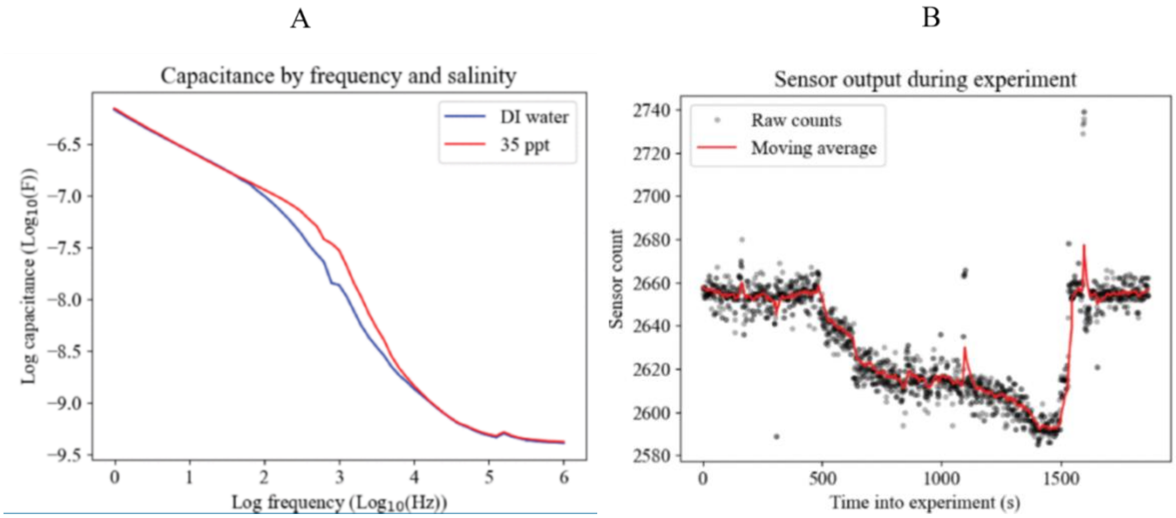

Figure 10: (A) The capacitance of the gel coated parallel plates is shown as a function of frequency for different salinities: 35 ppt and DI water. (B) Sensor output during an experiment, showing changes in salinity. Sensor outputs are shown over the course of an experiment. Distinct levels for the different salinities are visible for 0 ppt (time < 500), 33.5 ppt (500 < time < 600), 35.2 ppt (600 < time < 1250) and 37.2 ppt (1250 < time < 1500), and returning to 0

While initial experiments were promising, further characterization of the salinity sensor elucidated multiple challenges associated with sensor performance and ultimate integration, which are summarized below:

- *Equilibration time*: Measured diffusion through the hydrogel insert is on the order of hours, rather than minutes. Therefore, when switching the system to a solution of a different salinity, the sensor is slow to respond. While this could be optimized, it is not practical for use in rapidly changing conditions, such as a dynamic marine environment.
- *Nonlinearity*: We collected capacitance as a function of frequency for multiple concentrations of salinity. Figure 11 shows that the relationship between capacitance and salinity is not linear, and the trend is not easily representable with a mathematical relationship.

- *Non-reproducibility*: Efforts to characterize the sensor more thoroughly were plagued by issues with repeatability, which suggests that in certain cases, changes in capacitance are dominated by something other than salinity of the solution. This could include electrode size, shape and spacing, imperfections in the insulating coating, or inhomogeneity of the conductive hydrogel.

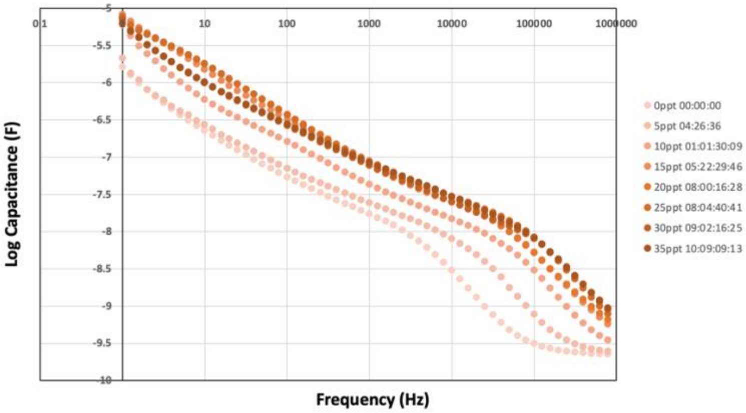

Figure 11: Plot of log(capacitance) versus log(frequency) to demonstrate the effect of salinity on capacitance across a range of frequencies.

For the reasons listed above, we discontinued efforts related to the Novel Two-Clock Salinity Sensor, and focused on characterizing and integrating a commercially available salinity sensor, discussed in the next section.

Integrated Sensor Technologies conductivity sensor

With a goal of demonstrating integration of a salinity sensor into the velella sensor, we surveyed commercially available conductivity-based salinity sensors. Our ultimate project goal is to create a nonrecoverable, low cost, lightweight, versatile sensing platform with salinity sensing capability.

The LFS1107 conductivity sensor from Innovative Sensor Technology (IST[2]) is specifically designed for low-cost ocean sensing. It is a four-electrode conductivity sensor with an on-board Pt1000 RTD (Resistance Temperature Detector), which allows for temperature-compensated conductivity measurements. The sensor itself, shown in Figure 12, has six electrodes. Two of the four conductivity electrodes use an AC voltage to drive a current in the medium. Using a high-impedance amplifier, the potential difference induced by the alternating current in the medium is measured. Given a known current and a measured voltage, conductivity of the medium can be calculated, which can be used to determine salinity. The conductivity range, operating temperature range, and additional key attributes can be customized.

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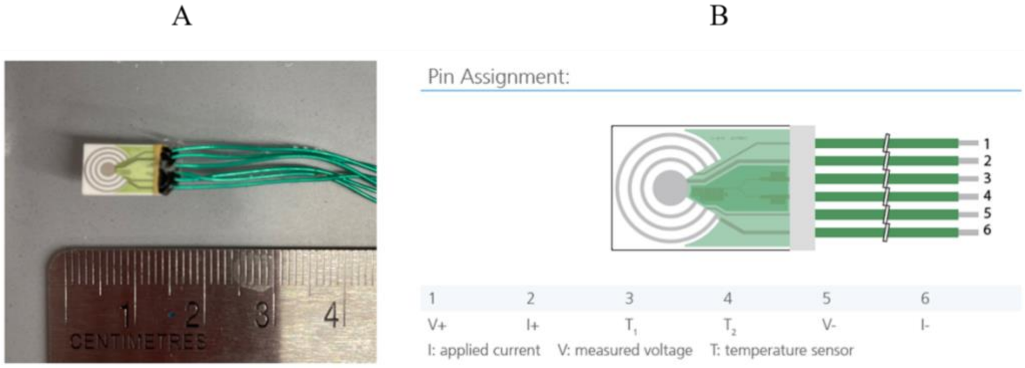
[2] https://www.ist-ag.com/en/about-us



1	2	3	4	5	6
V+	I+	T_1	T_2	V-	I-

I: applied current V: measured voltage T: temperature sensor

Figure 12: (A) A photograph of the IST LFS1107 salinity sensor, with ruler for scale. (B) Senor layout with pin assignment.

The IST sensor is relatively inexpensive at approximately $33 per unit, and is compact (11.3 x 7 x 0.63 mm (LxWxH)). It is also straightforward to integrate: the IST sensor board is accompanied with an evaluation board that provides the analog front end to control the sensor. The sensor board is calibrated by the vendor to a conductivity range expected of sea water. The sensor board reports the conductivity value over a popular communications protocol known as I2C, which is ubiquitous on embedded systems. From there, we can program almost any embedded system to read the conductivity values coming over I2C. We were able to program an Arduino to query and read the conductivity values coming from the IST sensor. The BlackSky board, which is based on a computer architecture similar to that of a standard Arduino Uno, was able to use this code and integrate it.

While the IST sensor is small, the evaluation board is comparatively large. However, the size of the board could be reduced, or completely replaced, in future iterations. The IST evaluation board costs approximately $85 dollars. The total solution from IST (sensor and accompanying sensor evaluation board) is $118. The cost would be reduced significantly in future iterations.

IST sensor characterization

We conducted benchtop characterization of two IST sensors, with an RBRconcerto[3] Conductivity Temperature Depth (CTD) sensor as a control. Sensors were placed in isolated baths of artificial seawater. Results are shown in Figure 13. There is a significant offset of conductivity values measured by each of the IST sensors compared to the RBR sensor. It is possible that the sensors were not calibrated correctly. Generally, they follow the stable trend of the RBR with no large increases or decreases in temperature or conductivity.

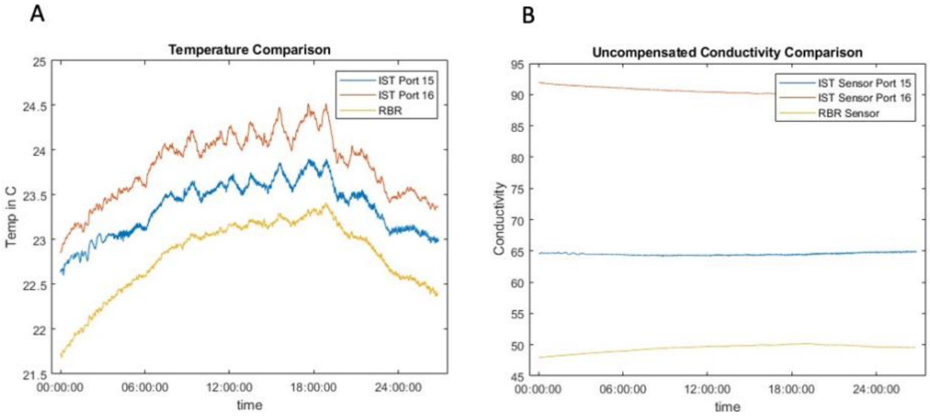


Figure 13: Temperature and Conductivity measurements collected from IST and RBR salinity sensors.

Throughout this effort, we designed a novel capacitance-based salinity sensor, but ultimately decided to procure and characterize a commercially available conductivity sensor. While the absolute conductivity value measured by these sensors is offset from our control, we expect that this can be overcome by improved calibration scheme. We also expect that there is utility in deploying large numbers of low-cost salinity sensors, even if they are less accurate than higher-cost options. Overall, the IST measurements (temperature, conductivity) are stable and follow the expected trend.

C. Objective 3: System-level design

Summary: The goal of this work was to design and integrate electronics into a self-contained sensor platform that does not require a power or data tether. Such a system is able to be deployed anywhere in the world, is self-sustaining, and does not have to be recovered. We designed and fabricated custom electronics and a novel biomimetic form factor to house the electronics.

Electronics design and integration

We collaborated with Blacksky Aerospace LLC, who designed, built, tested and evaluated the necessary electronics for power harvesting and power storage, sensor interface and sensor data readout, microcontroller-based data aggregation and storage, and data communication via an Iridium satellite modem to a control center.

Power Harvesting: Power harvesting electronics for the velella sensors were designed specifically for long-term operation under marine conditions. Commercially available thin film solar cells (Monocrystalline Solar Cell 198 mW 6.22 V) were connected to lithium ion batteries for power storage. The team incorporated an inductor-less design of maximum power point tracker (MPPT) for minimum electromagnetic (EM) signature profile.

Sensor Interface and Data Acquisition: The team developed dedicated high-precision electronics to interface with various sensors, including salinity, temperature, and position. Sensor readout frequency was adjustable within 1-30 Hz. Sensor data was stored internally in a non-volatile, ruggedized memory. A

CPU capable of low-power and sleep mode operation was programmed to control all peripheral electronic components.

Long-Range Datalink, Satellite Communication, GPS Receiver, Data Compression: The team developed dedicated long-range data communication electronics to monitor multiple velella sensors simultaneously, in near real-time. A miniaturized Global Positioning System (GPS) receiver was integrated to sense the position of the sensor, giving insight into ocean currents and drift behavior. A bi-directional Iridium satellite modem was integrated to provide worldwide data coverage and collection.

Operation notes

To enable long-term operation, the system is kept in sleep mode for the vast majority of the time. At a regular cadence defined by the user, the system wakes up, collects measurements, and transmits the telemetry packet over the Iridium satellite system. The cadence at which the system transmits can be updated once the system is deployed. In general, the faster the transmission cadence, the greater the power consumption. A deployment that requires frequent updates is possible to achieve but may require a larger battery or greater photovoltaic surface area. Currently, the software is configured to suspend transmitting telemetry packets if the battery voltage is below a certain threshold. By suspending telemetry, the system is able to stay in a low-power state until the solar panels are able to charge the battery past the programmed threshold. The telemetry packet currently communicates the following information:

1. Date and time
2. Device ID
3. Approximate latitude and longitude
4. Temperature of BlackSky board (as measured by an onboard temperature sensor on the BlackSky board)
5. Humidity (as measured by an onboard sensor on BlackSky board)
6. Battery voltage
7. Photovoltage voltage
8. Water temperature (as recorded by the IST sensor)
9. Raw conductivity value of the medium (as measured by the IST sensor):
10. Temperature-compensated conductivity (as measured by the IST sensor. The details for how this is completed is not currently clear)

Currently, telemetry packets are received by users via email. In future iterations, the data could be ported to a webpage or mobile app. It is possible to make the data public on the internet, and allow it to be updated continually. Note that the current prototype uses the public Iridium network. If desired, the system could be migrated to the DoD Iridium network.

Form factor design and fabrication

We focused on designing a buoyant, sea-stable, and watertight package inspired by the the velella. These small marine creatures passively traverse the ocean surface by catching the wind with a natural “sail.” A design methodology was formed to target the system's functional goals. The process considered the packaging, material, and biomimicry requirements of a system operating in the mimicked organism's environment. Here, we document the pathway from concept, to design, to manufactured prototype.

Functional goals of the system included:

- *Existing electronics suite:* The design and operating intent of this payload was pre-established and provided scope for packaging. The entire system must be contained and remain functional.
- *Biomimicry:* Where possible, the functional elements of the design should be molded to reflect the appearance of the velella species. The system must include a sail to mimic the organism's technique of catching wind for movement. The material selected should allow similar appearance to the translucent organism.
- *Operational state*: The velella sensor was required to float on the ocean surface. The payload required upright orientation, above the waterline, to send and receive communications.
- *Material environment***:** Velella traverse the ocean surface partially submerged. Any encapsulating material must resist exposure to the same conditions at sea as a surface vessel.

Electronics considerations: The fabrication of the velella prototype was an exercise in packaging electronics in a novel, biomimetic form factor. With any form of packaging, initial emphasis should be placed on ensuring full functionality of the payload. As the electronics and sensors were developed prior to the form factor, the packaging scope remained stable for a given system iteration. The final prototype's payload consisted of a GPS module, satellite datalink module, sensor processing module, battery, and Photo-Voltaic (PV) cells. All components shared general packaging requirements, with certain modules requiring specific considerations:

- *The GPS module* contains a patch antenna which must be located above the waterline and oriented towards the sky to ensure sufficient reception.
- *The satellite datalink module* contains both a patch antenna and an external antenna. The patch antenna must be oriented similarly to the GPS. The external antenna should be placed above the waterline and pointed upward.
- *The salinity sensor* should be exposed to sea water. It should be placed on a location which remains submerged
- *The PV cells* should be located on top of the Velella, oriented towards the sky to capture as much sunlight as possible.
- *All circuit boards* should be oriented to allow connector access during wiring. Board orientation should, where possible, allow shortest possible cable routing to reduce weight and volume

Biomimetic form factor: Velellas, also known as *By-The-Wind Sailors*, are small, soft-bodied organisms as shown in Figure 2. For our purposes, structures above the waterline, which could be assessed by eye and strongly influenced by sensor movement, were considered biomimicry-critical. Structures below the waterline were designed to ensure complete packaging and sensor stability, while remaining non-biofidelic. Components requiring direct exposure to the sky (PVs, antenna) were packaged at or above the waterline divide. The remaining electronics were positioned below the waterline, thus lowering the center of gravity.

Operational requirements: When in operation, the velella sensor platform must: float at the defined waterline, be fully sealed to prevent ingress or pooling of sea water, be resistant to capsizing in unfavorable conditions, should favor returning to a single upright state if capsized, and perform without active systems. To address these requirements, total system density was tracked during the design process, and buoyant features were sized to meet total system density goals.

Material: For the prototypes developed in this effort, a marine grade silicone was used due to exposure requirements. Eventually, silicone could be substituted for JHU/APL's novel degradable elastomer.

Payload Skeleton: An additively manufactured skeleton— an independent structure from the outer velella form factor— was designed to hold the electronics, providing a known geometric interface between the payload and packaging. Both 2D and 3D scanning techniques were leveraged to package the existing system, discussed below and illustrated in Figure 14:

- 3D scanning brought the populated circuit boards into a Computer Aided Design (CAD) file, allowing the designer to virtually manipulate components and define the packaging volume.
- 2D scanning brought in to-scale detail of the circuit boards themselves. By referencing dimensions, the designer was able to route the mechanical skeleton around electronic components and ensure clearances for cables and connectors.

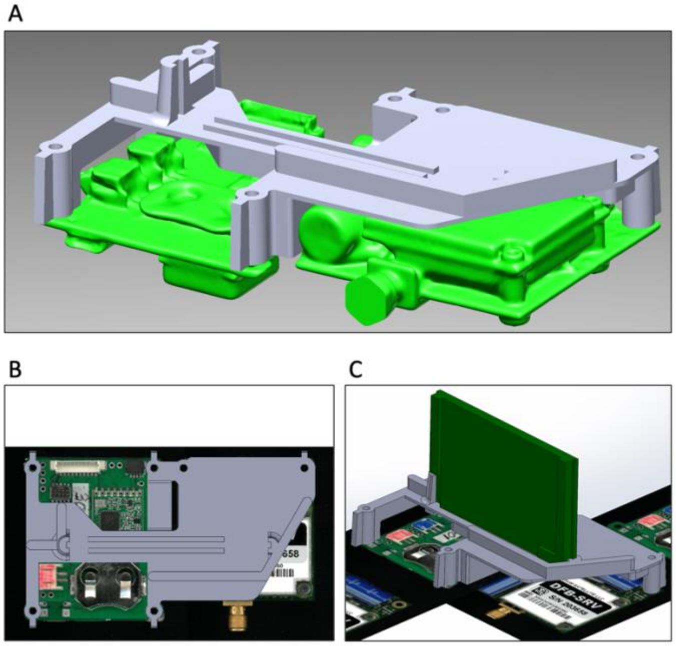


Figure 14: (A) CAD view of the payload skeleton with 3D scans of existing electronics fitted. Coupled with 2D scans and board dimensions, clearances for connectors and routed cables were checked prior to manufacture. (B) Top view of electronics skeleton showing alignment with to-scale 2D scans of circuit boards. (B) 3D view of skeleton with sensor board held in place.

Non-position-critical components were placed below the waterline. The IST sensor board and battery were oriented vertically, and the form factor closely hugged their outline. This kept clearance near the waterline to encircle the payload with buoyant air pockets (Figure 15). The result is a noticeable “keel” feature below the velella, with the salinity sensor exposed to the water at the lowest submerged location in the system. This doubled as a secondary stability feature, lowering the center of gravity to resist capsizing.

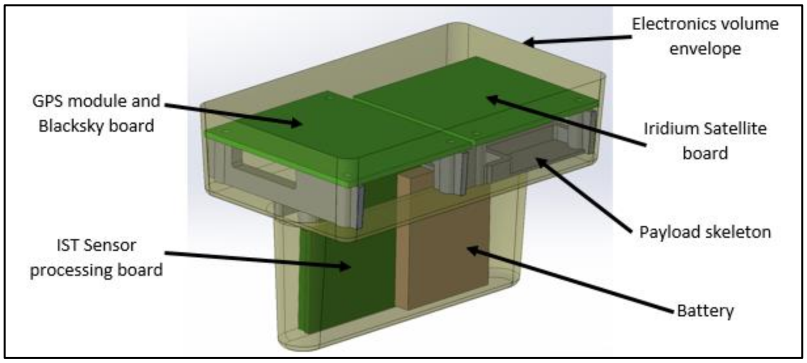


Figure 15: CAD representation of final electronics payload. Components within are identified. Salinity sensor not shown; would have exited bottom center to be exposed.

Outer mold line and buoyancy features: The placement of components defined an overall envelope which the final form factor had to encapsulate. The outer mold line is shown in Figure 16 (A, B), and discussed below:

- An elliptical hull shape was drawn around the electronics volume, providing room fore, aft, and to either side for buoyant air pockets.
- Ribbed “bulkheads” were included to maintain the velella’s structure and double as a risk mitigation feature should one pocket be breached.
- Depth of these pockets were driven by the target system buoyancy; deeper pockets encapsulated more air and provided more buoyancy.
- The protruding keel closely hugged the electronics, maintaining a minimum thickness for the chosen casting material. The keel was blended back into the hull to maintain a smooth surface.

The visible (above waterline) portion of the velella was designed with the primary goal of aesthetics in mind. Key features are shown in Figure 16 (C, D):

- Mimicking the Velella’s shape and sail were primary considerations.
- The sail was reproduced by importing and tracing a photo of an actual Velella.
- The tallest, central section of the sail accommodated placement of an external antenna.
- Where possible, the air pockets of the lower section were expanded up to the top boundary to increase self-righting buoyancy.

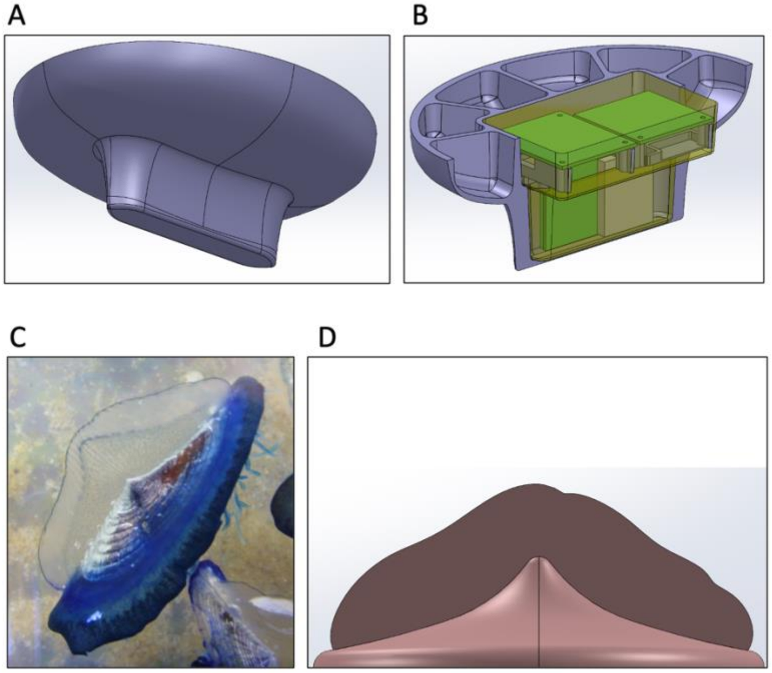


Figure 16: (A) Underside of submerged Velella form factor with blended keel visible. (B) Section view of the form factor showing the interface between electronics envelope and Velella. (C) Photo of velella used to trace sail geometry. (D) CAD view of sail geometry and top portion of Velella. Thickness of body was increased to incorporate more air volume for buoyancy.

Developing buoyancy and weight target: In order to provide a stable, floating platform for the payload, it was important to track the system buoyancy during the design process. It was determined that the best method was to choose a target "total system density" as it provided a quick and easy way to estimate bulk buoyancy. This density was calculated by taking the total theoretical weight of the velella system, divided by the volume it displaced in the water. So long as this density was below the density of water, the design iteration passed a "float" criterion. The estimated system density relied heavily upon the density of cast silicone. An upper conservative value of 1.5g/cm^3 was used. Standard values for water and air were used.

System density was calculated using Equation 1, where ρ is density in g/cm^3, V is volume in cm^3, and m is mass in grams. This density was then compared against the density of water per Equation 2 as a "float or no float" check. Realistically, the system needed additional buoyancy buffer to float, rather than be neutrally buoyant. A target buoyancy of 0.85 g/cm^3 was established and the criteria in Equation 3 was used instead.

$$\rho_{system} = \frac{\rho_{solid}V_{solid}+\rho_{air}V_{air}+m_{payload}}{V_{solid}+V_{air}} \qquad \text{(Equation 1)}$$

$$\rho_{system} < \rho_{water} \qquad \text{(Equation 2)}$$

$$\rho_{system} < 0.85 \qquad \text{(Equation 3)}$$

Design for Manufacturing (DFM): The waterline was chosen as a convenient splitting line for the casting mold. In order to achieved sealed air pockets, the design was sliced by a horizontal plane at this location. Each half would have a mold created separately, capturing both external and internal geometry. During manufacture, these halves were rejoined, sealing in air and encapsulating the payload. Mold creation from a master requires considerations for removing the master geometry after casting. Vertical walls often require a 'draft' angle of a few degrees. A three-degree draft was chosen and verified after modelling using SolidWorks' Draft Analysis tool. Sharp internal corners should be rounded to ease material removal and prevent stress concentrations in the final piece. These concentrations may cause tears when attempting to de-mold thin features. An internal fillet radius of at least 4 mm was used where the design allowed. Figure 17 depicts the draft and final designs.

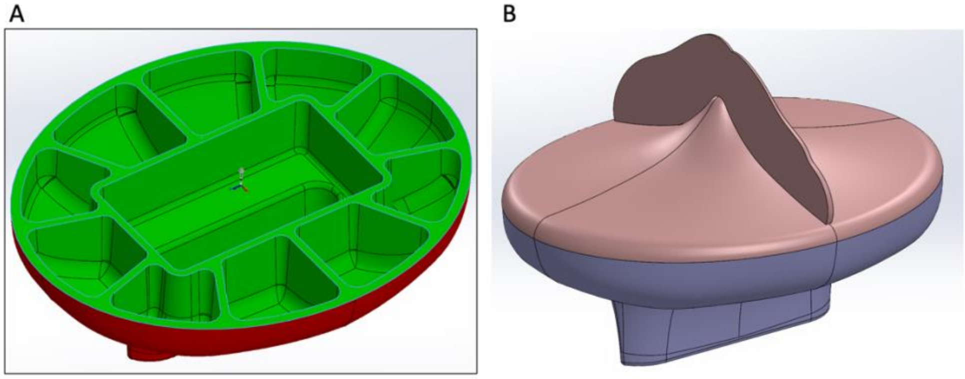


Figure 17: (A) Draft analysis of velella bottom mold master. The solid green color on internal features shows an appropriate removal draft for casting. (B) Final version of bottom and top form factor

<u>Prototype assembly</u>

Mold masters were printed via Fused Deposition Modeling (FDM), using an ABS filament. Mold masters are shown in Figure 18 (A, B, C), and final silicone molds are shown in Figure 18 (D). Care was taken to smooth surfaces during mold fabrication in order to a achieve a smooth, translucent casting.

The velella casting and assembly processes are documented in Figure 19. The velella body was cast using BJB Enterprises TC 5040, a room temperature, addition/platinum silicone rubber. The casts were allowed to cure overnight. Following cure, pass-throughs for the IST salinity sensor, antenna, and PV cells were cut. All components were pre-potted prior to velella assembly, and the skeleton to house the base electronics, discussed earlier, was utilized. All mating surfaces, including the velella sail, were adhered together using Nu-Sil R33-2186 silicone adhesive. Following assembly, the entire prototype was allowed to cure overnight.

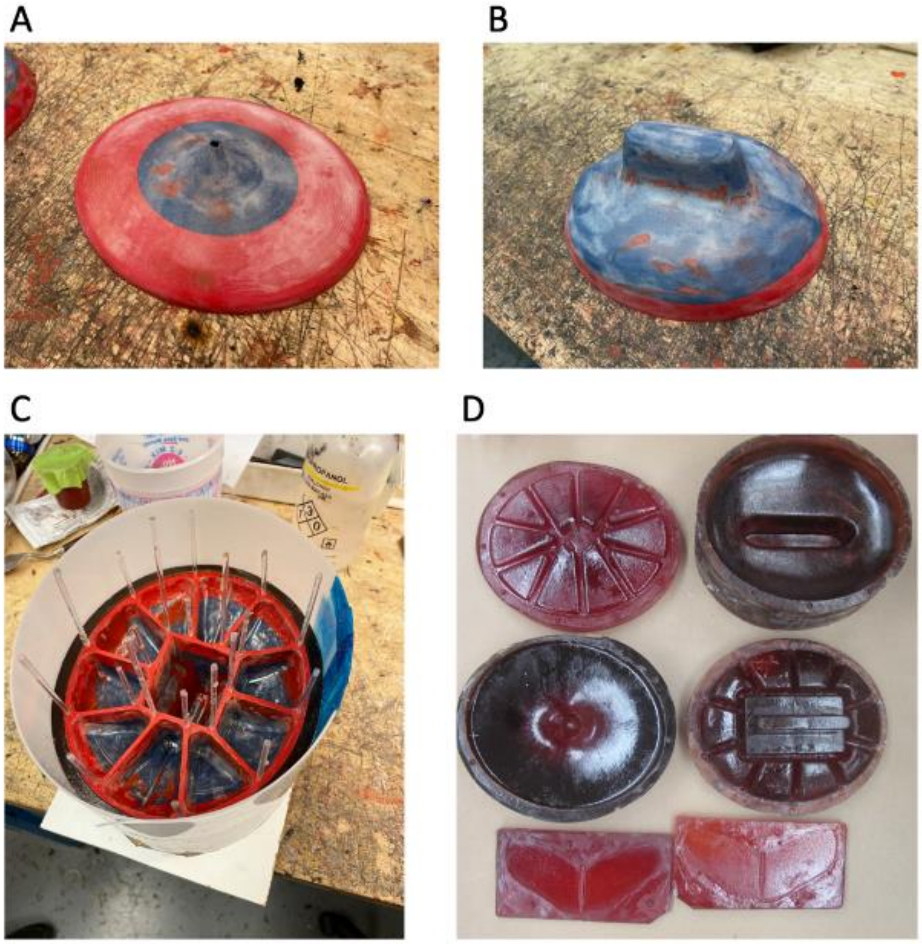


Figure 18: (A) Top mold master, (B) Bottom mold master, (C) Internal structures with the second half of the mold shown, the rods help with venting (D) Completed silicone molds

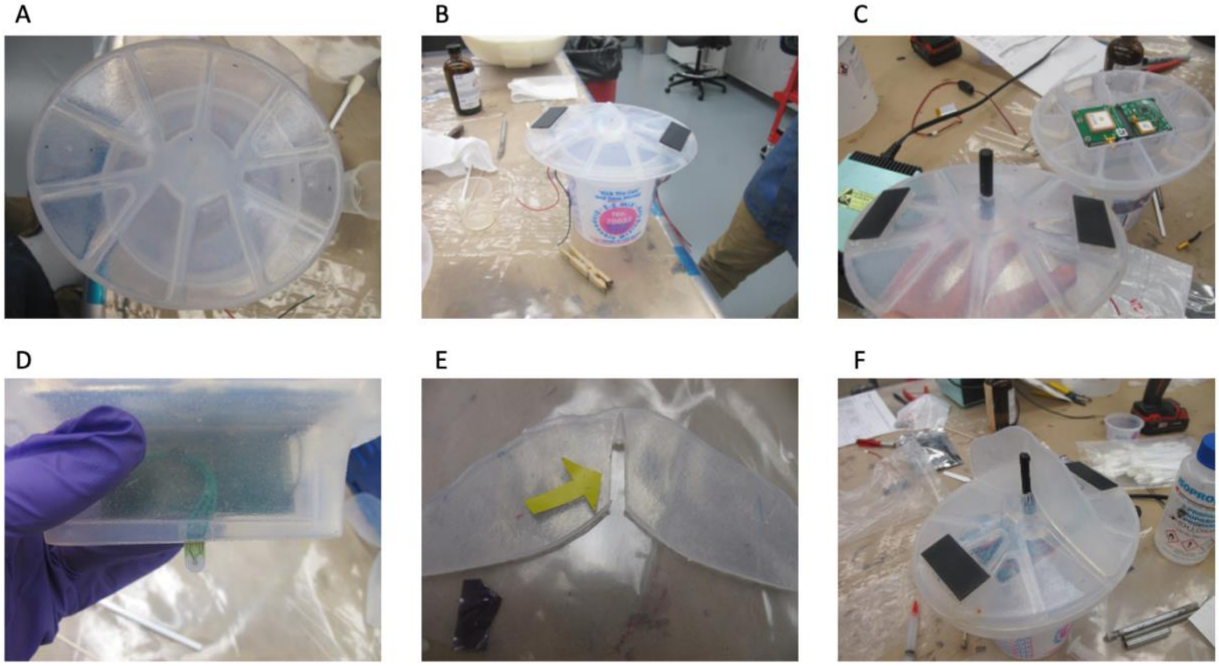


Figure 19: The velella assembly process. (A) The casts of the top and bottom base components (B) The PVs assembled above the pass-throughs (C) The electronics in the internal cavity and the antenna and PVs on the top (D) Placement of the IST sensor (E) The velella sails prior to attaching, and (F) The full assembled prototype. Final velella dimensions: 190 x 160 x 130 mm (L x W x H).

Prior to deployment, we conducted a number of preliminary float and buoyancy tests. The sensor was found to float stably on the surface of still water, and return to the surface upright after being forcefully submerged. A tethered velella sensor was thrown into the surf in the Pacific Ocean, and following multiple tumbles within a wave, returned upright. If the sensor was purposefully turned upside down, it would not right itself. We could adjust this in future iterations.

D. Objective 4: System deployment

Summary: Our team completed two successful deployments in the Atlantic and Pacific Oceans, demonstrating functionality of the electronics system and the full velella sensor prototype.

Atlantic Ocean Deployment

A velella sensor electronic package in ocean-proof housing was launched into the Atlantic Ocean in November of 2022. The goals of the Atlantic Ocean deployment were to demonstrate properly functional electronics, demonstrate data communication from the ocean, and test power harvesting and storage capabilities. Importantly, while the electronics were nearly identical to the electronics included in the final velella form factor (except for the salinity sensor), this test did not leverage the biomimetic shape of the velella. An image of the deployed electronics package is shown in Figure 20 (A). The package was deployed via weather balloon, which is also pictured (B). The trajectory of the balloon and ocean touch down is show in Figure 20 (C). Figure 20 (D) shows the system trajectory for the first three months. It was apparent that the sensor was roughly following the Gulf Stream. In mid-April of 2023, the system was tracked off the coast of the Azores.

The sensor communication worked seamlessly. The power harvesting and storage has been successful, maintaining a constant voltage since November 2022. As of mid-April 2023, the voltage is at 4.2 V, indicating a completely full lithium ion battery. Even if power harvesting were to fail now (due to biofouling, for example), we estimate that the batteries should last a full additional month.

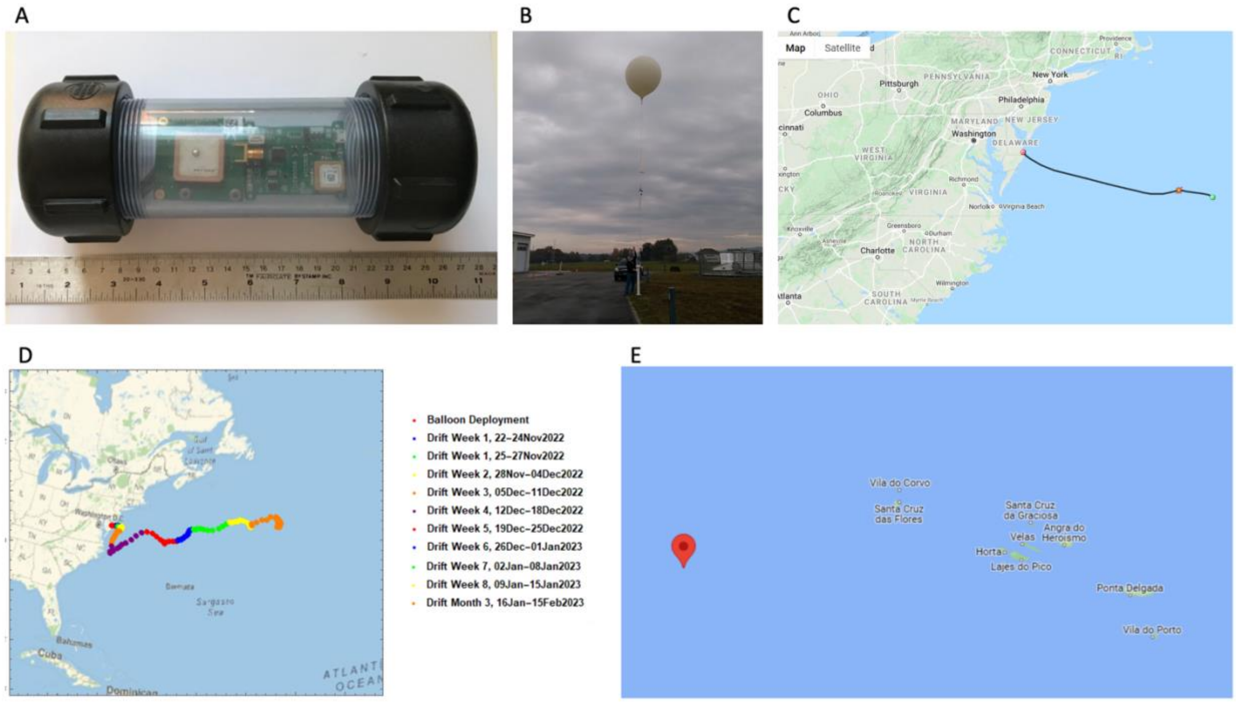


Figure 20: To test sensor electronics (power harvesting and data communication via Iridium modem), we deployed velella electronics in a waterproof tube, shown in (A), via weather balloon shown in (B). Deployment via weather balloon and initial ocean touch down are shown in (C). The system trajectory for the first three months is shown in (D), with the location of the sensor on April 17, 2023, off the coast of the Azores, shown in (E)

Pacific Ocean Deployment

In March of 2023, we deployed a full velella system, including the full electronics package with an IST salinity sensor, and a biomimetic form factor. The system was placed into a bucket with multiple holes, which was then placed in the ocean, secured to a dock at the Naval Postgraduate School in Monterey, CA, (Figure 21).

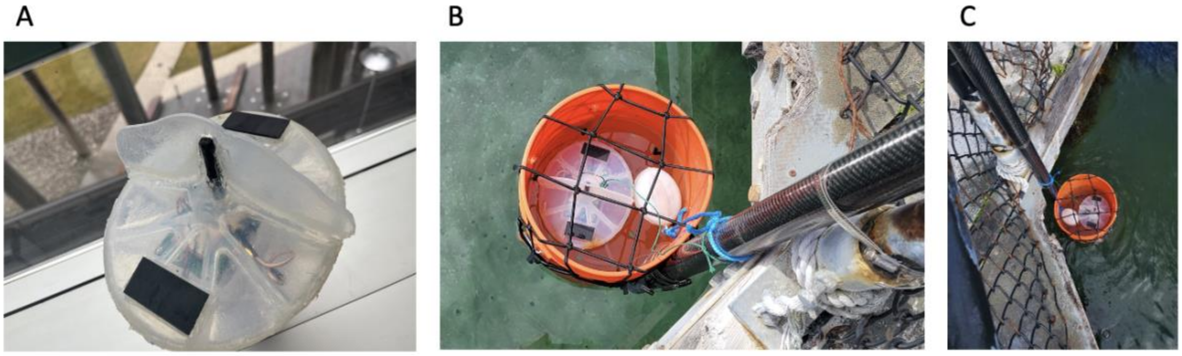


Figure 21: (A) Full velella prototype following assembly in Laurel, Maryland, (B, C) Deployment off of a dock in Monterey, CA, contained within a bucket for easy monitoring

Example data retrieved from the velella system are shown in Figure **22**. The IST sensor is quite stable with respect to temperature and conductivity. The accuracy and stability of the compensated conductivity is partly a function of the algorithm that IST uses. We note that in this measurement and in our benchtop measurements of the IST sensor, there appears to be a constant offset of conductivity (and therefore salinity.) We expect this could be solved by better sensor calibration. At the time of this report (April 30, 2023), the sensor remaned in the ocean, actively sending data and being monitored by NPS.

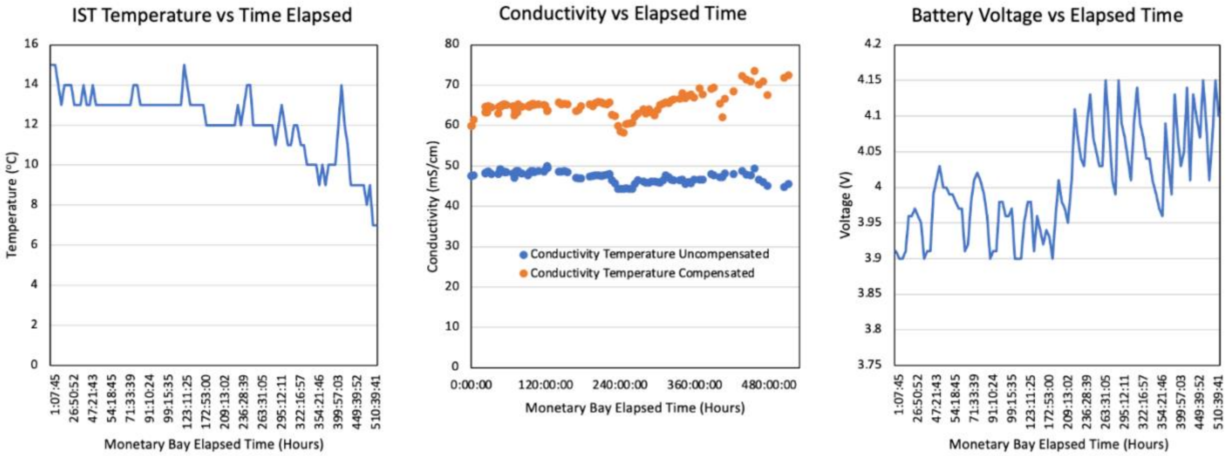


Figure 22: *Data retrieved from the velella sensing system in Monterey (A) IST Temperature as a function of time (B) Conductivity as a function of time and (C)Battery Voltage as a function of time.*

E. Next Steps

Within this project, we developed a novel, low-cost, velella-inspired sensing platform. Leveraging a unique form factor, soft materials, and low-cost electronics, this sensing platform was designed to float on the surface of the ocean, collect pertinent environmental information (temperature, position and salinity), and relay data over satellite to a central location for analysis. Towards this goal, we demonstrated the development of a novel degradable elastomer, explored new strategies for salinity sensing, developed a low-power, high-functioning electronics suite, designed a biomimetic buoyant form factor, and successfully deployed a fully functioning velella sensor.

Additional opportunities for device optimization remain. If pursuing salinity sensing using the IST sensor, we need to better understand the source of the offset of the IST salinity sensor, compared to control sensors. We also would also like to remove the dependence of sensor operation on the vendor-supplied characterization board, and integrate IST sensor controls directly into the BlackSky board. This would reduce size, weight and cost of the electronics payload.

Leaning into the versatility of the platform, and the potential uniqueness of movement (more dependent on the wind due to the sail than the current below), we could explore the movement and coverage of large collections of velella sensors. This would be especially interesting if size and form factor were varied. We know that we could substantially reduce the size, weight and power of the sensor platform by removing sensing modalities. A distributed collection of smaller velella-shapes sensors could provide a powerful tool for collecting oceanic information.

Ultimately, we see these sensors as incredibly adaptable platforms, which could be equipped to support a number of research and surveillance needs. The size, shape and color of the velella sensor could be modified to meet a specific need. Salinity sensors could be augmented or replaced with other sensing modalities.

III. Opportunities for Training and Professional Development

Salinity sensor development and characterization efforts have provided a rich opportunity for JHU/APL staff with expertise in electrical engineering, materials science and electrochemistry to collaborate and share cross-domain insights. JHU/APL intern staff contributed to the hydrogel synthesis research and gained exposure to a diverse range of technical domains the systems level sensor platform development and testing.

Form factor development offered an opportunity to connect modeling and fabrication domains with biomimetic operation, bridging across disparate technical groups within the research department.

Additional professional development activities throughout the work have included: attendance at the Materials Research Society Fall Meeting, interdisciplinary symbioses based on current atmospheric UAS-based marine environment sensing (ongoing ONR SBIR Phase II), long distance low SWaP communication technologies (ongoing NASA SBIR Phase II), and weather balloon-based sensor measurement and deployment technologies (ongoing AFRL/NRL Coalition Warfighter Project (CWP)) towards low SWaP ocean surface platforms and commercialization thereof.

Further, the velella sensor development has motivated ongoing discussions with multiple oceanographers, some within JHU/APL and some at other institutions.

IV. Dissemination to Communities of Interest?

Preliminary data of the novel salinity sensor was presented in the IEEE Oceans conference paper “Robust Ocean Salinity Sensing” in September 2021.

Long distance communication technologies and near ocean surface effects for low SWaP sensor platforms are currently being discussed with ONR and NPS.

A manuscript discussing the design and fabrication of the velella form factor is in preparation.

JHU/APL published a press release on our external website discussing the velella sensors and their potential impact, entitled: *Inspired by Jellyfish, APL Researchers Float a Versatile Sensor Platform*. *https://www.jhuapl.edu/news/news-releases/230427b-versatile-velella-sensors-for-ocean-research*

V. Technology Transfer

JHU/APL filed a non-provisional patent application for the novel “two clock” salinity sensor in January 2022, entitled “Parallel Clock Salinity Sensor.”

JHU/APL submitted an invention disclosure on the degradable elastomer material in April 2023, entitled “Biodegradable Ester-Based Elastomer”

JHU/APL submitted an invention disclosure on the Velella inspired sensor platform in May 2023 entitled “Bio-mimetic Ocean-traversing Sensor Platform”

VI. Participants

JHU/APL:
Leslie Hamilton
Daniel Ayoub
Joel Sarapas
Nick Kantack
Collin McDermmot
Kyle Lowery
Craig Leese
Kevin McCafferty
Mairead Bartlett
Ryan Carter
William Cheezum
Khamphone Inboune
Spencer Langevin
Brooke Luisi
David Owneby
Arica Puccio
Avrami Rakovsky
Drew Seker
Adam Simmonds
Zhiyong Xia
Morgan Trexler
Amy Halligan
Amanda Green
Jen Skerrit

Blacksky:
Raymond Hoheisel
Sean Fox

Collaborating entities:
James MacMahan, Naval Postgraduate School (NPS)

VII. Students

Tessa Van Volkenburg pursued her Doctorate of Engineering (D. Eng) with Johns Hopkins University during this time period.

VIII. Products

1. Conference Paper
    a. Title: Robust Ocean Salinity Sensing
    b. Authors: Kantack, Nicholas; Langevin, Spencer; Tessa, VanVolkenburg; Skerrit, Jennifer; Xia, Zhiyong; Hoheisel, Raymond; MacMahan, James; Brown, Sean
    c. Conference Name: OCEANS 2021
    d. Conference Date: 20-23 September 2021
    e. Conference Location: San Diego, USA
    f. Publication Status: Published
    g. Publication Date: 15 February 2022cdscwwdeddeedc
    h. Publication Identifier Type: DOI
    i. Publication Identifier: 10.23919/OCEANS44145.2021.9705686
    j. Acknowledgement of Federal Support? Yes

https://ieeexplore.ieee.org/abstract/document/9705686/authors#authors

2. Conference Paper
    a. Title: Utilization of Various orth-nitrobenzyl groups (oNBs) on the Degradation Times for Acrylamide based Hydrogel Systems
    b. Authors: Spencer Langevin, Tessa VanVolkenburg, Nick Kantack, Zhiyong Xia
    c. Conference Name: ACS Spring 2021
    d. Conference Date: April 5-16, 2021
    e. Conference Location: Virtual
    f. Publication Date: April 5-16, 2021
    g. Publication Identifier Type: *none*
    h. Publication Identifier: *none*
    i. Acknowledgement of Federal Support? Yes
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    k. Publication Status: Presented