# Final Technical Report of ONR Grant N000141812469

# Robust Co-Prime Sensing with Underwater Inflatable Passive Sonar Arrays

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## ABSTRACT

This final technical report describes the effort from May 2018 to September 2021 to accomplish the project objective of *Robust Co-Prime Sensing with Underwater Inflatable Passive Sonar Arrays*.

In many scientific and defense surveillance missions, reducing the sensing systems' size, weight, and power (SWaP) is critical to accomplishing the intended objectives [1]. The long-term goal of this research is to develop energy-efficient and low-cost underwater inflatable structures that will be the building blocks in many naval applications.

While compressive sensing (CS) has been adopted at the backend to maintain signal fidelity with fewer data and reduce the sensing hardware's complexity, SWaP reduction can also be achieved with intelligent mechanical design. The inflatable structure is adopted for the mechanical design of this sonar array. The inflatable structure, also called the deployable structure, is a folded package with compact stowed dimensions. It can be detached from a carrying platform and morphs into its final form at the destination. On the algorithm side, the concept of the co-prime array is adopted. A co-prime array employs two interleaved uniform linear subarrays with several co-prime elements and inter-element spacing. It can resolve a much higher number of sources than a conventional uniform half-wavelength spaced array for a given number of sensors. Therefore, integrating these two concepts, i.e., "two-way compression," reduces both the structural dimension of a sonar array and the number of hydrophones in the array.

During the three-year funding period, the team investigated alternatives to the conventional Mechanical Based Expansion (MBE), including Physics-Based Expansion (PBE) and Chemical Based Expansion (CBE). The feasibility of these techniques, particularly the PBE approach, has been validated through numerical modeling, lab test, and field study.

Our study has produced two pending patents, and one journal paper (in press). The results have also been presented at multiple technical conferences.

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# 1. OBJECTIVES AND APPROACH

The overarching goal of the proposed concept is to develop a transformative approach for enabling a UUV-based underwater deployable sensor network (UDSN) consisting of biodegradable (i.e., covert) nodes [2] (Figure 1). Before the deployment, UDSN nodes will be packed as UDS capsules in the UUV payload bay. The UUVs can then deploy the capsules at pre-defined locations. An underwater inflatable co-prime sonar array (UICSA) system forms one UDSN node with the sensors located on the inflatable structures. Once all the UICSA packages morph into the final forms, the density of the UDSN sensor network is defined.

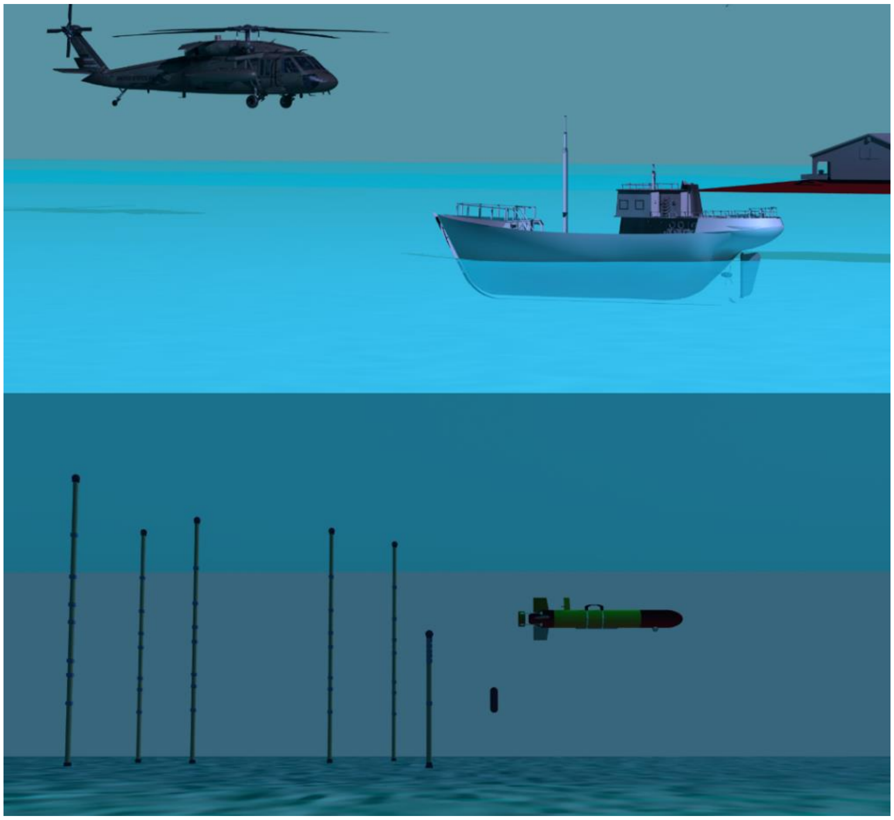
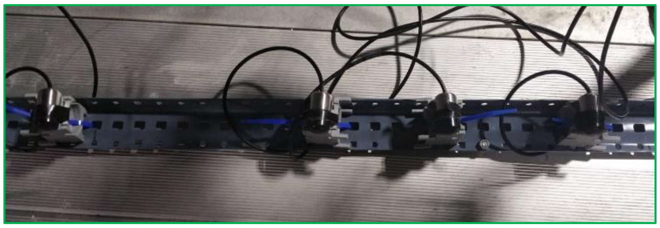
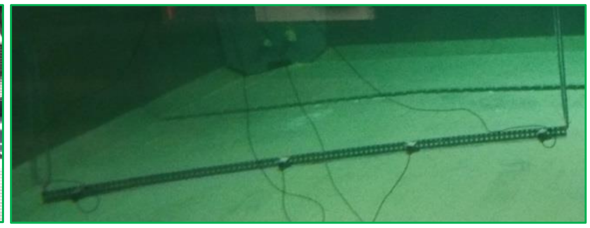


**Figure 1. The illustration of UDSN consists of multiple UICSA nodes that can be deployed from aerial planes, boats, or AUVs.**

To this end, the primary goals of this project are to develop one UDSN node – a UICSA prototype and the algorithms to optimize the processing of the array data in a non-ideal environment. The outcome of this project should provide the foundation for future endeavors to investigate the UDSN for surveillance of an extended area. The main focus of this project is to explore different “building blocks” that can be used to construct such energy-efficient deployable structures. Different designs have been evaluated through numerical modeling, lab tests, and field experiments.

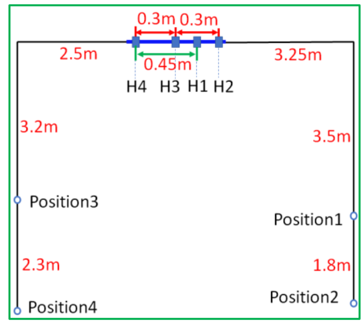


(a) Hydrophone array structure used in the experiment



(c) Underwater photos of the hydrophone array

(b) The structure attached to the catwalk on the test tank



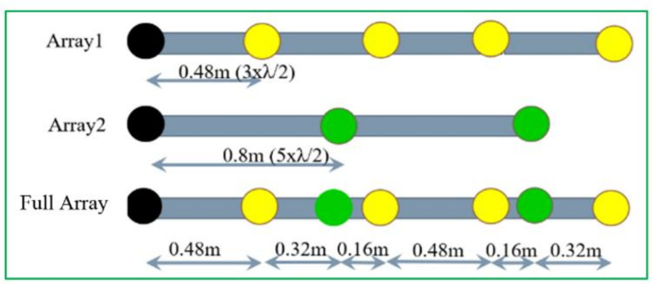

(d) Experimental environmental geometry layout

**Figure 2. Experimental layout and environment.**

# 2. ACCOMPLISHMENTS

## 2.1. Initial experimental study of UICSA [3]

During the year-one effort, two initial prototypes were constructed. In the first experiment, a fixed-length co-prime hydrophone array was constructed and deployed in the optical test tank at the Harbor Branch Oceanographic Institute (HBOI)/FAU. The goal of these tests was to acquire a dataset. For this purpose, a four-node co-prime array that consists of a two-node subarray and a three-node subarray was constructed. The structure was hung on a catwalk and placed horizontally in the water (Figure 2).




(a)

(b)

**Figure 3. 7-node UICSA sensor configuration. (a) Illustration of the array geometry (b) The actual prototype**

To investigate the underwater inflatable structure (UIS) design, an array using “dummy” hydrophones was constructed in the second experiment, focusing on vertical array design using floating UIS. In this current 7-nodes prototype, the length of the tube structure is 1.96m, assuming a 5Khz source frequency (Figure 3a). Flexible PVC film and dual lock strips were used to build an enclosure to simulate a container of UICSA components. Waterproof poly sheeting material with a thickness of 0.00015m (0.15mm/38Gauge) to fabricate the tube structure to be injected with water. Most of the components used in the main structure of the UICSA prototype, such as the joint assembly, the inlet, and the outlet node, were fabricated through 3D printing. The total length of the compacted UICSA prototype (Figure 3b) is 0.5m – a compression ratio of 3.92:1. Experiments were conducted at the 25’x30’x25’ Acoustic Test Tank at the Department of Ocean and Mechanical Engineering (OME) on FAU Boca Raton Campus. Figure 4 illustrates the different stages of the morphing process of the array using frames from the GoPro video. Figure 4a shows the initial status of the UICSA in the tank. Figure 4b-c illustrates the inflation process. Figure 4d shows the fully inflated prototype after a 4-minute hydraulic injection.

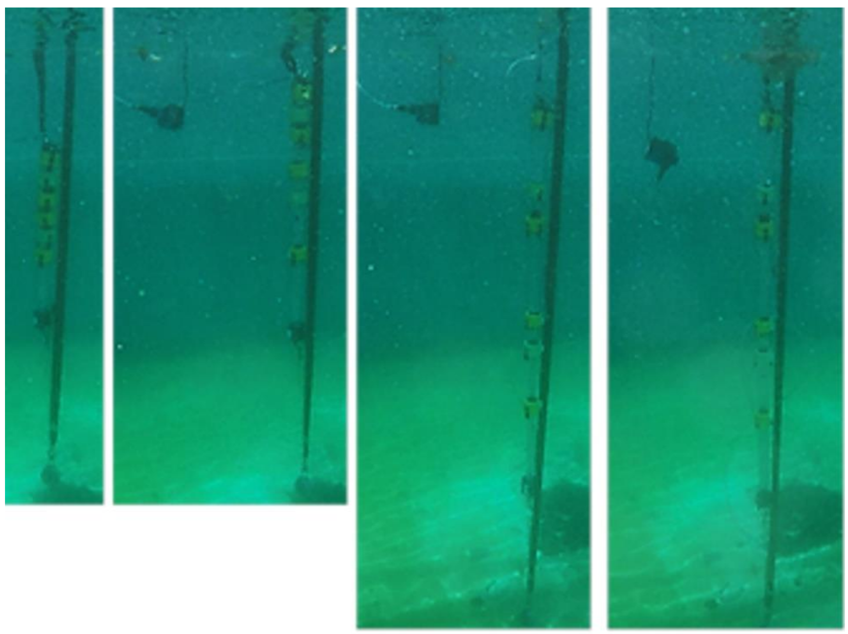


**Figure 4. Illustration of the prototype morphing process**

## 2.2. Developed a dynamic simulation of the UICSA Array using Orcina OrcaFlex™ software [3]

A robust simulation environment was constructed to evaluate different UICSA array design options. For this effort, the OrcaFlex from Orcina was adopted. Orcaflex offers a very straightforward approach to setting up and running simulations to model a submerged structure. Therefore, Orcaflex is more efficient and easier to use than ANSYS Aqwa. Another critical factor is that Orcaflex can analyze a UICSA structure in *8 minutes*, while Aqwa may take *more than 30 minutes*. In an initial test, a 4-node vertical UICSA structure under different current conditions was analyzed using OrcaFlex. The array length was assumed to be 3m, anchored at a depth of 142m. Figure 5a illustrates the array structure. The input parameters are shown in Figure 5b. Figure 5c illustrates the array deformation under different current conditions (vertically uniform current was assumed). Our collaborators at Temple University provided the information in their co-prime array algorithm development effort.

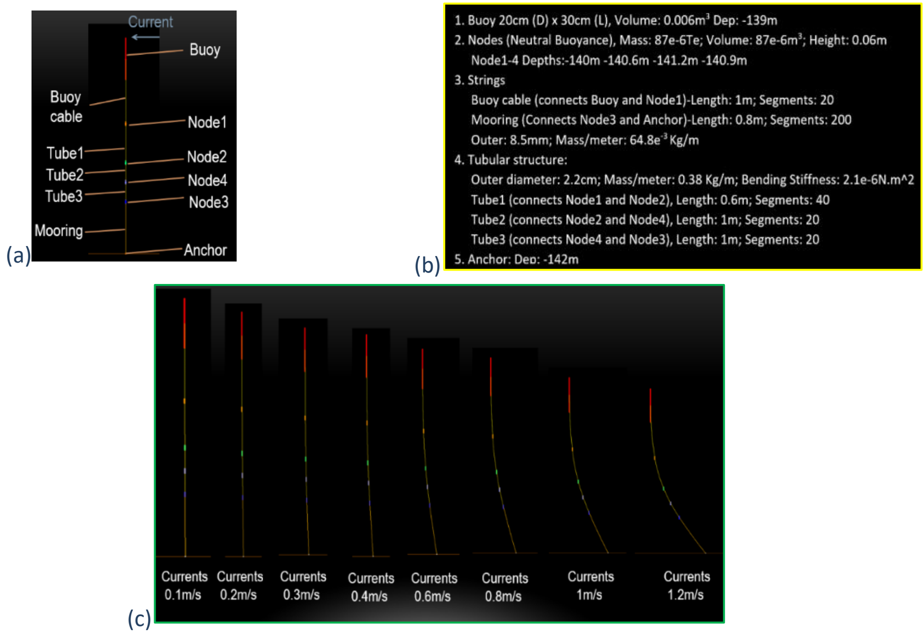


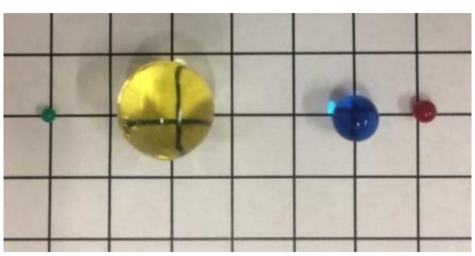

**Figure 5. Illustration of the Simulation of a 4-node UICSA structure using OrcaFlex**

## 2.3. Investigated alternative approaches to construct UIS [4,5]

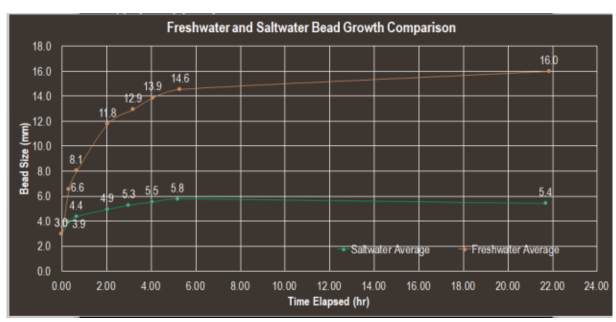
One of the most exciting achievements of our year-one effort is investigating alternative ways to construct the UIS. The pump-based UIS scheme, i.e., *mechanical-based expansion (MBE)*, has been studied and used in many naval applications. For example, RE2 Robotics has developed the underwater inflatable robotic arm under ONR funding. However, MBE has some deficiencies:

a) The pump will be frequently turned on to inject water into the enclosure to maintain sufficient structure rigidity, which consumes additional energy.
b) The underwater pump increases the stowed volume.

For these reasons, we explored more energy-efficient UIS construction approaches. We found two promising approaches: the physics-based expansion (PBE) approach using hydrogel beads and the chemical-based expansion (CBE) using polyurethane expanding foam.



(a) Hydrogel beads in dry, swollen, and two dehydration states




(b) Comparison of the expansion of hydrogel beads in freshwater and saltwater

**Figure 6. Illustration of the expansion of the hydrogel beads under different conditions**

The hydrogel beads are water-absorbing polymers that can transform from a dense, dehydrated form into a gel with a larger volume by absorbing water molecules into their structure. One very attractive feature of the hydrogel beads is their ability to expand when they contact water. *Such expansion does not need* *external energy*. Using low-cost, off-the-shelf hydrogel beads, experiments were conducted at FAU HBOI and OME to gain an initial understanding of this type of material. As shown in Figure 6a, the beads could expand substantially in freshwater. The " freshwater average" curve also confirms this in Figure 6b. The issues with the off-the-shelf hydrogel beads are 1) the expansion was substantially less in saltwater and 2) It took a relatively long time (several hours) to achieve the final expansion volume. However, it is worth pointing out that rapid swelling hydrogel material has been studied extensively for various medical applications. In this regard, a fast-swelling hydrogel that can expand under the condition of a deep ocean (high pressure, low temperature, and saltwater) will be worth pursuing.

In the CBE approach, polyurethane foam or expanding foam was investigated. Such foam, in general, is developed for the construction industry for sealing, grouting, structural reinforcement, and concrete lifting. In this case, the expansion was realized through chemical reactions – an expansive, exothermic reaction between two liquids (A-side and B-side). As with hydrogel beads, in collaboration with expanding foam manufacturer – HMI Corporation, a series of experiments were conducted at HBOI to gain insight into this type of material and their applicability to construct UICSA structures and possibly other undersea structures. The main focus under testing was HMI HF402. Some interesting properties of this material include:

- Fast expansion - it took about one minute for the reaction to begin (Figure 7). The foam was fully cured within *five minutes*.
- An expansion ratio of ~700% was achieved with HF402. Even a higher expansion ratio may be possible with better control of the material mixing.
- Very importantly, *the foam is capable of expansion in saltwater*.

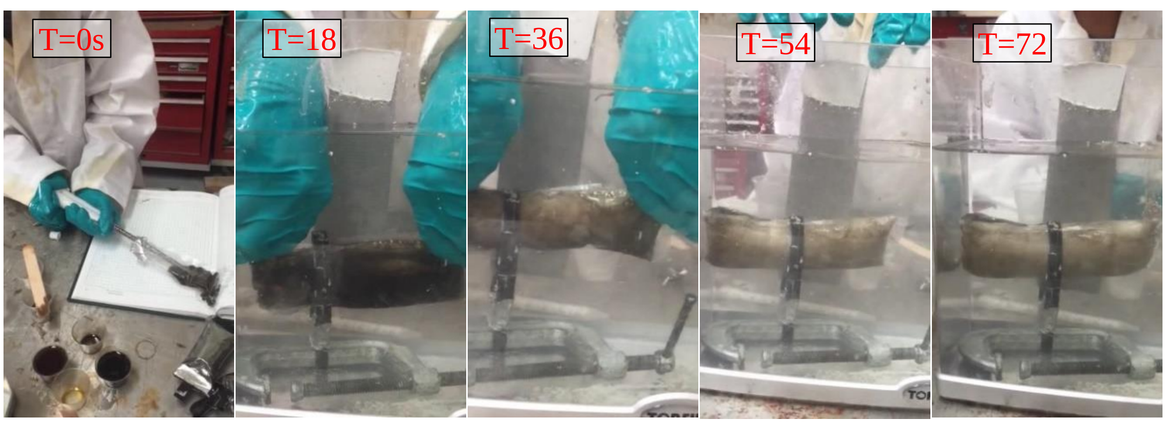



**Figure 7. Time lapsed sequence (at 18-second intervals) to illustrate the expansion of HF402 foam**

The ability of the foam to withstand high pressures was tested in a chamber containing pressurized water (Figure 8). A hand-powered pump was used to adjust the pressure. A sample with an initial volume of 150mL and a weight of 21.5g was placed inside the chamber. The pressure was gradually increased to 1200psi (i.e., 3000ft of depth). The sample retained the initial volume of 150mL, albeit the weight was increased to 108.6g due to water absorption.

(a)  (b)

**Figure 8. (a) Pressured water test chamber (b) REU Summer Intern Shadi Bavar and HBOI machinist Mike Young during the experiment**

## 2.4. Continued effort to investigate alternative approaches to construct UIS [6]

Building upon the initial investigation of the development of the *physics-based expansion* (PBE) approach using hydrogel beads and the *chemical-based expansion* (CBE) using polyurethane expanding foam – two alternative UIS designs address the deficiencies of the traditional *mechanical based expansion (MBE)* UIS, one of the subsequent focus has been developing further understanding of these alternative UIS designs. CBE has two advantages over MBE: a) *energy-efficiency* — power will only be needed during the initial mixing process (i.e., minutes) to induce the expansion; no external power will be required to sustain the structure; b) *durability* —the solid rigid structure that won't be subject to wrinkling and buckling. A CBE UIS can be recovered after the mission is over. The sensors and other components will need to be removed from the foam for repackaging for redeployment. The CBE design is more suitable for *disposable, single-mission deployment* using low-cost sensors (i.e., hydrophones) and electronics. The CBE-based rigid UIS can be fabricated on-demand on the "mother vessel" deck carrying raw material and different molds. Sensors can be secured to locations on the pre-inflated UIS that will ultimately allow them to move into the precise working positions once the foam expands and cures. The amount of foam expansion will be controlled by the liquid resin volume included in the structure.

**Table 1: Benefits and detriments of different UIS options [6]**

| UIS Options | MBE | CBE | PBE | |
|---|---|---|---|---|
| | | | Hydrogel beads | Aquagel |
| Initial volume | Large | Small | Small | |
| Initial weight | Heavy | Light | Light | |
| Initial expansion speed | Quick (minute-level) | Quick (minute-level) | Slow (~ hours) | Fast (~minutes) |
| Power consumption for expansion | Bulky battery | Minimum (initial resin mixing) | Not required | |
| Power consumption for maintenance | Period inflation required | No | No | |
| **Noise from the UIS** | Pump inflation | No | No | |
| Durability (expanded structure) | Thin-film tube | Rigid beam | Semi-rigid beam* | |
| Reusability | Yes | No | Yes | |
| Cost for expansion required components and materials | Pump: low to medium/high**<br>Battery pack: medium/high** | Low | Low | Medium*** |
| Fabrication process complexity | Easy | Medium | Easy | Easy |
| **Expansion in Sea Water** | Yes | Yes | No | **Yes** |

* The stiffness of PBE UIS is determined by the packing density of the WSM and WSM swelling ratio. Infilling leakage may occur when the WSM density is over a maximum allowance at 5.2/1000 (WSM initial vs. target volume);

** Cost increases with water depth;

*** Aquagel is priced at $5/g. One gram of Aquagel can achieve a swollen volume of 36mL.

The PBE design using recoverable water-swollen material (WSM) such as hydrogel beads will be preferred for the applications requiring the UIS to be reusable and re-deployable. The PBE design employs a permeable tube to form the UIS to allow contained WSM to contact the surrounding water. The PBE UIS absorbs water from the surroundings and expands to desired geometry for data collection. The infilled WSM absorbs water molecules to achieve volume expansion and can shrink back to its initial volume through dehydration, which leads to reusable array design. WSM-based PBE design can accomplish the expansion process without *external power or additional intervention* after deployment. The swollen WSM contributes to a semi-rigid solid beam. The rigidity can be controlled by the density of the WSM inside the structure. The PBE UIS leads to better performance than the MBE UIS due to the external-energy-free passive expansion and the robustness again potential damages to the structure (i.e., punched holes or animal bites). In Table 1 above, we compare the pros and cons of the MBE, CBE, and PBE designs, where red cells represent restrictions, the acceptable conditions are marked in yellow, and the advantages are shown in green.

The PBE design utilizes WSM as infilling to achieve expansion after morphing. One typical WSM is the hygroscopic gel (hydrogel) of superabsorbent polymer (polyacrylamide and polyacrylate). The hydrogel can grow over 250 times [5] and shrink back to its initial volume through dehydration, leading to a reusable array design. Unlike MBE and CBE, the PBE design employs a permeable tube to form the UIS to allow WSM to contact the surrounding water. Hydrogel beads can be utilized as the infilling in the nylon sleeve to create the UIS. The hydrogel beads have a relatively slow swelling speed (several hours).

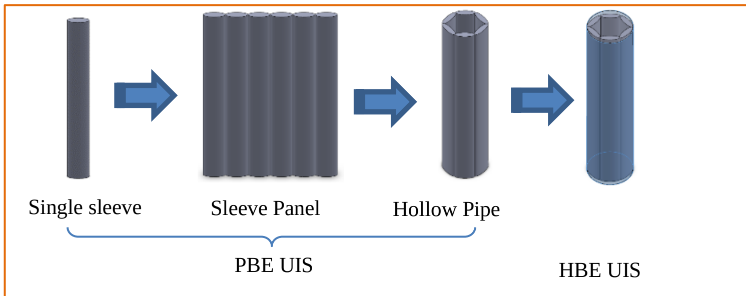



**Figure 9. PBE and HBE UIS design concept**

In contrast, the MBE (with a powerful pump) and CBE UISs can fully expand within several minutes. The PBE design is practical for small diameter nylon sleeves where reasonable stiffness can be achieved. A hollow pipe-shaped design can be employed to achieve sufficient rigidity for large-span structures. A set of small diameter nylon sleeves is combined to form a pane in this design. The panel can then be rolled to create a large diameter pipe, as shown in Figure 9. PBE design permits a larger surface area to contact water and expands quicker than a solid beam structure. In a numerical study conducted using Orcalflex [5], sensors installed on the UISs could keep the deflection within 1/10th of the targeting wavelength [5].

Low-cost WSM, such as the hydrogel beads, may take several hours to fully grow under normal pressure, which may elevate the risk of PBE UIS entangled and twisting due to ocean currents and marine life. This can be addressed by using fast swelling WSM (i.e., Aquagel: https://akinainc.com/polyscitech/products/aquagel/index.php), albeit at a higher cost. Another alternative, inspired by the discussion with Dr. Michael Traweek at ONR Code 32, is a hybrid design (HBE) that integrates MBE and PBE. Such HBE can complete the initial expansion quickly (via MBE) and requires no additional energy to maintain structural stiffness (through PBE). The HBE UIS uses watertight films as an external layer, permeable fabrics as an internal layer, and WSM as the infilling to realize the PBE UIS expansion. The outer layer ensures water retention after the initial expansion through water injection. After the initial pump injection, the flat structure turns into a thin-wall tube containing pressurized water. It maintains specific stiffness against external forces. In the meantime, the permeable inner layer allows WSM infilling to contact water and start the expansion. The internal PBE layer eventually becomes a solid beam after full expansion and reinforces the rigidity to support long-term deployment. The expansion process of HBE UIS is illustrated in Figure 10.

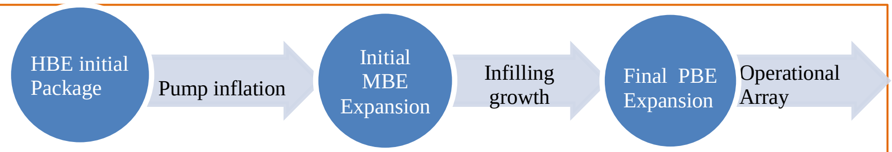



**Figure 10. HBE design expansion process**

## 2.5. Experimental study of PBE UICSA

In year two, our experimental study focused on PBE and HBE UIS. HBOI team first evaluated the hydrogel beads' performance at different pressure levels using a water pressure chamber. Hydrogel beads with different colors were placed in the sealed chamber. The chamber was pressurized to reach 1241kPa (equivalent to 125 m depth). Another set of beads was placed in a water cup under normal pressure as a controlled trial. The beads could fully expand in pressurized water, as shown in Figure 11a. The fully swollen beads under atmospheric pressure are shown in Figure 11b. After the swollen beads were retrieved from the pressure chamber after six hours, the diameters of these swollen beads were roughly 14mm (Figure 11c), and the diameters of the swollen beads submerged in the water cup were about 15.8mm (Figure 11d).

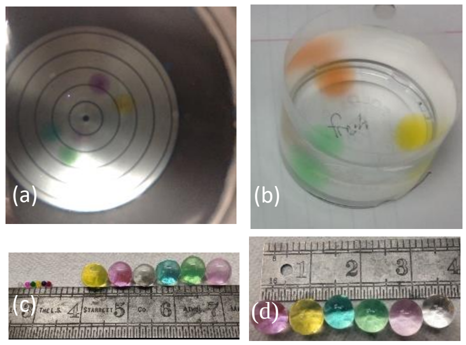



**Figure 11. Hydrogel beads performance**

In comparison, the diameters of the dry beads were approximately 3.2mm. Therefore the fully swollen beads were about the same size regardless of the applied pressure. Some of the issues with the hydrogel beads include the slow swelling speed, and the expansion ratio may be significantly reduced by the electrolytes in a solution, like seawater. An alternative is to use Aquagel from AKiNA Inc., particularly Aquagel-XS, as the WSM infilling in a PBE UIS. Aquagel-XS is chemically similar to standard super porous hydrogel but modified to have higher strength [12]. The swelling capacity of Aquagel-XS is around 20 to 30 times. From our previous study, Young's modulus of infilled hydrogel beads can reach up to 70MPa. We expect Aquagel-XS to reach a similar level of performance. The year-three study evaluated the Aquagel-XS used in PBE UIS through lab tests to assess Aquagel-XS. We are especially interested in the following properties:

- Expansion ratio;
- Expansion speed under different pressure levels (i.e., water depths);
- Expanded structure strength.

HBOI team conducted the feasibility test of the 4-element HBE-based UICSA [15]. Figure 12 presents the expansion process of the 4-element HBE-based UICSA. The prototype required an underwater pump at the bottom end for water injection. The top-end needed to be connected with an opened pressure relief valve to allow the flow from bottom to top and ensure that the internal nylon sleeve is submerged. The bottom end was also tethered with weight, and the top end was secured with a crossbar over the water tank to keep the array stretched. Figure 12a reveals the initial state of the structure, which is flat and slack. Once the pump started to inject water into the array, the UICSA became stiffer due to the pressure difference. Then, the hydrogel beads grew to a large volume and reinforced the structure stiffness, as seen in Figure 12b. It is worth noting that the UIS was tilted to ensure that the structure remained underwater since the tank was not sufficiently tall.

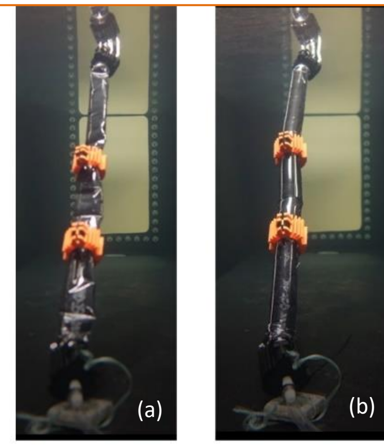



**Figure 12. 4-element HBE based UICSA expansion process**

We also designed a 7-element PBE prototype using hydrogel with a total length of 2.1m at the System and Imaging Laboratory (SAIL) at HBOI. The prototype adopts the aforementioned hollow pipe design consisting of six sleeves. The combined 6-sleeve panel is shown in Figure 13a. Figure 13b depicts the prototype with the sensor holders installed at pre-determined locations. The fabricated PBE UIA prototype was then submerged in a test tank at HBOI SAIL to validate the structural performance. The expanded PBE UIA is shown in Figure 13c. The compression ratio of the prototype with sensor mounts is 4.28. *The compression ratio without the sensor mounts will be significantly higher. Our estimate will be close to 40.*

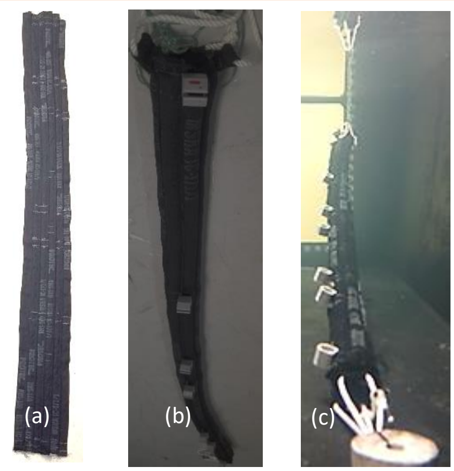



**Figure 13. PBE UIS prototype in testing in the SAIL water tank**

One significant achievement in our year-two effort is that this 7-element PBE prototype was successfully used in our initial field test at the HBOI channel. The Harbor Branch channel outlet connects with Indian River Lagoon and introduces the currents from the East to the West. To avoid multipath arising from the floor/walls, the deployment site depth needs to be over 15 feet. The boat employed for array deployment could drift under the waves, currents, and wind during the field test. To mitigate the impact of the current in the channel, the array was deployed from a boat (Harbor Branch Pontoon #2) tied to the seawall post. Site C turned out to be the best option because it is close to the seawall and is sufficiently deep. The purple pentagon marked in Figure 14 represents the Pontoon #2 parked perpendicular to the seawall with the bow reaching Site C.

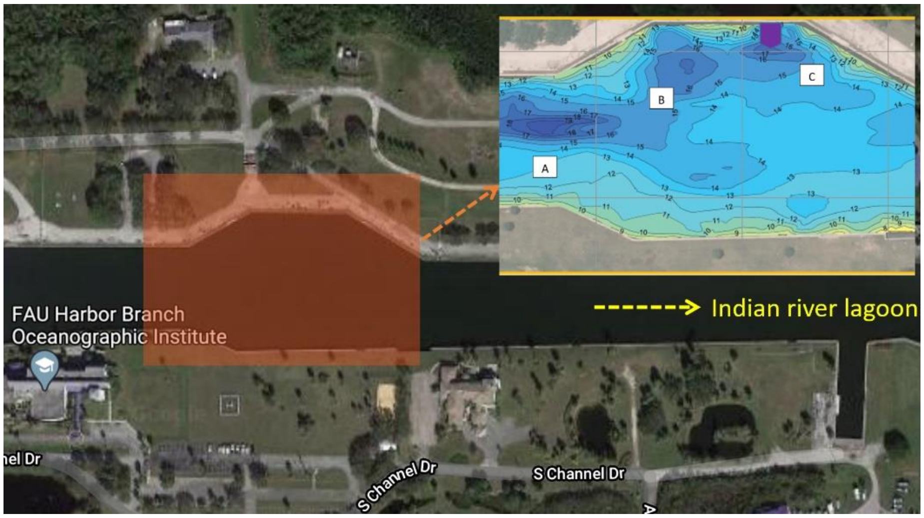



**Figure 14. Harbor Branch channel and site selection.**

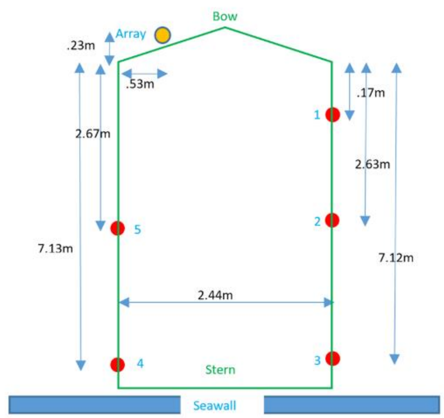



**Figure 15. Field test configuration.**

Since the channel serves as a habitat for marine animals, such as dolphins and manatees, the power of the sound source used in the experiment was required to be below 60 dB. As the embedded Aquarian H2a hydrophone can distinguish such signal levels within 15m range, the speaker must be deployed from the boat instead of a far-field location. We pre-expanded the prototype in the Systems and Imaging Lab (SAIL) indoor tank overnight to meet another four-hour time limit to operate in the channel. We examined it to ensure that the desired stiffness was achieved before the field test the next day.

The boat was anchored using a three-point mooring during the test to mitigate drifting. The stern was tied to the post next to the seawall. After the array was secured at the desired depth, an INSMY IPX7 waterproof speaker was deployed from pre-determined locations around the boat at a 0.5 m depth, pointing towards the array. The experimental layout for the acoustic tests is shown in Figure 7. The red dots denote the speaker's locations, and the yellow dot indicates the array position. At each location, a monochromatic measurement where the speaker played a looped 2.5 kHz single tone and a multi-frequency measurement with the speaker emitting a chirp signal of bandwidth 300 Hz centered at 2.5 kHz. The deployed array recorded the data using two Zoom H6 data loggers with a sampling frequency of 96 kHz. We also deployed a 7-element co-prime array on a rigid structure and repeated the same experiments as that for the UICSA prototype.

To validate the acoustic performance of the UICSA, our collaborator at Temple University processed both the single tone and the chirp measurements from the field test. Due to the constraints imposed by the channel dimensions, the speaker positions 1, 2, and 5 in Figure 15 are closer to the array and, thus, exhibit a much higher deviation from the far-field source approximation than positions 3 and 4. Therefore, these were excluded from performance evaluation for the case of 2.5 kHz single tone data. On the other hand, for near-field source localization with the chirp signals, we considered speaker positions 1 and 2 only.

Table 2 shows the nominal DOA for speaker positions 3 and 4 based on the ground truth, with $\theta_t$ and $\theta_b$ denoting the respective directions of the speaker relative to the top and bottom hydrophones of the co-prime array and $\bar{\theta}$ being the average DOA. Ideally, the angular spread across the array should be zero under far-field conditions. Although the considered speaker positions do not satisfy the far-field source's exact condition, we expect reasonable estimation accuracy with far-field processing. Since only a single acoustic source was present per experiment, we employed OMP with a sparsity level set to 1 for DOA estimation. For both the UICSA and the rigid array, we used measurements from speaker position 3 for calibration and retained the exact calibration for processing data from position 4. The last two columns of Table 2 provide the resulting DOA estimates for the UICSA and the rigid array, respectively. The estimated DOA using both arrays falls within the corresponding nominal angular spread and is close to the corresponding average DOA for each speaker position. These results corroborate that the UICSA provides similar performance to a rigid co-prime array.

**Table 2. Nominal and Estimated Source DOAs.**

| Speaker | Nominal DOA (deg) | | | DOA Estimate (deg) | |
|---|---|---|---|---|---|
| | $\theta_t$ | $\theta_b$ | $\bar{\theta}$ | UICSA | Rigid |
| Position 3 | 3.77 | 17.68 | 10.72 | 10.54 | 10.72 |
| Position 4 | 3.88 | 18.16 | 11.02 | 12.88 | 9.64 |

The normalized near-field beamforming spectra are depicted in Figure 16, where the actual source positions are marked with "o." The array is aligned along the positive y-axis. At a propagation speed of 1500 m/s for sound in water, the range resolution is 5 m for the 300 Hz bandwidth, causing the main lobe to be extended in range. However, the peak intensity value, which is the source location estimate and marked as "+" in Figure 16, is very close to the ground truth for the UICSA. Only position 1, which is self-calibrated, is accurately estimated for the rigid array. For position 2, although the direction of the source is resolved, the location estimate exhibits a significant bias. We later discovered that the first hydrophone malfunctioned during the field experiment. This specific hydrophone is *essential* for reliable processing. The omission of this hydrophone reduces the degrees of freedom offered by the co-prime array. Its loss due to malfunctioning leads to an erroneous estimate by the rigid array.

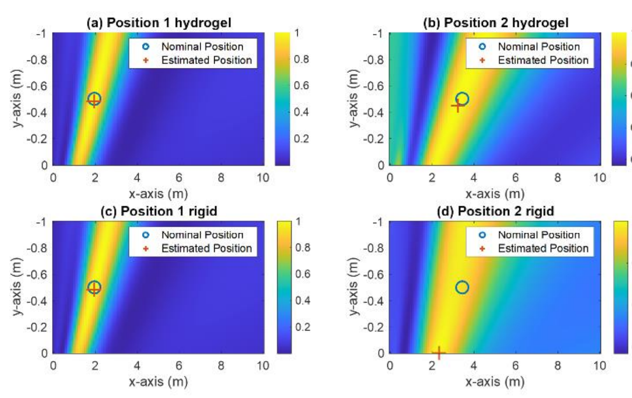


**Figure 16. Normalized near-field beamforming spectra.**

### 2.6. Development of the low-cost subsea dataloggers

Low-cost subsea dataloggers were also developed to support the UICSA prototype tank and field tests. Two datalogger designs have been investigated in this work with the hope of using off-the-shelf technology to replace what could previously only be done with expensive custom hardware. The processors used in these concepts, the Teensy 4.0 Audio Adapter and the CTAG BEAST, were initially designed for musicians who require the ability to manipulate multiple audio channels simultaneously. This capability, however, also enables the construction of dataloggers capable of recording perfectly synchronized multi-channel audio – a requirement for passive phased sonar arrays. Each datalogger carries the additional benefit of low power consumption, which permits the array to be deployed for several hours before recovery. Future versions of the dataloggers are expected to have mission durations comparable to existing commercial systems. This paper follows the development process of both concepts and compares each of their performance. The first concept, the Teensy, consists of two Teensy 4.0 control boards, each sandwiched between two Teensy Audio Adapters. This assembly can record up to eight channels of audio in near-perfect sync. The second concept, the BEAST, consists of a BeagleBone Black single-board computer augmented with a CTAG BEAST cape. This system is capable of recording eight channels of perfectly synchronized audio. These systems were tested in the field with a four-element co-prime sonar array.

For this project, any candidate systems developed would more or less share the same hydrophone array. The systems would use Aquarian H2a-XLR hydrophones in a co-prime configuration. The array structure is covered in more detail in [6]. These hydrophones, while expensive, are readily available and still cheaper than industry solutions.

After the hydrophones, the next most important part of the system would be the ADCs. These would need to handle ideally eight or more channels of audio data at a sampling rate of around 25 kHz (this was selected to provide plenty of headroom for an array listening at approximately 2.5 kHz) and with a sample depth of at least 12 bits. Such ADCs exist on the market but finding one with the proper specifications is difficult. Ideally, each system would use a single ADC to avoid synchronization issues between ADCs. Next, each system would require a processor to handle and organize the incoming digital audio data. Such a processor would need to be fast and capable enough to record a high-sampling rate. Ideally, this should be possible without reducing the bitrate or sampling frequencies of the audio streams. This kind of power can be challenging to find in small form factors but is becoming more common with the rise of consumer-grade SBCs. Finally, the processors would require a storage medium for the audio data. This would need to handle large amounts of data in real-time like the processor. The obvious solution to this storage problem would be a microSD card. The only limitation is that these cards need to be paired with an appropriately sized RAM buffer to avoid frequent write operations, which can slow the system considerably. This is especially the case as the number of channels increases.

The first solution considered was based on the Teensy 4.0 microcontroller, a powerful board that comes with off-the-shelf audio processing expansions. When combined with two audio shields, the Teensy is theoretically capable of recording four channels of synchronized mono audio at 44.1 kHz with a sample depth of 16 bits. These audio shields stack onto the top and bottom of the Teensy, resulting in the assembly shown in Figure 17. The total cost of a teensy datalogger is approximately $50.

**Figure 17 - The Teensy datalogger**

The Teensy 4.0 is one of the more powerful Arduino-compatible boards. It is equipped with a 0.6 GHz CPU, 1 MB of RAM, and various low-level interfaces. Combined with an SGTL5000 processor on each audio shield, it can handle a significant amount of data in real-time. That said, the Teensy does have some significant limitations. First, the configuration used here can only support four audio channels. Its small RAM also means that it cannot adequately buffer SD card writes when recording at 44.1 kHz. Instead, it must first be down-sampled to 22.05 kHz to avoid falling behind and buffer overruns. This, however, is generally offset by its small form factor and low power consumption, both of which make it ideal for small deployable sonar systems.

The second solution was a BeagleBone Black equipped with a CTAG BEAST audio processing cape. This system can process up to eight simultaneous mono inputs at a frequency of 192 kHz and a sample depth of 16 bits. This system can be purchased pre-assembled and pre-loaded with the custom Bela OS, a derivative of Xenomai Linux. The assembly can be seen in Figure 2 next to the Teensy. The BEAST costs approximately *$450*. The BeagleBone Black provides all the processing power for the BEAST system. It is equipped with a 1 GHz CPU, 512 MB of RAM, and various onboard networking and other interfaces. All of this makes it significantly more powerful than Teensy. Interestingly, early battery life tests do not indicate correspondingly higher power consumption. Both the BEAST and the Teensy seem to require roughly the same power. The BEAST's large RAM means that it has no difficulty recording eight channels of 44.1 kHz data. However, the BEAST comes with its own set of disadvantages as well. The high processing power is handy, but the size of the platform limits the utility; as shown in Figure 18, the BEAST is much larger than the Teensy. Indeed, the BEAST requires much larger housing than the Teensy. Another limitation of the BEAST is in the way it is programmed. Programming the BEAST is done using the Bela IDE, a web-based programmer hosted on the BEAST itself. Unfortunately, this IDE is not available without the BEAST, so it can be a difficult platform to program remotely. This contrasts with Teensy, which requires an adequately configured Arduino installation to write code [7]. This code can then be verified, saved, and handed to someone else for programming.

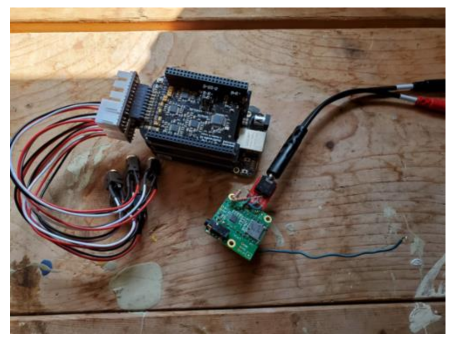


**Figure 18 The BEAST (top) and Teensy (bottom)**

The completed housing with everything connected and integrated can be seen in Figure 19. This housing can protect the datalogger down to at least 100 m, providing power for missions several hours long and being reset with no need to open the enclosure and risk the integrity of the watertight seals.


**Figure 19 - Completed housings for the Teensy and BEAST**

After completing the construction of the Teensy, we tested it in the field with a mockup of the UICSA, shown in Figure 4. This mockup was a simple rigid array designed to float vertically under the water surface. The rigid array mimicked the first 4-element segment of the 7-element non-uniform array. An underwater speaker played a 2.5 kHz tone and served as the sound source

This speaker was held just below the water's surface at 2.6 meters in front of the array, as shown in Figure 20. These tests were conducted without housing, with the Teensy sitting on the dock next to the array. The Teensy's recording performance was compared against a Zoom H6 Handy recorder. Both recorders were configured to capture 90 seconds of audio throughout two trials. The array location, sound source location, frequency, and recording gain were all held constant between trials. Since a single array was used for data collection with Teensy and Zoom, the measurements were performed sequentially. The ambient noise is expected to vary across the Zoom and Teensy measurements.

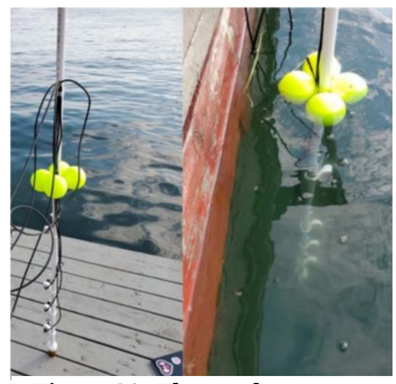


**Figure 20. The mockup array. Test setup on left and testing configuration on the right**

The data collected from both loggers were first filtered to remove out-of-band noise and then processed using conventional beamforming under far-field assumptions to estimate the source direction. For both loggers, the data from trial one were used for calibration. The calibrated beamformer was then used to estimate the source direction from trial two measurements. Due to the constraints imposed by the field test environment and the array length, the speaker position is not truly in the far field of the array. Therefore, the source direction varies from sensor to sensor rather than is constant. The nominal source direction ranges from -4.40° to -17.10° with an average value of -10.75°. The estimated directions are listed in Table 3 for both data loggers. We observe that the DOA estimates are within the nominal DOA range and close to the average value in both cases. The results of this test indicate that the Teensy performed well, with source estimation results comparable to that obtained with the Zoom. The low noise level and the excellent frequency response make the Teensy a promising candidate for further development.

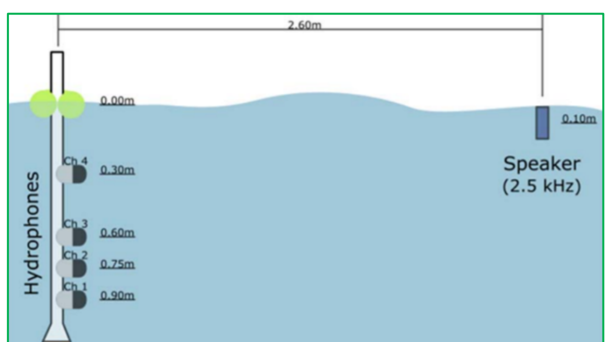



**Figure 21. Experimental setup**

**TABLE 3. DOA Estimates Using Data from Teensy and Zoom**

| Data logger | Trial 1 (used for calibration) | Trial 2 |
|---|---|---|
| Teensy | -11.37° | -10.65° |
| Zoom | -10.63° | -8.94° |

## 2.7. UICSA Release Test at FAU Acoustic Test Tank

A fully submersible seven-element UICSA array was constructed with the data logger ready. There are two improvements compared with the prototype built in the earlier effort:

1) The data logger is integrated into the UICSA array. This allows the array to be fully submerged, whereas the data logger was constrained in the dry environment in early tests.
2) Aquagel® superporous hydrogels from PolySciTech were used to build the array.

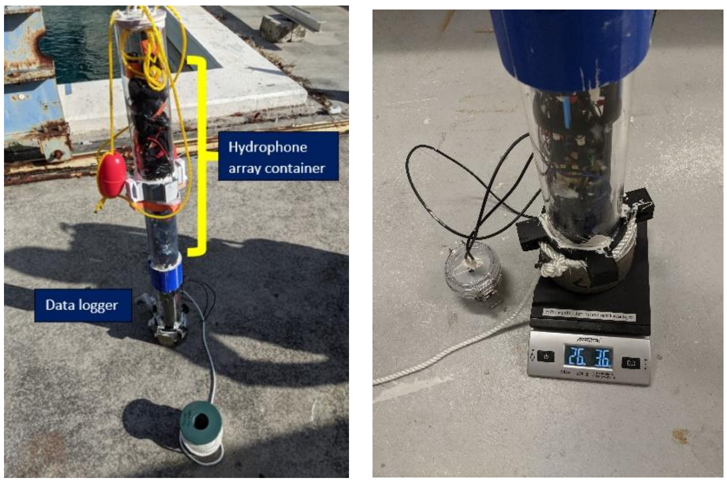



**Figure 22. Aquagel based 7-element UICSA array**

While we previously validated the feasibility of building a UICSA array using low-cost hydrogel beads, one fundamental limitation was that such material would not expand in salted water. It also took a long time (i.e., hours) for the material to be fully expanded. Aquagel allows the preparation of hydrogel systems that change their dimensions in ***about one minute***. The material achieves a similar expansion ratio in ***both fresh and salted water***. One disadvantage of the Aquagel is the cost. One pound of Aquagel costs about $700, whereas one pound of conventional hydrogel costs less than $10.

A 7-element array was built using the material (Figure 22). The array essentially has two sections. The top section is the container of the hydrophone array elements. The bottom is the data logger housing. The array has a total length of 55”, a diameter of 6”, and a dry weight of about 26lb.

The array deployment was conducted at the FAU OME Acoustic test tank. The array was pre-assembled and dropped from the catwalk from about the tank (Figure 23a). A mechanical latch will be released from the impact of the array hitting the tank floor. This will allow the array to be extended from the housing and inflate (Figure 23b).

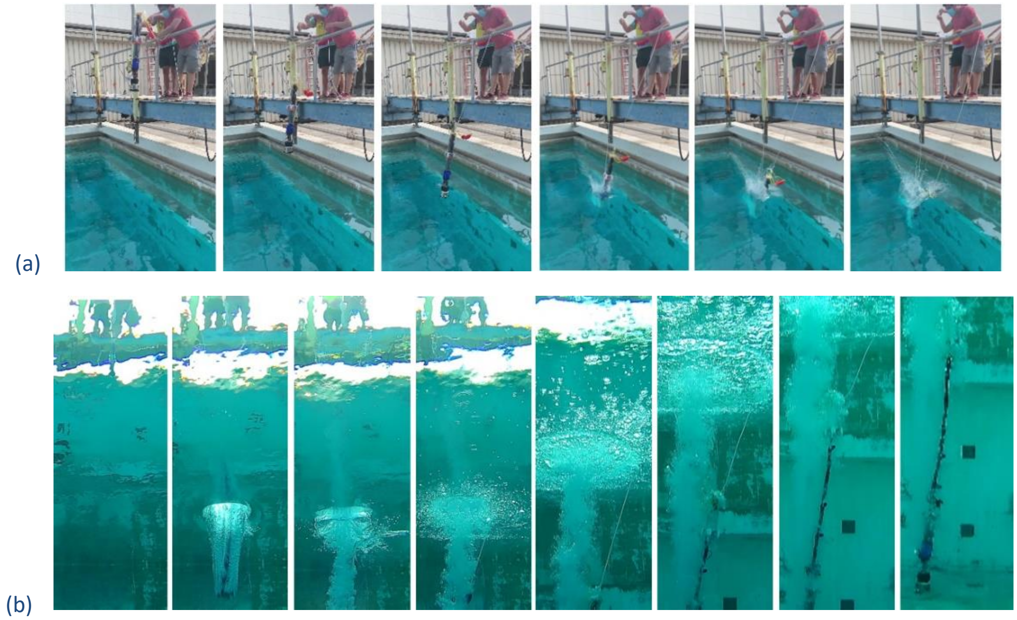



**Figure 23. Deployment of the 7-element array. (a) Video frames capture the release process above water. (b) Video frames capture the underwater portion of the release process.**

The array becomes fully expanded in less than 10 minutes (Figure 24)

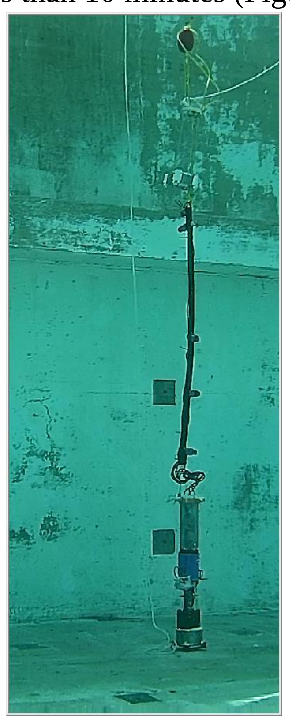


**Figure 24. The array status ten minutes after the release. The array can be seen to be fully expanded.**

## 2.8. Field Test UICSA at Lake Denton

As the final task in the project, a field test was conducted on September 23, 2021, at Lak Denton, Florida (Figure 25), where HBOI maintained a test platform. The Aquagel-based hydrophone array previously tested at the FAU OME test tank was again deployed.

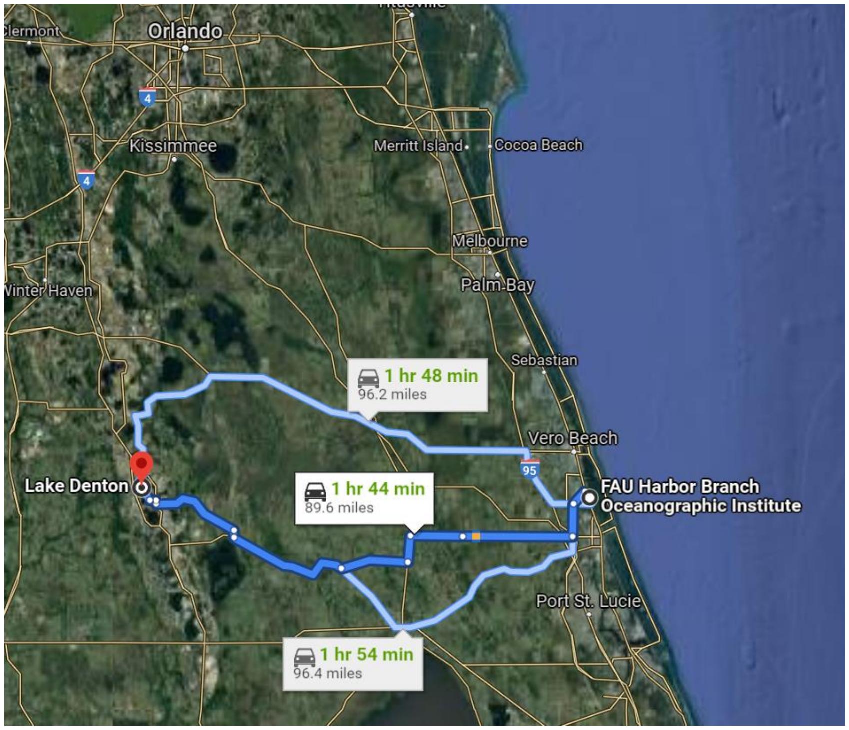



**Figure 25. Lake Denton Test Site**

During the tests, the arrays were pre-assembled and prepared onshore. They were then carried using a kayak to the site in the middle of the lake for a release test (Figure 26).

**Figure 26. Postdoc Associate Dr. Yanjun Li and graduate student Casey Den Ouden prepare the arrays for the deployment tests**

The experiment's main objective was to validate the array can achieve the required rigidity during field deployment. At the start of the deployment, the array was thrown into the water from the kayak. The array was deployed to a depth of 30 ft and then allowed a specific amount of time (10 minutes) to solidify. The boat then moved away to conduct acoustic tests using a bow-mounted speaker (Figure 27).

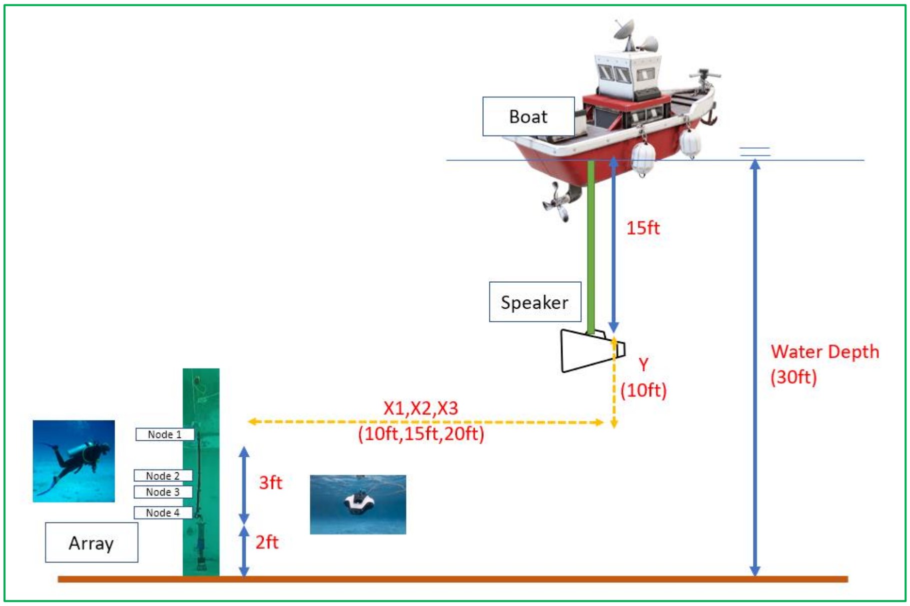



**Figure 27. Lake Denton test setup.**

The initial plan involved using a mini-ROV to image the deployment process in the test tank. Unfortunately, the ROV motors malfunctioned during the experiment. As a result, we could not record the actual deployment process as we did in the FAU OME test tank. The ROV camera captured the expanded array (Figure 28a). A diver from the HBOI diving team manually inspected the array to validate its rigidity (Figure 28b).

(a)

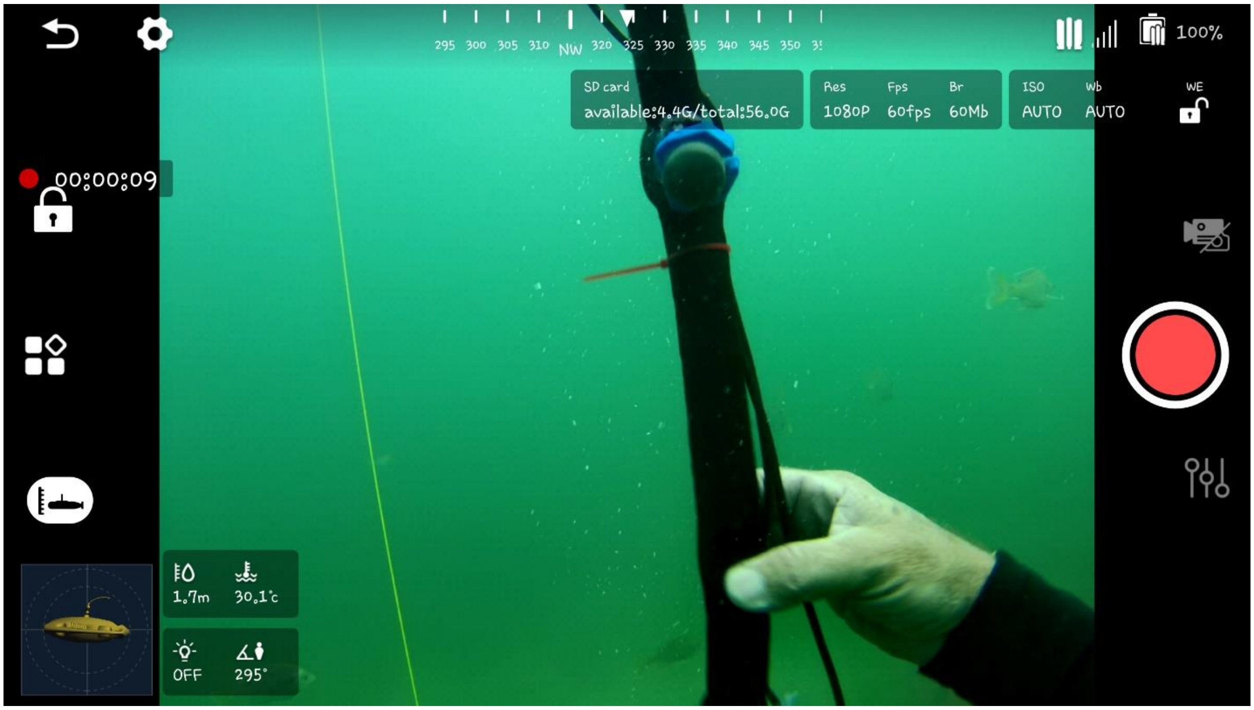
(b)



**Figure 28. (a). Expanded array captured using mini-ROV. (b) The diver validated the array rigidity after 10 minutes.**

## 3. IMPACT/APPLICATIONS

We regard this project as a paradigm shift in how to develop/design UIS. To this end, we investigated various aspects of developing energy-efficient approaches to realize underwater inflatable structures. We believe the outcome of this project help to address many issues with the existing pump-based UIS design: requiring energy to sustain the structure, interference to the hydrogen array operations (i.e., noise from outgassing, pump, etc.).

The work covered concept validation, design, prototyping, laboratory validation tests, and field performance tests. In particular, the UIS design concept with four different approaches, namely, MBE, CBE, PBE, and HBE, was detailed. The HBE/PBE-based UICSA prototype was fabricated and deployed in the lab test tank, which validated the prototype's performance as proposed. We validated the PBE-related infilling WSM's performance, which can swell and maintain its integrity at > 100-meter depth in the pressure chamber test. Using measurements with a PBE design in field tests, we demonstrated that a UICSA could accurately estimate sources.

While substantially more work will be needed to realize the vision of water swelling material-based energy-efficient UIS, this project laid a solid foundation for such an endeavor. We envision the alternative concepts (i.e., MBE, CBE, PBE, and HBE) explored within can be used as the "building blocks" to realize different underwater structures instead of a solid cylindrical beam. For example, two-dimensional sonar array configurations can be realized using Aquagel-based PBE "building blocks."

# 4. TRANSITIONS

Leveraging the results from this project, the PI has submitted two SBIR proposals in collaboration with HMI Corporation (neither was funded):

- NOAA SBIR NOAA-OAR-OAR TPO-2019-2005899: Underwater Expandable and Reinforced Cast (U-CAST) for Rapid Coral Restoration

- NAVY SBIR N204-A03: Focus Area 2: Underwater Inflatable Array Using Hydrofoam and Water-Swelling Material Integration

# 5. PERSONNEL SUPPORTED ON THIS PROJECT

| | | |
|---|---|---|
| PI/co-PIs: | Dr. Bing Ouyang | |
| Postdoc Researcher: | Yanjun Li | |
| Graduate Student: | Casey Den Ouden | |
| | Ether Weber | |
| | Lorenzo Michieletto | (University of Rome) |
| Undergraduate Students (Summer Internship) | | |
| | Jordan Thomas | |
| | Shadi Bavar | |
| | Chloe Alex Schaff | |

# 6. RELATED PROJECTS

N/A

# 7. PUBLICATIONS ACKNOWLEDGING ONR GRANT N000141812469

Journal Papers


[1] Y. Li, B. Ouyang, T. Zhou, J. Thomas, S. Bavar, E. Weber, L. Michieletto, T.-C. Su, and F. Ahmad, "Laboratory and Field Experimental Study of Underwater Inflatable Co-prime Sonar Array (UICSA)," Journal of Civil Engineering and Construction, (Accepted).


Conference Presentations


[1] B. Ouyang, Y. Li, T. Zhou, T. C. Su, F. Dalgleish, A. Dalgleish, and F. Ahmad, "Compressing two ways: the initial study of an underwater inflatable co-prime sonar array (UICSA)," in Compressive Sensing VII: From Diverse Modalities to Big Data Analytics (Vol. 10658, p. 106580H). SPIE, 2018.

[2] Y. Li, B. Ouyang, F. Dalgleish, A. Dalgleish, T. C. Su, S. Baver, J. Thomas, T. Zhou, and F, Ahmad, "Mechanical design consideration of an underwater inflatable co-prime sonar array (UICSA)," in OCEANS 2018 MTS/IEEE Charleston (pp. 1-8). IEEE, 2018.

[3] Y. Li, J. Thomas, B. Ouyang, T. C. Su, T. Zhou, and F. Ahmad, "Design and experimental study of Underwater Inflatable Co-prime Sonar Array (UICSA)," in Proc. OCEANS MTS/IEEE Seattle, 2019.

[4] Y. Li, A. Schaff, S. Bavar, B. Ouyang, T. Su, T. Zhou, F. Ahmad, "Design and Implementation of Underwater Inflatable Co-prime Sonar Array (UICSA)." In Proc. Global OCEANS 2020 Online Conference, 2020

[5] C. A. Schaff, Y. Li, B. Ouyang, C. D. Ouden, T. Zhou, F. Ahmad, "Development of a low-cost subsea datalogger for passive phased sonar arrays," Proc. SPIE 11730, Big Data III: Learning, Analytics, and Applications, 2021

[6] Y. Li, C. A. Schaff, G. Sklivanitis, B. Ouyang, T.-C. Su, and F. Ahmad, "Comprehensive Study of Underwater Inflatable Co-prime Sonar Array (UICSA)," in Proc. OCEANS MTS/IEEE, 2021.

<u>Patent Applications</u>

- Patent Application PCT/US2019/045905B: Ouyang, T.-C. Su, Y. Li, and S. Bavar, "Chemical reaction activated expanding material for underwater deployable structures," 10/09/2018.
- US Patent Application 20210284303: Ouyang, T.-C. Su, Y. Li and J. Thomas, "Energy Efficient Underwater Inflatable Array Using Hydrofoam and Water Swelling Material," 09/16/2021.

## References


[1] Blue Technology: transfer of innovation solutions to sea basin economies, [Online]. Available:https://www.msp-platform.eu/fundings/blue-technology-transfer-innovation-solutions-sea-basin-economies. [Accessed: July 24, 2021].

[2] B. Ouyang, Y. Li, T. Zhou, T. C. Su, F. Dalgleish, A. Dalgleish, and F. Ahmad, "Compressing two ways: the initial study of an underwater inflatable co-prime sonar array (UICSA)," in Compressive Sensing VII: From Diverse Modalities to Big Data Analytics (Vol. 10658, p. 106580H). SPIE, 2018.

[3] Y. Li, B. Ouyang, F. Dalgleish, A. Dalgleish, T. C. Su, S. Baver, J. Thomas, T. Zhou, and F, Ahmad, "Mechanical design consideration of an underwater inflatable co-prime sonar array (UICSA)," in OCEANS 2018 MTS/IEEE Charleston (pp. 1-8). IEEE, 2018.

[4] B. Ouyang, "Underwater sensing solutions: Structures and Sensors," NAVSEA Cardrock DTLe Presentation, October 10, 2018.

[5] Y. Li, J. Thomas, B. Ouyang, T. C. Su, T. Zhou, and F. Ahmad, "Design and experimental study of Underwater Inflatable Co-prime Sonar Array (UICSA)," in Proc. OCEANS MTS/IEEE Seattle, 2019.

[6] Y. Li, A. Schaff, S. Bavar, B. Ouyang, T. Su, T. Zhou, F. Ahmad, "Design and Implementation of Underwater Inflatable Co-prime Sonar Array (UICSA)." In Proc. Global OCEANS 2020 Online Conference, 2020

[7] Aquarian Audio Products. H2a-XLR Hydrophone User's Guide. [Online].Available:http://www.aquarianaudio.com/AqAudDocs/H2a_XLR_manual.pdf. [Accessed: August 31, 2020]

[8] PJRC. Teensy 4.0 Development Board. [Online]. Available:https://www.pjrc.com/store/teensy40.html. [Accessed: August 31, 2020].

[9] PJRC. Audio Adaptor Boards for Teensy 3.x and Teensy 4.x. [Online]. Available: https://www.pjrc.com/store/teensy3_audio.html. [Accessed: July 1, 2021].

[10] Bela. CTAG BEAST Starter Kit. [Online]. Available: https://shop.bela.io/products/ctag-beast-starter-kit. [Accessed: August 31, 2020].

[11] C. A. Schaff, Y. Li, B. Ouyang, C. D. Ouden, T. Zhou, F. Ahmad, "Development of a low-cost subsea datalogger for passive phased sonar arrays," Proc. SPIE 11730, Big Data III: Learning, Analytics, and Applications, 2021

[12] "AQUAGEL." [Online]. Available: https://akinainc.com/polyscitech/products/aquagel/index.php. [Accessed: July 24, 2021].

[13] GLADIUS MINI S Underwater Drone with a 4K UHD Camera, [Online]. Available: https://www.chasing.com/mini-s.html. [Accessed: July 24, 2021].

[14] Y. Li, C. A. Schaff, G. Sklivanitis, B. Ouyang, T.-C. Su, and F. Ahmad, "Comprehensive Study of Underwater Inflatable Co-prime Sonar Array (UICSA)," in Proc. OCEANS MTS/IEEE, 2021.

[15] Y. Li, B. Ouyang, T. Zhou, J. Thomas, S. Bavar, E. Weber, L. Michieletto, T.-C. Su, and F. Ahmad, "Laboratory and Field Experimental Study of Underwater Inflatable Co-prime Sonar Array (UICSA)," Journal of Civil Engineering and Construction, (Accepted).