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Link Foundation Fellowship Report

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Introduction

Developed with the support from USDA-NIFA through the National Robotics Initiative (NRI 2.0), the Hybrid Aerial Underwater robotiCs System (HAUCS) framework is a Cyber-Physical System to provide automated monitoring of vital environmental metrics of each pond on aquaculture farms [1]. In particular, the HAUCS sensing platform is a hybrid robotic system consisting of an aerial drone and underwater sensing payload integrated through a winch and short-range wireless link. The platform has been successfully demonstrated on the farm for collecting fundamental pond data such as dissolved oxygen (DO) and temperature (Figure 1) [2].

![Figure 1](image1.png)

Figure 1. (a) A flow chart describes the current HAUCS robotic sensing platform. A winch will release the sensor payload into the pond for measurement when the drone reaches the desired location. The sensor data will be sent from the topside module via the ESP ON wireless link. The topside will relay the data to the control center via long-range communication links such as LoRa. (b) Frames from the video clip taken during the field test of the platform at the collaborative farm – Flowers Fish Farm. The frames illustrate the drone taking off, deploying payload, retrieving the payload, and flying back to base [2].

However, from the field tests, one weakness identified in current design is the need of a robotus, lightweight, robotic extension capable of multiple degrees of freedom.

A prototype consisting of two-unit Kresling patterns was developed (Error! Reference source not found.). The results of lab tests to demonstrate the design feasibility were presented in [2].

![Figure 2](image2.png)

Figure 2. First prototype using Kresling pattern Invalid source specified. (a) collapsing sequence of an individual section, (b) comparison of single and double section extensions.
With the support of the Link Foundation Fellowship, one next objective was evaluating the optimal actuation for the system. Variable stiffness material-based actuation used in many soft robotic applications was the primary focus [3], such as Shape Memory Polymer (SMP). A second task was to miniaturize the structure by refining the composites used in the system. The third task will be the integration of a payload (i.e., an underwear camera), the robotic extension, and the flight controller to support system-level tests in the lab and field demonstrations.

Results

From the prototype illustrated in Error! Reference source not found., various types of actuators were investigated. Initial concepts were centered around micro servos and gear drives to rotate the center shaft. However, these components would severely impact the SWaP (size, weight, and power). Investigations shifted to smart materials to optimize the system SWaP. The extension arms were redesigned to be printed with electrically conductive shape memory polymer filament. Through initial testing of material properties, it was discovered that the conductivity of the part was too high. To compensate, a channel was created within each bulkhead of the extension arms to house straight-trained nitinol wire (Figure 3). The concept being that the nitinol will aid in extension via its own shape memory effects, as well as speeding up the extension process.

![Figure 3](image-url). A channel was built into the SMP extension arm to accommodate nitinol wire to aid with the extension process.

Once the SMP arms were operating as desired, the design was incorporated into an assembly. The first design (Figure 4a) utilizes four nitinol impregnated SMP arms to perform the extension and four nitinol springs to retract the unit. Through laboratory testing, it was determined that the compressive force of the springs were too strong for the enhanced SMP arms.
Figure 4. The three final design concepts explored a series of combinations of SMP and nitinol. (a) This design utilizes four SMP arms and four nitinol springs. (b) This concept eliminates the SMP arms in place of straight-trained nitinol wire. (c) The final design has two SMP arms aided by two straight-trained nitinol wires and two nitinol springs.

A secondary design was developed eliminating the use of SMP arms and instead incorporating four straight trained nitinol wires (Figure 4b). This design was also extensively desktop tested, while this unit extended and retracted, its movements were not predictable without the rigidity provided by the SMP arms. Various ensembles were tested, removing springs or adding straight trained wire. The results remained the same regardless of the arrangement.

Lastly, Figure 4c utilizes a combination of two enhanced SMP arms and two straight trained nitinol to extend the structure. Two nitinol springs are then used to close the unit. This design performed the most reliably, achieving successful extension and retrieval consistently. The unit was tested in 47 laboratory experiments to validate the results gathered.

Figure 5. The proposed multi-stack element. (a) Design rendering in Fusion 360 of the structure in different stage of unfolding. (b) Lab test video frames of the structure at different stages of unfolding.

To build upon the single-stack unit developed above, an arrangement was created to accommodate multiple elements (Figure 5). The two SMP arm design encourages alternating arm attachment. By varying the placement of the arms, the system is able to reduce the surface area and maximize the expansion ratio.

Significance and Impact

While other researchers have developed an array of Origami-inspired technology, only one other group has developed a robotic arm for drone attachment. Kim et al. developed one such system, their design utilizes the Yoshimura Origami pattern in addition to a locker system (Figure 6) [4]. Their platform is actuated through motors and held in tension by a central wire and internal locker flaps (to keep the arm rigid when extended).
This design is limited by SWaP, the motors siphon power away from the drone, limiting the flight time. Additionally, the indirect actuation of this structure requires full extension or retraction. The internal tendon system eliminates the potential for partial operations. Perhaps the biggest disadvantage with this design resides within its adaptability. The combination of the tendon and locker system equates to single axis manipulation and utilization of only two degrees of freedom.

Figure 6. Kim et al. designed an Origami-inspired robotic arm [4].

The HAUCS Kirigami enhanced system addresses these deficiencies, creating a highly functional design that can be adapted to other purposes. The HAUCS design reduces material, while utilizing smart materials that limit the power deflected from the drone operation. Similarly, the direct actuation of the SMP and nitinol components permits partial extension to tailor the extension for each operation. Lab tests also proved that by varying the applied voltage, the system can achieve all six degrees of freedom. The overall design is variable, in that it is easily altered to fit the requirements of the operation.
Figure 7. An illustration of a potential assembly arrangement generated by varying electrical applications to explore more degrees of freedom. (a) Design rendering in Fusion 360 of the structure in different stages of unfolding. (b) Lab test video frames of the structure at different stages of unfolding.

Future Applications

The overarching goal of the proposed research is to augment the HAUCS platform to support sophisticated operations beyond DO monitoring, such as observing fish activities using underwater cameras or conducting physical sampling (Figure 8a-e). The augmented HAUCS framework is envisioned to revolutionize the pond aquaculture farm operations and bring fundamental changes to maritime applications such as coastal zone water quality monitoring and harmful algae bloom detection. Another potential application of the HAUCS platform is to act as a high-bandwidth gateway to connect the above-water control centers and the autonomous underwater vehicles (AUVs) through an RF-optical communication link (Figure 8f).

Figure 8. Illustration of different use cases (a) flexible length against water level (with a gripper end), (b) partially retracted for variable-length extension, (c) retracted during flight, (d) flexible bending angle (attach a camera at the end), (e) An example of non-linear, multiple degrees of freedom actuation. (f) Long-range High-bandwidth gateway using the underwater optical link and above-water radio link.
References


2. A list of all archival journal papers or scholarly reports, either published or expected to be submitted/published.

- Ph.D. Dissertation (Expected Dec. 2023);
- A conference paper is being prepared to be submitted to 2024 SPIE CDS Ocean Sensing and Monitoring conference.
- We also are planning to include this research in a journal paper under preparation for MDPI Remote Sensing Special Issue on “Advancement in Undersea Remote Sensing”.

4. How did the Fellowship make a difference?

The support from the Link Foundation Fellowship was critical for the fellow to successfully expand her research beyond refining existing robotic extension designs in support of the HAUCS project. With the support, the fellow was able to explore innovative ways to activate/control the structure using smart materials such SMP. This work laid the foundation for her fellow researchers to realize the robotic extension design and field test with the HAUCS platform.