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Work-in-Progress: Development of a new hands-on STEM program for biologically inspired maritime robotics

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Abstract

This paper documents the work-in-progress to develop a STEM outreach program providing 9th-12th grade high-school aged learners with an introduction to biologically inspired underwater robotics using lighter-than-air (LTA) vehicles. This work includes prototype kit development targeting a comparable cost per kit as SeaPerch ($179) and SeaGlide ($249) and instructional materials comprised of demonstration videos and standards-aligned written curricular content to facilitate classroom implementation. LTA vehicles are utilized specifically for their unique ability to demonstrate fundamental concepts applicable to both aircraft and underwater vehicles including structural analysis, aerodynamics and hydrodynamics, biologically inspired propulsion, systems engineering, and swarm dynamics, without requiring student access to pools or other bodies of water.

Of modern naval relevance, LTA vehicles provide an opportunity to demonstrate key concepts applicable to submarine design without dependence on access to water. The Naval Research and Development Framework and corresponding Addendum speaks to the need for "[u]ndersea dominance…as the Navy designs and build the next generation of strategic and tactical submarines" including "[e]xpanded use of autonomous undersea vehicles…" [1]. Furthermore, the Addendum's Integrated Research Portfolio on Warfighter Supremacy speaks to training and education as well as development of biologically inspired autonomous systems. Current interest in biologically inspired vehicles is documented in the Navy's proposed FY22 budget [2]. Hands-on robotics activities using LTA platforms provide a novel opportunity to develop the future naval workforce by promoting interest and learning in underwater and unmanned systems without the need for access to a pool or lake to test in. This paper documents work-in-progress to develop a SeaPerch-inspired educational kit. The kit will include three hulls - balloons to be filled with helium in shapes that idealize the shapes of sea creatures: a hemisphere to emulate a jellyfish, an ellipsoid to emulate a tuna, and a flying wing to emulate a ray. Both propeller and flapping propulsion options will be provided to expose learners to traditionally and biologically-inspired propulsors. By using idealized geometries, fundamentals of aero/hydrodynamics like added mass effects that are often ignored because they are relatively small for aircraft but of relevance for submarines and LTA vehicles can be demonstrated.[3]

Navy supported STEM programming such as SeaPerch, and more recently SeaGlide, have been enormously successful for fostering an interest in engineering and robotics with participants in all 50 states and 35 countries with growth from 22 regional SeaPerch competitions in 2014 to 89 regional competitions in 2018 [4]. The SeaPerch kit-based structure has proven pivotal for widespread adoption, though access to water is a barrier. The described activities take a logical step in kit-based naval STEM outreach activities, without the constraint of water, and targeting high-school aged learners.

Team

A key component of this project was building a development team with diverse, multi-disciplinary expertise. With a desire to use the *B*iologically-inspired, *L*ighter-than-air, *I*nstructional, *M*echatronics *P*rogram (BLIMP) as a platform to teach high-school aged students about structural engineering, hydrodynamics, biologically inspired propulsion, system design, and swarming, the project needed a mixture of expertise from multiple disciplines in engineering, science, and education. The desire to ensure it would be a captivating program for high-school aged learners motivated inclusion of a cohort of undergraduate researchers, overseen by a MS-level student, who could view the kit, instructional components, and website with media savvy more closely aligned to the desired user population than the faculty experts. These priorities led to a large team which includes faculty members from mechanical engineering (2 – one expert in naval engineering with depth of experience in STEM outreach, one expert in autonomy and robotics), electrical and computer engineering (2 – one expert in robotics and lighter-than-air vehicles, one expert in STEM education), systems engineering and operations research (1 – expertise in collaborative autonomous systems), physics (1 – expertise in STEM education), environmental science and policy (1 – expertise in translating science research into experiential learning programs). The graduate researcher was drawn from electrical and computer engineering with a strong background in LTA vehicles and is conducting his MS research in LTA vehicles. The undergraduate research assistants on this project were selected for interest in the project and complementary diversity of STEM backgrounds, namely they are majoring in mechanical engineering (2), systems engineering (1), and environmental science (1).

Curriculum

Under the BLIMP program, the team is developing a standards-aligned written curriculum with ten lesson plans and supporting videos, disseminated via a website. The ten lessons fall under five lesson strands on structural engineering, basics of aero/hydrodynamics, basics of biologically inspired propulsion, an introduction to system design and integration, and an introduction to swarm dynamics and agent-based modeling. Significant concepts within each lesson strand and corresponding Next Generation Science Standards [5] and Common Core State Standards [6] are summarized in Table 1.

Lesson Strand	# of lessons	Significant Concepts	National Standards
Structural Engineering	3	- Model physical systems with free body diagrams - Formulate static equations of equilibrium for trusses - Apply vector analysis to estimate forces on a structural member - Calculate centroids and moments of inertia for different cross sections including thin-walled structures	- NGSS HS-ETS1-2 "Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering" - CCSS.Math.Practice.MP1 "Make sense of problems and persevere in solving them" - CCSS.Math.Practice.MP4 "Model with Mathematics"
Aero/ hydrodynamics	3	- Diagram and describe the forces on a body moving in a fluid	- NGSS HS-ETS1-3 "Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including

		- Describe similarities and differences in loads on a body based on fluid properties - Use wing geometry to achieve desired stability, strength, and weight characteristics	cost, safety, reliability, and aesthetics, as well as possible social, cultural, and environmental impacts" - CCSS.Math.Practice.MP1 "Make sense of problems and persevere in solving them" - CCSS.Math.Practice.MP2 "Reason abstractly and quantitatively" - CCSS.Math.Practice.MP4 "Model with Mathematics"
Biologically-inspired propulsion	2	- Diagram, compare and contrast the relative contributions to thrust from pushing, pulling, or flapping forces in tuna, jellyfish and rays	- NGSS HS-PS2 Motion and Stability: Forces and Interactions - NGSS HS-Life Science: The performance expectations in the topic Structure and Function help students formulate an answer to the question: "How do the structures of organisms enable life's functions?" - CCSS.Math.Practice.MP3 "Construct viable arguments and critique the reasoning of others."
System design and integration	1	- Describe system mission requirements - Describe system functions and physical components - Perform system functional decomposition and build a functional flow diagram - Integrate system functions and physical components to achieve mission requirements	- NGSS HS-ETS1-4 Engineering Design: "Use a computer simulation to model the impact of proposed solutions to a complex real-world problem with numerous criteria and constraints on interactions within and between systems relevant to the problem." - CCSS.Math.Practice.MP4 "Model with Mathematics" - CCSS.Math.Practice.MP5 "Use appropriate tools strategically"
Swarm dynamics and agent-based modeling	1	- Identify how use of a multi-agent system can assist in accomplishing a prescribed mission objective - Diagram and describe a model of a multi-agent system	- NGSS HS-LifeScience 2-8. "Evaluate evidence for the role of group behavior on individual and species' chances to survive and reproduce." - CCSS.Math.Practice.MP4 "Model with Mathematics"

Table 1: Mapping of lesson strands to significant concepts and national standards.

Each of the ten lessons follows a standardized format, for ease of use by teachers and students in a classroom or club environment. The lessons open with a statement of learning objectives and alignments to Next Generation Science Standards and/or Common Core State Standards. A supplies list is provided, so that learners can immediately find the kit components needed to complete the specific lesson, and the units used in the lesson are stated. Each lesson then has three subparts, an initial one that introduces the core concept, followed by applications and further technical depth. Each lesson has at least one hands-on activity to encourage engagement with the material. Individual lessons conclude with a bonus activity or research challenge for highly motivated students. For example, one bonus activity ties to history and literature through the book *The Deltoid Pumpkin Seed (*John McPhee) that documents the Aereon 26 flying wing aircraft. Another activity reinforces biologically inspired engineering by asking students to devise a fish-tail connection structure using what they learned about gusset plates. And another bonus activity delves into the hydrodynamics of using balloons for interplanetary exploration. Where applicable, lessons are tied to each other and/or to the completed kit. For example, a hydrodynamics lesson asks students to modify their completed vehicle using the fluids knowledge they have developed to apply dihedral to their flying wing shaped BLIMP.

Kit

The kit is designed to provide a biologically-inspired lighter-than-air education opportunity to high-school aged learners. Within each kit there are 3 hull designs, a hemisphere (idealized jellyfish), ellipsoid (idealized tuna), and flying wing (idealized ray), with generalized sketches in Figure 1. Additionally, there are two propulsion options in each kit: propeller and flapping wing and/or tail to illustrate mechanical versus natural propulsion.

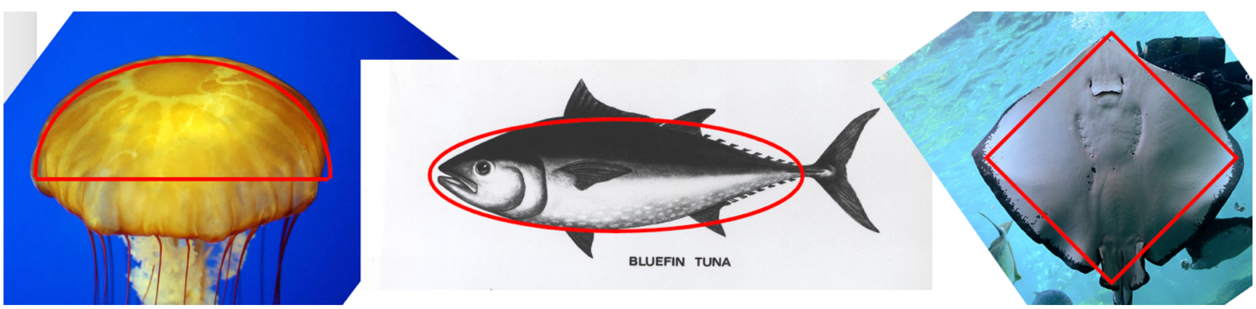

Figure 1: Idealized geometry for jellyfish, adapted from [7], tuna, adapted from [8], and ray, adapted from [9].

At the time of this writing, the kit components are being finalized. The starting point for kit design are the LTA research platforms utilized by a participating faculty member on this project, see Figure 2. Each vehicle is an idealized shape inspired by a different underwater animal to compare/contrast different propulsion mechanisms and mechanical advantages. Prior work by co-author Nowzari's research group [10] includes the development of the necessary electronics and control system for a spheroidal, propeller driven LTA vehicle. Their electronics and control package, details of which can be found at [10], are leveraged for this kit, permitting the kit development efforts to focus upon creation of shape and propulsion options through which one can provide students hands-on learning opportunities to build understanding of structural engineering, aero/hydrodynamics, biologically inspired propulsion, as well as system design and integration. Furthermore, a focus on kit affordability permits groups of students to develop swarms of LTA vehicles through which swarm dynamics and agent-based modeling can be demonstrated. The final kit components will include three mylar balloons corresponding to the three biologically inspired shapes, motors, wiring, speed controllers, servos, microcontroller board, batteries, and other electronics components needed to program and launch a BLIMP – modularly implemented for use on any of the three shapes, as well as supplemental materials for completing the lessons (string, balsawood, putty, etc…). Additionally, a teacher kit is devised that contains shareable and/or hazardous materials, such as soldering irons and cutting utensils.

Figure 2: Nowzari's research group LTA vehicle testing in the Nguyen Engineering Building atrium.

During curriculum development, the team decided to use either components of the kits or the completed BLIMP to illustrate the science and engineering lessons, but the curriculum would not be a 1:1 mapping to construction instructions. The kit and lessons are designed to provide different approaches to the material - students who want to dive into the curriculum first can build their background understanding before starting kit construction while students who dive straight into construction can circle back to the curriculum. The design is intended to support standards-aligned classroom activities or hands-on robotics club engagement. As such, kit construction instructions are provided in addition to, and separate from, the curriculum described previously.

Website

All educational materials developed under this program are designed to be disseminated electronically. An in-progress website has been launched at https://blimp-robotics.org. This site is organized to provide ease of access to content on:

- The kit, with ordering information and assembly instructions (pending)
- Lesson plans, organized by technical focus area, including worksheets for students, which state the learning objectives for each lesson, required kit components to complete any given lesson, units used in each lesson, and tie-ins to standards. A sample snapshot of a lesson introduction is provided in Figure 3.
- Terminology, summarizing key technical terms used throughout the lessons, with anchors to facilitate hyperlinks within the lessons
- Resources, a vetted collection of videos and related educational content to support kit assembly and learning in each of the five technical focus areas. Additionally, ten new videos are being professional produced to supplement the lesson plans.

<table>
<tr><th colspan="2">A Biologically-inspired, Lighter-than-air, Instructional, Mechatronics Program (BLIMP)</th></tr>
<tr><th colspan="2">Basics of Structural Engineering | Part 1 of 3</th></tr>
<tr><td>Learning Objectives
After completing this lesson, the student will be able to model physical systems with free body diagrams and to use that model to formulate static equations of equilibrium for trusses.

Next Generation Science Standards
• NGSS HS-ETS1-2 "Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering"
Common Core State Standards
• CCSS.Math.Practice.MP1 "Make sense of problems and persevere in solving them"
• CCSS.Math.Practice.MP4 "Model with mathematics"</td><td>Supplies
• Ruler
• Balsa wood sticks
• Pins
• Knife (see teacher or parent)
• Scale
• Spring balance
• Bubble level

Units Used
• Mass: kilogram (kg)
• Length: inch (in)
• Length: centimeter (cm)
• Length: meter (m)
• Time: second (s)
• Force: Newton (N)
(1 N=1 kg m/s^2)</td></tr>
<tr><td colspan="2">Part A: What is a free body diagram
The very first step in solving structural engineering problems is to draw what is known as a free-body-diagram. If you have taken physics, you may have done this already! This is a simple process and is very helpful in modeling physical systems. Let's start with an example, picture a car. Draw a sketch of the car you're picturing (do not worry if art is not your thing, the goal here is to capture the physics, this is not an art contest).</td></tr>
</table>

Figure 3: Snapshot of introduction to sample lesson plan.

At the time of this writing, much of the content is in draft form, and as such, the website is presently a skeleton with largely only the terminology and resources sections complete. The outlined format has the benefit of ease for addition of content as it is finalized. That said, it is anticipated that the curriculum and kit will be finalized well before the ASEE 2022 conference, and as such, the interested reader is encouraged to visit the website for the latest status of the BLIMP program. Notably, during the website development, the art skills of an undergraduate member of the team have been used to make it visually captivating as well as science-informed as shown in Figure 4. The present illustrations are still conceptual and will be finalized by the website's official publishing date.

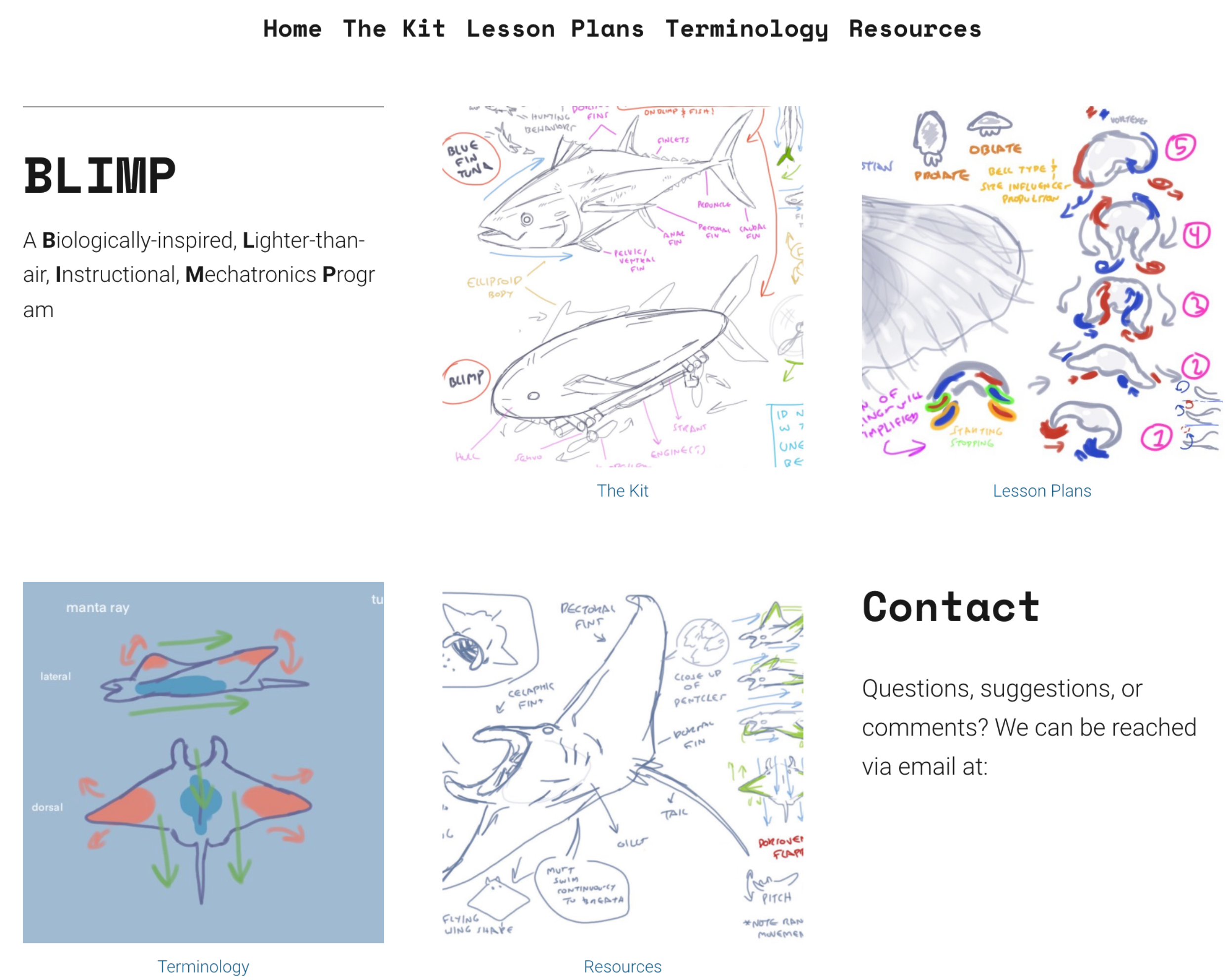

Figure 4: Screen capture of work-in-progress program website.

Next Steps

The initial project timeline called for kit development to be largely complete prior to development of the supporting curriculum. In reality, we found that in order to develop the kit, we needed to sketch out the curricular modules in parallel to ensure the kit included the requisite components. As such, at the time of this writing, February 2022, the undergraduate engineers on the team, supported by one MS-level graduate student, are finalizing the kit components to reflect the curriculum that was developed from October 2021 to January 2022. Next steps include scripting and recording supporting videos, adding all content to the website, and conducting student and educator kit testing with focus groups to solicit feedback with which to improve upon the kit and curriculum. It is anticipated that the kit and curriculum will be ready for use by the Fall of 2022.

That said, for widespread implementation, the team anticipates a number of follow-on actions will be required. Specifically:

(1) Kit mass production and distribution. Under this grant, the team is building 50 student kits and 10 supporting teacher kits. In the model of SeaPerch, student kits contain the key components, whereas teacher kits contain higher cost, shareable items (such as soldering irons) and/or safety critical items (cutting utensils). The team expects to use 30-40 student kits and 5-7 teacher kits during focus groups, internal team testing, and to provide to the

sponsor. Limitations to widespread kit production include both cost and time. Materials costs for the kits are currently estimated at approximately $200, and each mylar balloon BLIMP requires specialized equipment and approximately 20 minutes (e.g. 50 kits, with 3 balloons each, is approximately 50 hours of manufacturing time). Scaling up this activity will require a partner who can mass produce kits and distribute them in an affordable and effective manner. Similarly, a mechanism to offset the costs of kits for early adopters would lower barriers to entry to this program.

(2) Teacher training. In parallel with kit mass production and distribution, we anticipate the need for teacher training sessions. Under this kick-off effort we are developing a series of videos to supplement the developed lessons, but recognizing the value of hands-on exposure for educators considering classroom implementation, the next phase should include direct teacher training.

(3) Longitudinal assessment. While we plan to conduct focus groups for this initial effort to finalize the kits and lessons, any scale-up effort would benefit from a longitudinal assessment on the impact the BLIMP program has on student-interest and learning about biologically-inspired vehicles, lighter-than-air platforms, robotics, or the engineering disciplines contained in the lessons: structural engineering, aero/hydrodynamics, biologically inspired propulsion, system design and integration, and swarm dynamics and agent-based modeling.

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References

[1] Office of Naval Research (ONR), "Naval Research and Development: A Framework for Accelerating to the Navy & Marine Corps After Next," https://www.onr.navy.mil/our-research/naval-research-framework, 2018.

[2] Tingley, Brett, "The Navy is Developing 'Bio-Inspired' Drones that Transition Between Air and Water," *The Drive*, https://www.thedrive.com/the-war-zone/41044/the-navy-is-developing-bio-inspired-drones-that-transition-between-air-and-water, June 15, 2021.

[3] Mueller, Joseph B., Michael Paluszek, and Yiyuan Zhao, "Development of an Aerodynamics Model and Control Law Design for a High Altitude Airship," https://doi.org/10.2514/6.2004-6479, AIAA 3rd "Unmanned Unlimited" Technical Conference, Workshop, and Exhibit, September 20-23, 2004, Chicago, Illinois.

[4] Groark, L., K. Cooper and D. Davidson, "The SeaPerch Evolution: From Grassroots to a Global Community," 2019 IEEE Integrated STEM Education Conference (ISEC), 2019, pp. 274-280, doi: 10.1109/ISECon.2019.8882075.

[5] Achieve, Inc., "DCI Arrangements of the Next Generation Science Standards," https://www.nextgenscience.org/sites/default/files/NGSS%20DCI%20Combined%2011.6.13.pdf, November, 2013.

[6] Common Core State Standards (CCSS) Initiative, "Common Core State Standards for Mathematics," http://www.corestandards.org/wp-content/uploads/Math_Standards1.pdf, 2021.

[7] Dan90266, "A Pacific sea nettle (*Chrysaora fuscescens*) at the Monterey Bay Aquarium in California, USA.," https://commons.wikimedia.org/wiki/File:Jelly_cc11.jpg, August 25, 2005.
[8] NOAA Central Library Historical Fisheries Collection - Image ID: fish5372, NOAA's Historic Fisheries Collection. http://www.photolib.noaa.gov/htmls/fish5372.htm, Public Domain, https://commons.wikimedia.org/w/index.php?curid=24708251, N.D.
[9] Amada44, "Dasyatis brevicaudata (short-tail stingray or smooth stingray) in uShaka Sea World," https://commons.wikimedia.org/wiki/File:Dasyatis_brevicaudata_006.jpg, July 31, 2011.
[10] Patriot Pilots, "Build Your Own Blimp," https://sparx.vse.gmu.edu/GetInvolved.html, 2021.