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Lessons Learned in the Development of a STEM Outreach Program for Biologically Inspired Underwater Robotics

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Lessons learned in the development of a STEM outreach program for biologically inspired underwater robotics

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Abstract

Following our work-in-progress paper and presentation in 2022 [1], this paper documents efforts to develop a STEM outreach program in biologically inspired underwater robotics. This STEM outreach program includes a prototype kit, a standards-aligned written curriculum for classroom implementation, and supporting demonstration videos, assessed via focus group testing. The kit includes three different hull shapes, emulating different maritime species, and two different propulsion mechanisms, e.g., propellers and flapping, in a lighter-than-air (blimp) platform. With these components and supporting materials, the kit can be used to demonstrate how shape and propulsion influence hydrodynamic properties, stability, structural engineering, system design, etc. The curriculum is designed to guide 9^{th}-12^{th} grade students, classes, or afterschool groups through learning activities leveraging kit components and built blimps to further students' understanding of marine biology, form and function, balance, movement, and technical writing. Videos provide an engaging way for learners to interact with the content. In this paper, we expand upon the kit and curriculum development efforts introduced in [1] and videography summarized in [2], and we discuss the findings from the focus groups that helped us refine the kits and the curriculum so that it is suitable for a range of learning styles and abilities.

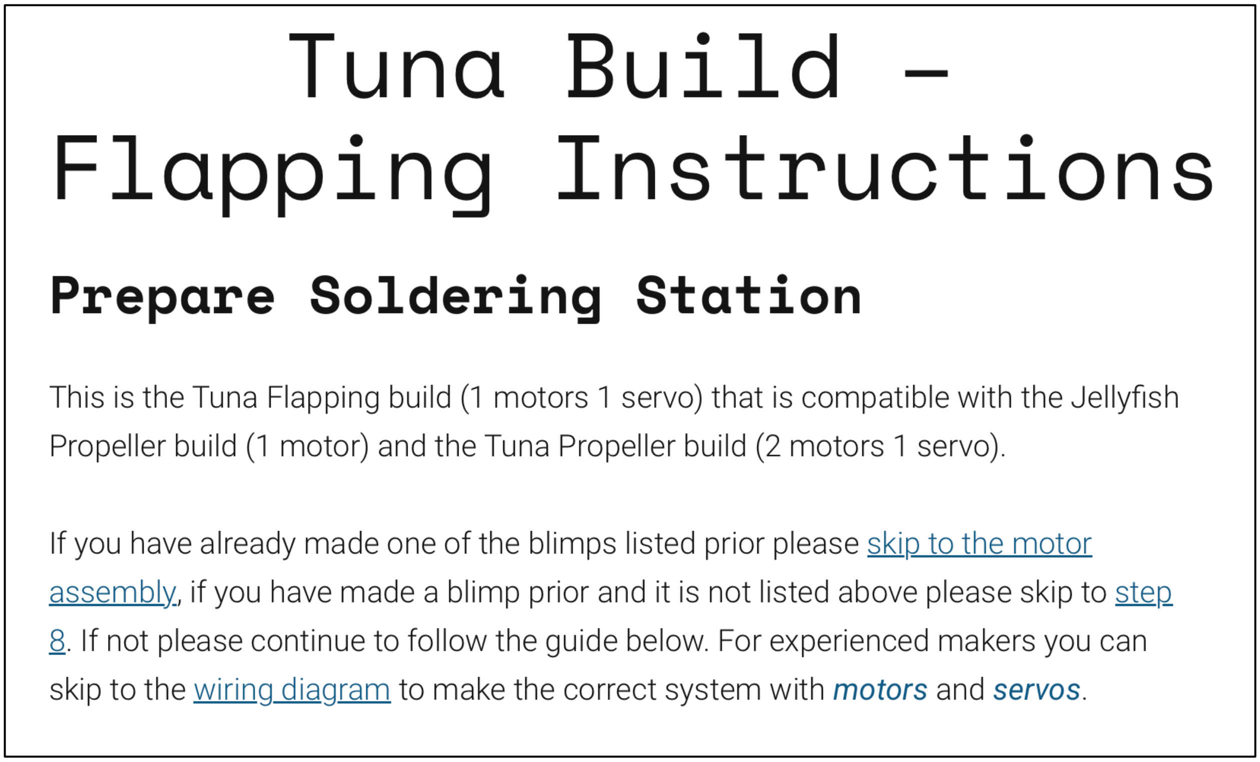
Kit

This *B*iologically-inspired, *L*ighter-than-air, *I*nstructional *M*echatronics *P*rogram (BLIMP) centers on a kit-based approach to biologically-inspired robotics. The developed kit provides learners the opportunity to emulate the behaviors of tuna, rays, and jellyfish, using both flapping and propeller-based propulsion; examples of three constructed BLIMPs are shown in Figure 1.

Figure 1: Constructed BLIMPs – tuna at left, ray in center, and jellyfish at right

The selection of these three different hull shapes and two different propulsion mechanisms was deliberate to facilitate use of the kit to demonstrate how shape and propulsion influence hydrodynamic properties, stability, structural engineering, system design, etc.

Additionally, because the supporting curriculum, discussed further in the next section of this paper, requires materials in addition to those needed to construct a BLIMP, student kits provide the majority of the supplies needed for the BLIMP build and the curriculum. The components of a single BLIMP kit can be used to construct any one of the three BLIMPs with either of the two propulsion mechanisms. These components can then be repurposed to build a different BLIMP hull with a different propulsion mechanism. That is to say, a student can initially build a tuna BLIMP that uses propellers, then repurpose the components into a ray BLIMP with flapping propulsion, but cannot build both BLIMPs simultaneously without supplementing their kit with additional electronics purchases. Build instructions specifically guide learners as to how to repurpose components if they have previously built a BLIMP as illustrated in Figure 2.



Tuna Build – Flapping Instructions

Prepare Soldering Station

This is the Tuna Flapping build (1 motors 1 servo) that is compatible with the Jellyfish Propeller build (1 motor) and the Tuna Propeller build (2 motors 1 servo).

If you have already made one of the blimps listed prior please skip to the motor assembly, if you have made a blimp prior and it is not listed above please skip to step 8. If not please continue to follow the guide below. For experienced makers you can skip to the wiring diagram to make the correct system with ***motors*** and ***servos***.

Figure 2: Opening portion of flapping tuna build instructions, guiding learners on how to repurpose electronics as applicable.

In total, six build guides are provided for:

- Tuna with propellers
- Tuna with flapping tail
- Ray with propellers
- Ray with flapping
- Jellyfish with propellers
- Jellyfish with flapping

Additionally, a software guide is provided that navigates students and teachers through software installation on the Feather microcontroller. Lastly, based upon user feedback, instructions are provided for use of a lighter weight battery, should one wish to increase payload capacity of their BLIMP through reducing weight. These guides are found at [3].

Drawing from the model of the SeaPerch Program [4] a teacher kit was also developed which includes supplies that due to cost, safety, and reusability are best managed by the teacher. The list of kit components for both the student and teacher kits, with links to vendors for those wishing to purchase components directly, is posted to the program website [5] and provided below in Table 1. The kit component lists do not include the mylar envelopes or helium. Additional components are 3D printed; the design files for those 3D printed parts are also linked on the previously mentioned website. Approximate cost of components for a student kit is $160 (not including mylar envelope or helium) and teacher kit components cost approximately $75. It is estimated a teacher would need 1 teacher kit for every 10 student kits.

Student Kit Item (quantity needed)		
1. Brushless Motors (3)	11. 300 mAh LiPo Battery (1)	19. Container (1)
2. Electronic Speed Controllers (ESCs) (3)	12. JST 1.25 mm 3 Pin Pair (15)	20. Round Balloon (3)
3. Servos (3)	13. 22AWG JST PH2.0 Battery Pair (3)	21. Long Balloon (3)
4. 5.0V Regulators (3)	14. Flat Ribbon Wiring (1)	22. Construction Paper (20 sheets)
5. Propellers (3)	15. Safety Glasses (1)	23. Scotch Tape (1)
6. Feather (1)	16. Robotic Fish Toys (2 – different shapes)	24. String (1)
7. Play-doh (Putty) (1)	17. Food Dye (1)	25. Balsa Wood Sticks (10)
8. Arduino Header Kit (1)	18. Light Air-Dry Foam Clay (1)	26. Balsa Wood Sheets (3)
9. Male Pin Headers (3)		27. Putty (1)
10. Charger (1)		28. Pins (20)
		29. Super Glue (1)
Teacher Kit (quantity needed)		
1. Soldering Iron (2)	5. Hex Keys 1.5mm (2)	8. Scale (1)
2. Wire Wrap (1)	6. Scissors (1)	9. Spring Balance (1)
3. Wire Stripper (1)	7. Knife (2)	10. 12 ft Tape Measure
4. Solder Wick (1)		

Table 1: Parts lists for BLIMP student and teacher kits. Lists with vendor links available at [5].

Curriculum

As described in [1], the original curriculum developed for this program consisted of three structural engineering lessons, three aero/hydrodynamics lessons, two biologically inspired propulsion lessons, one lesson on system design and integration, and one lesson on swarm dynamics and agent-based modeling. The developed curriculum utilized components of the BLIMP kit, or the BLIMPs themselves, to teach students about fish and robots, from how they are built to how they move. Content was aligned to Next Generation Science Standards [6] and Common Core State Standards [7]. Each lesson contained multiple parts of varying difficulty in an effort to guide students through key concepts.

User feedback indicated that the multiple-part approach appeared siloed and students could be either overwhelmed or bored with an initial step, resulting in potentially losing learners from concept threads altogether. In an effort to address this concern, we re-organized the content into a curriculum with subthemes of “A Day in the Life,” “Form and Function,” “Balance,” “Movement,” and “The Literate Engineer.” The content is largely unchanged from the original lesson plans, but the ten lessons with subparts were subdivided into 32 mini-lessons. Within each curricular topic, lessons are further organized by level of difficulty and color coded to indicate lessons with hands-on or simulation-based activities. While the mini-lessons are intended to progress in difficulty, linkages between different theme areas are woven throughout. In this manner it is our intent to empower students and teachers to build their own adventure utilizing the BLIMP kit with these lessons as a backdrop for learning. Furthermore, each lesson opens with a motivating question, and while tie-ins to national standards are still provided in language recognizable to teachers, the standards description provided in each mini-lesson is abridged so as not to distract from the material for students. Where appropriate, videos, as described in the next section, are woven into the mini-lessons. A summary of the curricular areas with lesson topics is provided in Table 2. Sample screen shots of a thematic area landing page and opening section of a mini-lesson are provided in Figure 3.

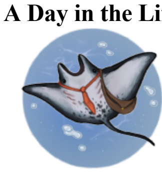
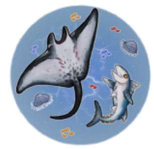
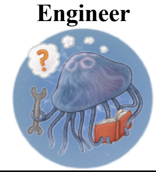
	A Day in the Life 	**Form and Function** 	**Balance** 	**Movement** 	**The Literate Engineer** 
Beginner	*Visualizing Life Histories of Tuna, Stingray, and Jellyfish* Constructing a 'Fish' Predators and Prey	*Free Body Diagrams* Trusses *Nature Walk* Gusset Plates Thin-Walled Structures	Centroids *Centers of Gravity and Buoyancy* Centers on an Airfoil *Wing Geometry*	Structure and Function Fish-bot Experiment Fin Modification	Planes, Blimps, and the Aereon 26
Intermediate	Collective Behaviors (BLIMPs) *What is a System?* Functional Flow and System Architecture System Performance Characterization and Evaluation *Collective Behaviors (Computer Simulation)*	Truss Analysis Vector Analysis	Moments of Inertia *Force Balance*	Pressure *Density* Viscosity Structures and Aero/Hydrodynamics	
Advanced	Agent-based Swarm Model			Added Mass and Drag	Interplanetary Exploration

Table 2: Mini-Lesson titles as mapped to curricular areas and level of difficulty. Lessons with original videos embedded in support of learning are indicated with italics.

For the interested reader, the curriculum is available at [8], and while no longer linked to the main website, the original ten lessons are available at [9].

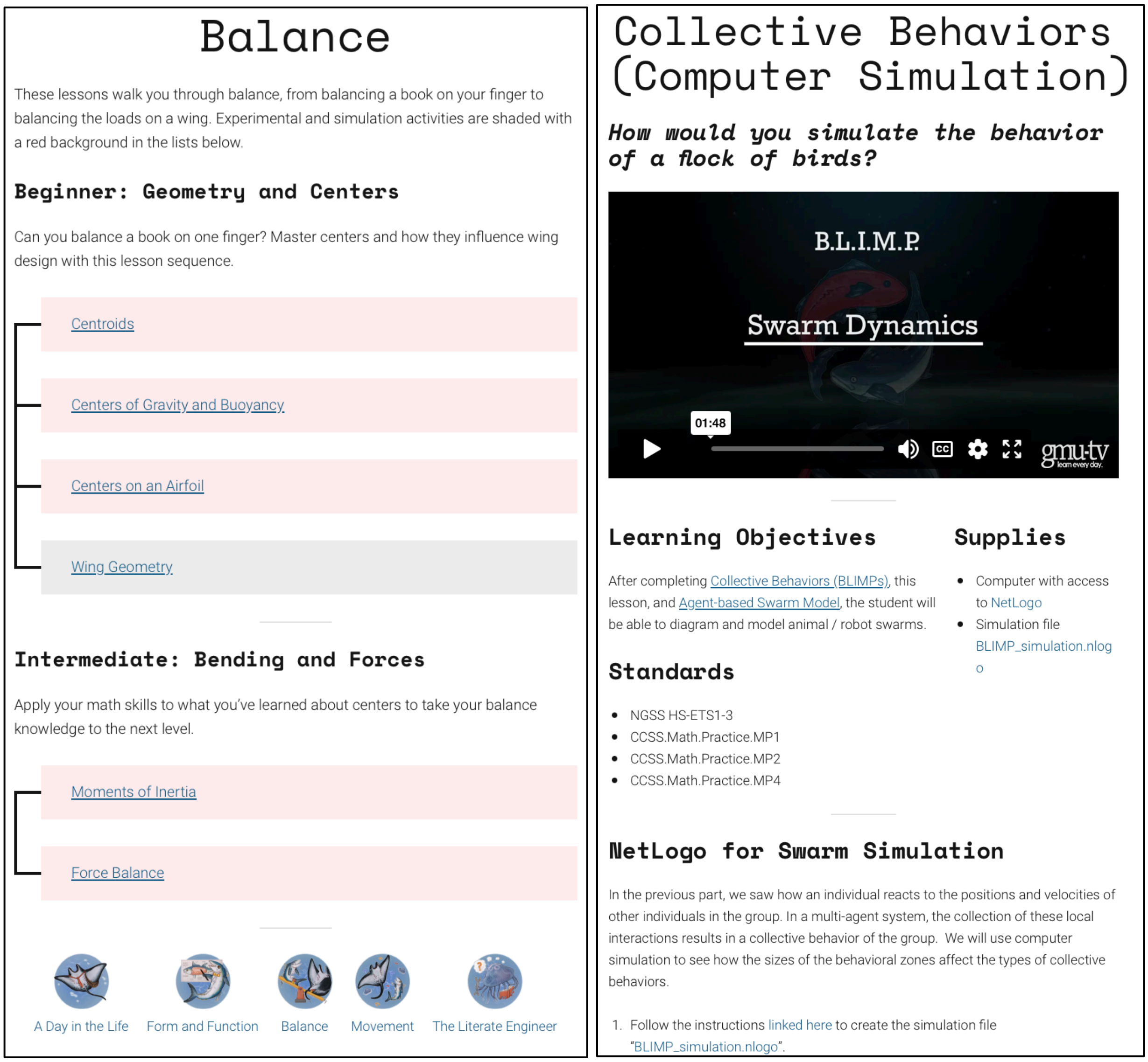


Figure 3: Landing page for "Balance" thematic area of the curriculum (left); opening section of a sample mini-lesson with embedded video (right).

Videos

To support the kit and curriculum effort, ten instructional videos were developed using professional video support provided by GMU-TV. The goal of the video portion of the project was to provide visual content helping make the kit and curriculum accessible to a multitude of learning styles. These videos have been shared publicly on YouTube, Vimeo, and the project website [10]. The ten released videos cover the following content areas:

Biologically-Inspired Propulsion

- This video provides an overview on the life cycles of tuna, jellyfish, and rays, showcasing how biology informs their movements.

Structural Engineering

- Free body diagrams, guiding learners through sketching a free body diagram of a BLIMP.

- Structures in nature, a narrated walk in a park highlighting connections between natural and manmade structures.
- Centers, which provides demonstrations of center finding activities for a variety of two- and three-dimensional shapes, including a BLIMP.

Aero/Hydrodynamics
- Buoyancy, with a demonstration of how the quality of helium influences the rate at which a balloon rises.
- Hydrostatic pressure, with an introduction to coding in MATLAB to calculate pressure as a function of depth.
- Kite aerodynamics, which uses kites to help illustrate the forces and moments on an airfoil.

Systems Engineering
- System design, introducing concepts related to engineering complex systems.

Swarm Dynamics
- Swarm dynamics, illustrating through demonstration how simple rules can result in swarming behavior.

BLIMP Construction
- Build video, providing a step-by-step guide to building a BLIMP.

The trifold release of videos via YouTube, Vimeo, and the project website is intended to maximize reach over multiple platforms. The videos posted to the project website are embedded within specific lessons of the previously described curriculum and incorporated as part of a resources page [10], which also provides a curated collection of publicly available videos and websites by other content creators that support learning in this domain. In Table 2, mini-lessons with embedded original videos are indicated with italics. For more information on the video effort, refer to [2].

Focus Groups and Demonstrations

Over the course of this effort, 43 BLIMP kits were distributed in varying degrees of completion – that is to say, some kits were delivered prior to kit design finalization in order to receive feedback on build instructions or provide training on construction. Of the 43 kits, 9 remained internal to the Mason team (e.g., were used by the PI/Co-I team in development of lessons, videography, training, demonstrations, or preparation for focus groups). The other 34 were distributed to students and educators. Kits (number indicated in parentheses) were distributed and/or feedback solicited via event-identified contacts at:

- Defend the Republic Spring 2022 (6)
- Defend the Republic Fall 2022 (3)
- International SeaPerch Challenge 2022 (7)
- American Society for Engineering Education Annual Conference 2022 (10)
- The Marine Technology Society Bioinspired Marine Systems Committee Seminar 2022 (1)
- SeaPerch Stakeholders Meeting 2022 (3)

In addition to connections established through these events, kits were provided to direct connections of members of the research team (4). Additionally, campers in a maritime robotics camp during the summer of 2022 were provided the opportunity to test fly a BLIMP as documented in [11].

We received feedback following a questionnaire from 12 contacts, a detailed report from 1 contact, and informal feedback from 4 others. The questionnaire used is provided in Appendix A. It is worth noting that while the questionnaire is phrased as though interviewing a student, it was used for students and educators alike. Different elements of the questionnaire were emphasized depending on target audience (e.g. with some subjects emphasis was placed on assessing the kit whereas with others feedback was sought on the curriculum).

Generally speaking, feedback was positive. For example, in response to the question: "In what ways would an exercise like this impact your interest in blimps, engineering, aerodynamics, hydrodynamics, biologically inspired design, etc?" one high school student wrote:

> *I think this enhanced my interest in engineering because seeing a new thing always interests me and I have never seen one of these blimps before.*

To the same question, a teacher responded with:

> *The increased student interest could improve course enrollment in the sciences, while also creating connections across the sub-content areas such as the biologically-inspired design tying zoology to more relevant projects or problems to solve, also shining a light on the influence of nature on design-based fields of any sort (engineering, aeronautics, racing, fabrication, etc.) Additional layers could be integrated to showcase career sectors and pathways to various types of careers not previously represented in our current course offerings (especially any technology-related fields)*

Constructive feedback has led to the previously described re-design of the curriculum delivery, clarification of build and software instructions, and inclusion of additional photographs in lessons and build instructions along with development of the build video. Furthermore, such feedback directly led to the addition of a lighter battery option in the kit and a video lesson focused specifically on use of MATLAB. Conversations with students and educators have pointed to the need for ensuring the BLIMP project content can be navigated either as a kit built first followed by lessons, lessons followed by kit construction, or kit and lesson progression in parallel. The cross-disciplinary ties between engineering and science have been commented on favorably. Based on observation, ease with which learners are able to fly the BLIMP also appears correlated to video game experience.

Metrics and Assessment

This project's public launch was with a website [12] that began sharing information about the BLIMP program in January of 2022. The website is hosted via the WordPress.com content management system, with analytics provided through that platform [13]. Figure 4 shows website traffic by month since project launch. Notably a distinct spike in traffic appears in June 2022, which likely correlates to traffic resulting from presentation and discussion at the 2022 ASEE Annual Conference [1]. Specific page traffic for both the month of June 2022, versus the whole of 2022 is shown in Figure 5. We see commonalities in that the home page, kit, terminology, and build instructions are frequently visited, and the transition from traditional lesson plans into a flexible curriculum is reflected as that curriculum was launched toward the end of 2022.

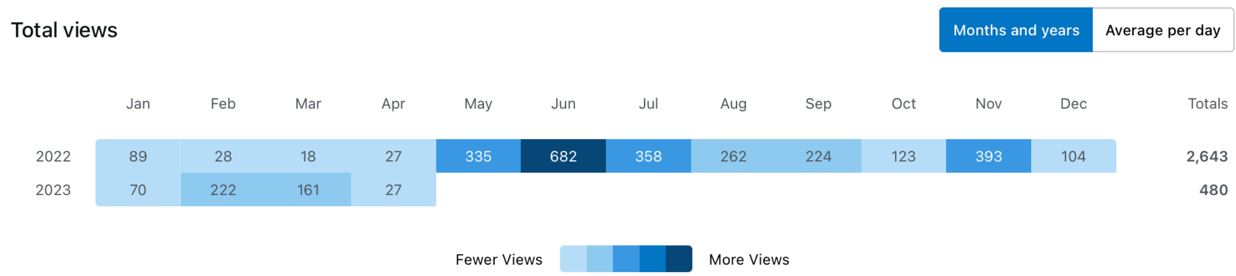


Figure 4: Project website views per month since launch; data analytics provided by WordPress.com current as of April 17, 2023 [13].

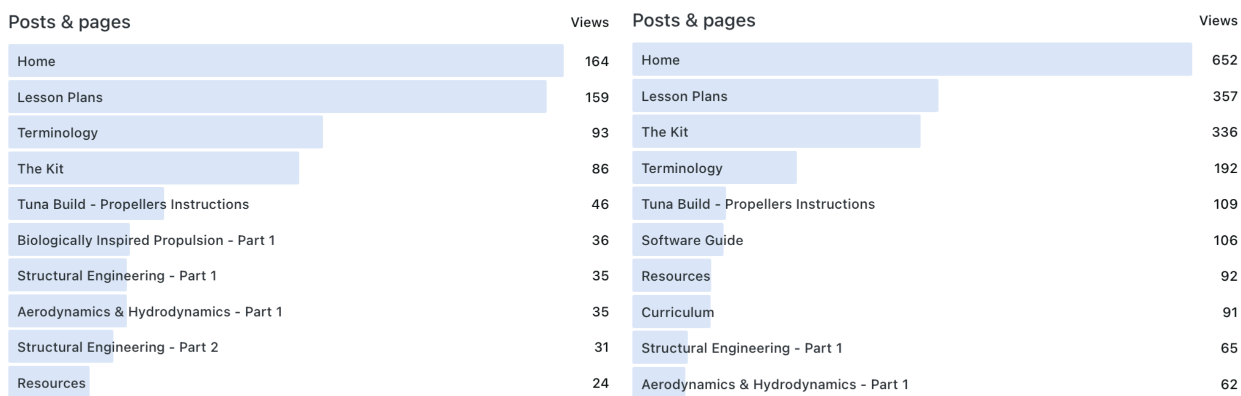


Figure 5: Page traffic during the month of June, 2022 (left) and full year 2022 (right); data analytics provided by WordPress.com [13].

It does appear that the vast majority of traffic is directly seeking information about the program, rather than being referred via search or social media (Figure 6 left) and that the majority of site traffic originates from the United States.

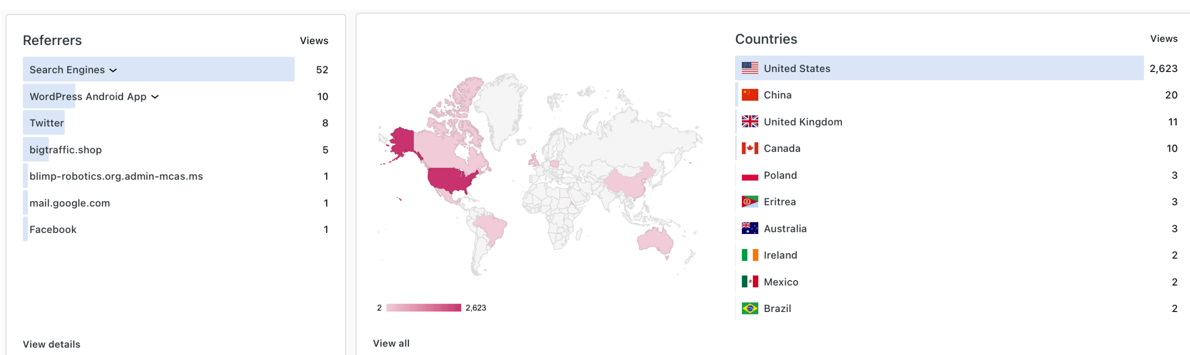


Figure 6: Sources of referrals to the BLIMP robotics website during 2022 (left) and nationalities of sources of traffic (right); data analytics provided by WordPress.com [13].

Conclusions

As described initially in [1], this project was created to inspire and enable high-school aged (9^{th}-12^{th} grade) students to learn about biologically inspired robotics, with the lighter-than-air platform illustrative for both air vehicles and submersibles, without reliance on pool or water access for instruction. Informed by the success of the ONR-funded, RoboNation SeaPerch model [14], a kit-based program was launched, with components deliberately selected to target a comparable price point per kit to the SeaPerch [4] and SeaGlide [15] programs. To support use of the kits, a standards-aligned curriculum and supporting videos were produced and launched via the program's website [12]. Student and educator feedback was solicited and utilized to refine the kit, construction instructions, curriculum, and video topics. Moving forward, to keep content timely and engaging, it would be worthwhile to continually add curricular modules, videos, and other resources as they become available.

In [1] we identified three follow-on actions required for widespread implementation: (1) kit mass production and distribution, (2) teacher training, and (3) longitudinal assessment. A partial solution to mass production and distribution constraint has been to post the full list of kit components with vendor links and 3D printer files to the program website [3]. In this manner, an educator is not dependent on the project team to provide kits for classroom use. That said, there are likely economies of scale to be had in centralized procurement and bulk packaging of kits. Furthermore, facilitating kit mass production takes the burden off educators on the procurement process. A mini-grant program to get kits into schools and after-school groups would likely also assist with early adoption of this program. To support teacher training, a complete build video was recorded and posted to the program website [3]. For further scale-up activities, based upon interactions with teachers and learners participating in the focus groups, it is anticipated that face-to-face trainings would bolster teacher confidence for use of this program in classroom and afterschool activities. With respect to longitudinal assessment, it would be of value to not only continue to track engagement metrics for this program, but also metrics for how this program fits within the broader Naval STEM outreach environment. That is to say, to the extent feasible, it would be valuable to track how BLIMP learners progress through programs like SeaPerch, SeaGlide, and BLIMP on into Naval internship programs [16,17] and graduate school and career enhancement pathways [18-20].

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Appendix A: Student Interview Protocol

SCRIPT: First, let me begin by thank you for taking time to test out our kits and talk with me about the experience. I am looking forward to learning about your experiences working with these blimp kits. I appreciate you signing the informed consent forms and I want to reiterate I will be recording this interview so that I may transcribe it later. I'd like to confirm once more that I do have your permission to record this interview.

Next, I wanted to explain that I will ask questions and allow you time to answer each question. I may also ask follow-up questions that allow me to understand your statements throughout the interview. Also, if at any time, you need me to repeat the question or stop for a break, please just ask.

Finally, I want to inform you of the purpose of this interview. The purpose of today's interview is to gain insight from your experience assembling the blimps particularly with respect to how we can improve both the instructions and the blimps themselves, understand how engaging these materials were for you, and get some first impressions from you on the lesson plans that we are putting together to go along with these kits. Once again, please note that the questions asked should be answered based on your experiences and perspectives. If at any time you do not want to answer a question or would like to end the interview you are welcome to do that, just let me know. Let's begin.

1. Can you tell me some basic information?
   - your name
   - your university and major
   - your year in college

2. Can you describe your prior experience with robotics in general and with lighter than air robotics in particular?

3. Can you describe your overall approach to assembling the blimp – in what order did you approach the assembly? Did you start with the instructions? How did you proceed?

4. Can you describe your approach to assembling the electronics? What went well? What was challenging? Did you follow the instructions? Were there things that could have been improve with respect to the instructions (for the electronics)?

5. Can you describe your approach for assembling the blimp itself? What went well? What was challenging? Did you follow the instructions? Were there things that could have been improve with respect to the instructions (for assembling the blimp itself)?

6. Can you describe your approach for getting the software working? What went well? What was challenging? Did you follow the instructions? Were there things that could have been improve with respect to the instructions (for the software)?

7. Were you able to get the blimp to fly? How difficult was it to get to fly? What did you do with it once it was flying? Did you enjoy getting to fly the blimp?

8. Is there anything else you would like to add about the experience of assembling the blimp?

9. We are going to switch gears now and talk a little bit about some materials that we have assembled to go along with the blimp kits. I would like each of you to select one of these lesson plans to have a look at and I will give you some time to read through it before we discuss it. Let me know when you have had a chance to read through the material.

10. If you were presented with these kits as a student do you think you would prefer to assemble the blimp first, or would you want to do the exercise and learn about some of the principles linked to the blimp first. Why?

11. What was the most interesting/appealing thing about the exercise that you were reading? Can you explain?

12. Are there things that you didn’t like about the exercise or think could be improved? What would those be?

13. In what ways would an exercise like this impact your interest in blimps, engineering, aerodynamics, hydrodynamics, biologically inspired design, etc?

14. If you were combining a lesson like this with the building of these blimps, how would you do it?

15. Is there anything else you would like to add or anything else I should have asked?