Bioinspiring an Interest in STEM

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***Abstract*—Attracting K–12 students to pursue careers in science, technology, engineering, and mathematics (STEM) is viewed as a critical element for benefiting both the economy and society. This paper describes an outreach program, conducted in a Brooklyn, NY, USA, public middle school, aimed at educating students in mechatronics, biology, and bioinspiration. The program is designed to foster student interest in STEM subjects, especially engineering-related concepts, by actively demonstrating their application in solving tangible real-world problems. It consists of a series of lectures and practical activities that culminate with a hands-on bioinspiration-based event at the New York Aquarium. Survey results show that students who participated in the program have a better understanding of the relationship between engineering and nature, demonstrate improved knowledge of select STEM topics, and are more interested in pursuing STEM careers.**

***Index Terms*—Bioinspired robots, educational technology, K–12 education, mobile robots, science, technology, engineering, and mathematics (STEM), underwater vehicles.**

I. Introduction

SEVERAL studies in the last decade report a steady decrease in the number of students enrolled in engineering programs at the university level, despite increasing need for science, technology, engineering, and mathematics (STEM) professionals [1]–[3]. Not only is engineering losing its appeal to younger students, but also the number of students pursuing STEM fields has been generally decreasing [4]. To change this trend, students must be motivated to approach STEM disciplines with more interest, starting from K–12 education [5], [6]. The use of technology and interactive elements in K–12 education has been shown to play an influential role in achieving this [7], [8].

Particularly effective are mechatronics-based programs [9]–[12], which apply physical systems, information technology, and decision making toward a common solution [13]. These programs can excite students about STEM fields and can improve learning of class material by allowing students to build connections across different topics and between the classroom and everyday life [14]. For example, in

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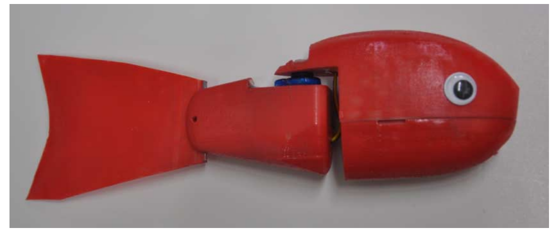

Fig. 1. Robotic fish used as a K–12 educational platform.

the program presented in [15], graduate students and faculty educate K–12 students on ocean research through lectures and hands-on activities, which are later linked to research through a field trip to the laboratory.

While many outreach programs are typically focused on exposing students to a specific discipline, such as engineering [9], [10], [16] or biology [17], [18], the emerging area of bioinspiration [19]–[21], which entails adapting solutions found in nature to address scientific problems, is relatively unexplored. The authors hypothesize that such an area could offer an ideal avenue to ignite students' interest across multiple science and technology fields, given its creative and interdisciplinary nature, its potential for hands-on demonstrations, and its close ties with students' daily experiences.

This paper describes the bioinspiration after-school program *NYU-Poly Mitsui USA STEM Learning Lab*, conducted in the 2012–2013 school year in a local Brooklyn middle school by graduate student members of the Dynamical Systems Laboratory (DSL) at the Polytechnic Institute of New York University (NYU-Poly), Brooklyn, NY, USA. The NYU-Poly Mitsui USA STEM Learning Lab is a voluntary after-school program, in which students attend the sessions on their own accord without receiving a grade. As such, the sessions are designed to excite and engage to the students so as to maintain attendance while delivering valuable educational content. Central to the program is the analysis and development of a miniature robotic fish [22], [23], shown in Fig. 1, as an exemplary instance of bioinspired design, with application in neuroscience and environmental engineering. For example, robotic fish can be integrated in established experimental paradigms to investigate functional and dysfunctional processes [24], [25] or can be deployed for water monitoring [26] and conservation strategies [27].

The feasibility of leveraging bioinspiration to ignite interest for STEM disciplines in K–12 students was demonstrated by this group in [28], which presented an hour-long hands-on activity focused on robotic fish and took place at the New York Aquarium. The activity consisted of K–12 students designing and making caudal fins for the robotic fish, after learning about fishes' swimming and locomotion through an organized tour of the aquarium, and becoming familiar with mechatronics concepts through an on-site presentation by DSL members. Each student had the chance to pilot the robot with their fin attached, and differences in swimming performance were observed in order to acquire firsthand learning of the principles of how fish swim. The program presented here draws inspiration from this informal activity. However, it engages students with a series of sessions throughout the school year, rather than on just a single occasion.

The NYU-Poly Mitsui USA STEM Learning Lab consists of six in-class sessions and a final event at the New York Aquarium at Coney Island, where students apply the knowledge acquired during the year toward a bioinspiration challenge. The final event allows students living in urban environments to build stronger connections between the interdisciplinary topics learned during the year and offers an ideal venue for involving them in a creative task. The program is based on the simple idea that STEM disciplines are not only part of structured learning, but are also useful to solve real-world problems. In this vein, the program integrates science and technology to offer a unique perspective on engineering thinking that highlights its roots and potential in biology [19]–[21].

To reinforce the connection between STEM concepts learned in class and practical applications, the program is constructed upon mechatronics-based hands-on activities, which have been demonstrated to effectively engage students in STEM learning [29], [30]. A "scientist in the classroom" approach [31] is used to orchestrate the program, whereby two graduate student members of the DSL, one specializing in mechatronics and the other in biology, take the lead in all the in-class sessions and the final event. Two high school docents serve as younger scientists with whom the middle school students can easily identify. One of the docents has research experience in the DSL [32], while the other has experience working in the Bronx Zoo and New York Aquarium. Owing to the complexity of some of the activities in the program, the targeted student age is middle-school level.

The goals of the program are to: 1) increase student interest in STEM subjects and careers, especially those related to engineering; 2) increase student awareness of engineering roles and the accessibility of engineering professions; 3) reinforce and expand on lessons learned in-class; and 4) emphasize the interplay of engineering and nature through bioinspiration. The impact of the program is assessed by a survey administered both to the students who attended the program and their classmates who did not.

II. Overview of the Sessions

The sessions are designed to gradually expose the students to each element of bioinspiration and become more focused as the year progresses. As classes must cover a predetermined amount of material as set forth by national standards, implementing additional scientific activities during normal class hours may be challenging [33]; to avoid this problem, the sessions are held during a 2-h window as an after-school program.

Prior to the development of the program, discussion with the teachers involved and the principal of the school informed the selection of topics to be covered. No special recommendations were given to the teachers on the selection criteria for the students, except for the age group, which was sixth and seventh grades. The sessions are designed to take into account the New York State intermediate-level science core curriculum [34] and provide both practical and fundamental experience for students in select science standards. The first two sessions are introductory lectures on mechatronics and biology. The third session is a hands-on activity where students construct robots that locomote using oscillatory motion. The fourth session focuses on the marine environment. The fifth session investigates the propulsive mechanism of a bioinspired robotic fish, and the final session focuses on biodiversity. While the first two sessions have limited interdependence and could be interchanged, session three builds on session one, and session five builds on session four. Similarly, the event at the aquarium is based on sessions five and six. To satisfy these dependencies while retaining the attention of students regardless of their particular interest, the sequence of sessions is structured to alternate between mechatronics and biology. Due the hands-on nature of the activities, each session is held multiple times so that the class size does not exceed 20 students.

A. Session 1: Introduction to Robotics and Mechatronics

In this first introductory session, students are given a broad overview of robotics and mechatronics to serve as a foundation for the next hands-on mechatronics sessions. The session begins with several interactive class discussions on robotics and mechatronics. First, the class is asked to define a robot, and students discuss what qualities should or should not be included and where they have seen robots in either real-life or fiction. The class generally decides that it is difficult to fit a single definition to the word "robot," as many different forms of robots exist. Next, the class discusses why robots are useful, and the graduate student instructor presents his research using a mobile robot for environmental monitoring [35], [36]. Students are taught about the various components of typical robots. Specifically, students identify potential sensors for a robot by recalling the five human senses and then determining what would be an analogous sensor for each of them.

As most mobile robots have wheels, examples and discussion of wheeled mobile robots are provided [37]. The students are shown the relationship between the mathematical concepts of circumference, radius, and the mathematical constant π learned in class, and how this can be used to determine the distance a wheeled mobile robot travels, following the lecture in [38]. By programming a wheeled mobile robot to travel a specified number of wheel rotations, the students calculate how far the robot will travel based on the wheel diameter. They then check this distance using tape measures, which provides them with valuable experience in using measuring tools.

Some examples of mobile robots that utilize oscillatory motion for locomotion are shown in a video. The students are led to the conclusion that many of these designs draw inspiration from nature and may outperform more conventional wheeled mobile robots in certain environments. For example, they are taught that a legged robot is likely to perform better on rough terrain than a wheeled robot [39].

B. Session 2: Introduction to Biology

This session aims to familiarize the students with biology. A brief introduction is provided to define what the study of biology entails and to offer the students a thorough understanding of what roles biologists play. To increase students' interest in this subject, an experiment is performed based on concepts previously learned in class. Since the scientific method is fundamental to performing experiments and validating hypotheses in biology, the lesson is organized into two main topics: the scientific method and biological classification.

The main points of the scientific method are discussed, and as an exemplary protocol for hypothesis testing in animal behavior research, the notion of a behavioral preference test is introduced [40]. Examples from DSL research conducted by one of the instructors [24] and one of the docents [32] are used to motivate the use of this powerful method.

To apply the scientific method that students previously learned in class to a genuine scientific scenario, a mock preference test is implemented in the classroom. The experiment consists of two fish tanks containing one fish each, placed side by side. At the beginning of the experiment, an opaque sheet of plexiglass is positioned between the tanks so that the fish cannot see one another. Prior to removing the plexiglass sheet later in the experiment, students hypothesize how the behavior of the live fish will change as a result. After, the students use the scientific method to conclude whether or not each fish spends more time near the side of the tank closest to the other tank, thus determining if the fish display a social behavior and stay in the vicinity of one another. In this activity, students gather, analyze, and interpret data. The students then construct reasonable explanations based on the data and evaluate their hypotheses in light of the data.

Following the activity on the scientific method, students are introduced to biological classification and are assigned worksheets on which to define and identify various biological families and species. This topic is shown to be important to bioinspiration, whereby engineers often borrow ideas from nature to design more performing and efficient devices [19]–[21]. It is explained to students that a biologist uses this classification system to define groups of biological organisms on the basis of shared characteristics [41]. The activity starts by introducing animals, and students are asked to make some assumptions about the name of the animal's family. Then, some names of species are presented to the students and they are encouraged to link each species with the correct animal picture.

C. Session 3: Bioinspired Walkers

By involving students in building a robot, many opportunities can arise to explain and illustrate scientific and engineering concepts [42], [43]. In this session, students are provided with an experience in designing and constructing a basic bioinspired robot. The goal of the activity is to create a robot that moves through oscillatory motion as shown in examples in the first session. Through the use of oscillatory motion, the students create a bioinspired type of locomotion, and, in the pursuit of this goal, they are educated on the basics of electronics. In the process of creating the robot, students also learn about the various electronic components comprising a robot and perform mathematical calculations. Furthermore, they are taught to look toward nature to solve the engineering problem of creating a net movement from oscillatory motion.

The robot in this exercise consists of a single servomotor controlled by a microcontroller. The students are first provided with the individual components that comprise the circuit. As in the first session, the role of each component is explained, and its biological analog is found through an interactive discussion. By following instructions from the graduate student, the students assemble the circuit. The microcontroller, a TI MSP430, is the first element introduced. They are told this is the "brain" of the robot, responsible for setting the motor speed based on an external stimulus. The next two components are voltage regulators—one of which brings the battery voltage of 9 V down to the 3.3 V needed for the microcontroller, while the other regulates to the 5 V needed for the servomotor. The connector for the servomotor is finally attached to the circuit, followed by the 9-V battery. At this point, the circuit is powered, and the motor begins to oscillate. The microcontroller is programmed to alter the oscillation frequency of the servomotor as a function of the input voltage to one of the analog-to-digital converters; because there is no voltage at that particular pin in this phase of the exercise, this may cause the circuit to behave erratically.

The students are then given a set of various resistors and, through a worksheet, identify the resistance of each based on the color codes. The concept of a voltage divider is introduced, and the corresponding circuit diagram is presented and explained. Different voltages are applied by the students to the microcontroller by varying the resistors R_1 and R_2 and using the equation $V_{\mathrm{out}} = V_{\mathrm{in}} \times R_2/(R_1 + R_2)$, where $V_{\mathrm{in}} = 3.3$ V and V_{out} is the voltage applied to the analog-to-digital converter. The students can then determine the relationship between voltage level and oscillation frequency.

In the final stage of the circuit construction, the students use a photoresistor to replace one of the resistors in the voltage divider. The photoresistor is described as light sensor, whose resistance depends on the ambient lighting of the environment, and can be thought of as an eye for the robot. The photoresistor is used to make the servomotor oscillate faster or slower by varying its arrangement within the voltage divider when exposed to light or shade. Each student's decision on its placement essentially determines the behavior of their robot.

Once the circuit is complete, students use pipecleaners, popsicle sticks, and paperclips to construct bodies for the robots. By attaching appendages to the servomotor in an appropriate fashion, the oscillatory motion can cause a net movement of the robot.

D. Session 4: The Marine Environment

This session introduces students to the marine environment as a precursor to the marine-based mechatronics activities to follow. The marine environment is very diverse, and animal characteristics vary as a function of the different zones [41], [44]. This is of great interest to engineers designing and developing environment-specific bioinspired robots [19], [45]. The session begins with a brief introduction to the zonation of the marine environment and a discussion on biological variations within the marine environment [41].

The students learn about the concept of zonation as well as the adaptation of animals to different zones [44]. The main objectives of the session are to enable the students to describe the habitats of marine organisms and the distribution patterns of marine life.

Students are instructed that organisms are not distributed homogeneously in all parts of the ocean due to physical and biological factors. To introduce variations within the marine environment and the forms of life, a vertical classification based on depth, light, temperature, salinity, and quantity of food is presented as well as a horizontal classification based on substrate. Concerning different forms of life, marine animals are classified based on their body shape, fin shape, position of the mouth, position of the eyes, and body color. The students are engaged in an activity on identifying the habitats of specific animals based on the aforementioned characteristics.

Finally, students are tasked with identifying the different parts of fish, for example, the caudal fin, pectoral fin, and dorsal fin. An interactive discussion takes place where students hypothesize the role of each these parts. After viewing several videos of different fish species swimming, a class discussion takes place on why some species have different fin shapes, how this affects their swimming performance, and why the fish adapted to its environment in this way.

E. Session 5: Investigating Flow Patterns

Following on from the previous session, the last in-class mechatronics session focuses on the propulsive mechanism used by live fish. The session begins with a short lecture on how fish swim. Specifically, it is explained that for a fish to swim effectively, they have to perform many tasks, including staying upright, controlling buoyancy, and overcoming the force of drag due to the water [46]. The way that fish perform these tasks is explained, and emphasis is placed on the effect of the shape of the fish's body and fins. The term "vorticity" is introduced as the mechanism that both birds and fish use to develop thrust for moving [47]. Additionally, it is explained that the phenomenon of schooling offers hydrodynamic advantages to fish since they can use the wake of their neighbors to reduce their energy expenditure [48]. This is also presented to the students as work performed in the DSL, where a robotic fish is shown to create a hydrodynamic advantage for live fish, thus promoting leadership [49].

To determine the role of fin shape in the flow patterns produced by a robotic fish, the students design a flexible tail for a robotic fish. In order to assess the performance of their design, the students construct a flow-visualization device, which consists of a tank filled with fluid with a servomotor fixed to one of the walls of the tank. Attached to the servomotor is the rigid portion of the tail of the robotic fish, to which the flexible portion created by the students attaches. The students alter the circuit that they constructed for the hands-on robotics activity to include a potentiometer, which controls the frequency at which the servomotor oscillates.

The activity starts by filling the tank with water, attaching the flexible fin, and powering the circuit to induce the oscillation of the tail. The students quickly notice that it is difficult to visualize the flow patterns generated by the tail using only water. The students are given two substances to add to the water to enhance the flow visualization: food dye and vegetable oil. Although the food dye initially serves as a good medium for flow visualization, it quickly diffuses in the water to create a homogeneous fluid. Students are then encouraged to notice that the vegetable oil does not mix with the water and facilitates the flow visualization process.

Using the flow visualization apparatus, the students vary the frequency of oscillation of the tail (constructed of the rigid portion and flexible portion) by using the potentiometer. The students are asked to find the frequency that produces the largest vortices for their tail design. Although the apparatus does not directly yield the frequency at which the tail beats, students are instructed to manually approximate the frequency by counting the number of back and forth motions of the tail in a specific time window. By comparing their frequency values to those of other groups, the students are encouraged to recognize that both the frequency of oscillation and the geometry of the tail affect the flow patterns produced by the flexible tail [22]. Finally, the students use tails of different rigidity to conclude that the stiffness of the tail is also a factor in the flow patterns produced [50].

F. Session 6: Biodiversity

The last session focuses on biodiversity, which deals with the variation of life forms within a particular ecosystem [51]. The aim of this session is to educate students on biodiversity and the different strategies of conservation biology used to preserve it. The session starts by introducing students to the concept of biodiversity, and then presents current and possible future strategies of conservation biology. Specifically, the importance of the roles of zoos and aquaria [52] in conservation plans for short and medium terms is discussed, ending with a presentation on the strategies of these institutions. In particular, as the final event of the program takes place in an aquarium, it is emphasized that the purpose of the aquarium is not only entertainment, as it plays a crucial role in conservation of the biodiversity of marine animals. In the context of biodiversity conservation, the bioinspired robotic fish is introduced as a tool created by engineers to help biologists study live animals [22]. This example provides a scenario that is alluring to both students interested in mechatronics and those interested in biology, while tapping into the core of bioinspiration.

Using the components of biodiversity, a classification system based on three different factors (genetic, species, and ecosystem) [53] is illustrated through a series of images that convey these concepts. For example, various canine species are presented to demonstrate genetic diversity; a human, and elephant, and a flower are considered to illustrate species diversity; and images of a desert, forest, and coral reef are shown to demonstrate ecosystem diversity.

In the context of conservation biology, the roles of zoos, aquaria, and botanical gardens in education, conservation, and research are emphasized, and threats for biodiversity are examined in an interactive discussion where historic and current data on biodiversity are shown and interpreted by the students. The students are encouraged to make educated guesses as to possible reasons for the change in biodiversity over time and brainstorm solutions to restore it.

Finally, the DSL robotic fish is presented in most of its relevant aspects, spanning the fabrication process, mechanical design, electrical circuits, and practical implementations. Students are given smaller-scale replica fish, fabricated on a three-dimensional (3-D) printer, which they paint to be biomimetic with a species of their choice. This lesson emphasizes the interplay of engineering and nature by combining a robotic design component with knowledge of characteristics of fish species. It is explained that the robotic fish is a device engineered to modulate the behavioral response of live fish, and, as such, it is important to consider certain aspects of the target species when determining the coloration and aspect ratio of the robot. To motivate scientific thought in the students, two scenarios are presented in the context of a robotic fish interacting with a live fish; in one scenario, the robotic fish resembles a conspecific, and in the other a predator. The students are asked to hypothesize how the appearance of the robot may influence the behavioral response of the live fish in each case. Following a discussion, research results are presented where a robotic fish whose coloration matches that of zebrafish is found to be more attractive to zebrafish [24]. Alternatively, if the robotic fish is colored to mimic a predator, a repulsive behavior is observed [25]. These examples illustrate how conservation biology can use a combination of engineering tools and biological factors to achieve its goals.

III. Aquarium

The activity at the New York Aquarium is the culminating event of the program and capitalizes on the work presented in [28]. Upon arriving at the aquarium, the students are taken on a 30-min tour of various fish species by an outreach specialist of the aquarium. The tour consists of a refresher on fish anatomy including the names and functions of various fish fins and an exhibition of different fish. At the beginning of the tour, the students are encouraged to take note of how the various fish may swim through different motions, how different species have different tail shapes, and how different species may move faster or with more agility than others.

After the tour, the students are brought to an education hall within the aquarium where the hands-on activity takes place. The room is set up to have multiple stations. At one station, students are again exposed to the anatomy of the robotic fish; shown parts such as motors, batteries, microcontrollers; and explained how the various control parameters of the robotic fish affect its swimming. For instance, the students observe that they will be able to control the tail beat amplitude and frequency. As this session is focused on directly observing robot swimming performance, the students are told to consider how these parameters may effect the swimming performance of the robot. The students are also given a means to control the offset of the oscillating tail, which the students later discover is useful for controlling the turning motion of the robot.

Before controlling the robotic fish, the students visit another station where they design and cut their own flexible fins much as they did in the flow visualization activity. The students are asked to recall what they observed on the tour of the aquarium. For instance, if they want a fast-moving robot, they may want to base their design on a fast-moving fish that they saw during the tour. Alternatively, the students can simply use their imagination in designing the flexible fin.

Upon having their tail attached to one of the robots, the students are given an Apple iPod Touch, which hosts an in-house developed application for controlling the tail offset and tail beat frequency and amplitude of the robotic fish [54]. The flow visualization activity illustrated the effect of tail shape on flow patterns produced by the robotic fish, but this experience allows the students to directly observe the effect of fin shape on fish swimming performance.

IV. Assessment

The assessment of the program was based on quantifying the interest of students in STEM subjects, their performance on content-related technical questions, and their perception of the field of engineering and its accessibility for them and their peers. A total of 42 participants were surveyed at the end of the program, and the same surveys were administered to a control group of 56 students who did not participate in the activities.

Students participated in the program either at their own will or at the instruction of their teacher, for logistic reasons related to parallel activities taking place in the after-school time. Thus, not all students involved in the program had an *a priori* inclination for STEM disciplines; conversely, some of the students who displayed interest in the program were not able to join it. The control group was selected from students who were classmates of the participants during normal school hours, including those not admitted to the program, to avoid potential sources of error due to different interest in STEM, class performance, and socioeconomic backgrounds.

The survey was divided into three sections. The first section, containing questions 1–5 (Q1–Q5), consisted of fill-in-the-blank questions that elicit basic demographic information, such as the student's grade, and other questions useful for understanding the student's perception of STEM, including his/her favorite subject, what he/she wants to be in the future, and his/her understanding of what engineers do. The second section (Q6–Q10) consisted of five multiple-choice questions on topics covered during the program. The third section (Q11–Q16) was composed of six statements with which students had to rate their level of agreement. Q1 and Q2 asked if the student participated in the after-school program and their grade level, respectively. The differences in responses between the two groups for the remaining questions Q3–Q16 were assessed using a nonparametric Mann–Whitney U-Test [55].

The answers to the questions Q3 ("What is your favorite subject in school?") and Q4 ("What do you want to be when you grow up?") were divided into STEM and non-STEM disciplines. Of the students who participated in the program, 64% indicated a STEM discipline in their responses to Q3, and a similar proportion of 61% of students not involved in the program indicated a STEM discipline as their favorite subject ($p > 0.05$). The responses to what the students want to be when they grow up (Q4), however, show a significantly higher percentage (45%) of STEM careers (such as marine biologist, engineer) in the students who participated in the program when compared to those who did not (23%) ($p < 0.05$), suggesting that the program has a positive effect on student interest for

TABLE I
CORRECT ANSWERS (IN PERCENT) FROM PARTICIPANTS AND NON-PARTICIPANTS FOR QUESTIONS Q6–Q10

	Participants	Non-participants
Q6	52	45
Q7	57	25
Q8	52	52
Q9	74	70
Q10	76	70

STEM fields. Interestingly, with respect to non-STEM careers, 24% of the students selected athletics-related professions (basketball, football, and baseball players) and 17% law enforcement (policemen and FBI).

The responses for Q5 ("Please give an example of one thing engineers do.") are divided into the following categories: fabrication (make things), maintenance (fix things), both fabrication and maintenance, and other. The responses from the students involved in the program gave 48% maintenance, 33% fabrication, 14% other responses, and 5% both maintenance and fabrication as examples of something that an engineer does. The responses from students not involved in the program, excluding blank responses, were 41% maintenance, 29% fabrication, 24% other responses, and 6% maintenance and fabrication, similar to the participants' responses ($p > 0.05$). The specific answers of the students suggest confusion about the difference between a mechanical engineer and a mechanic; in fact, 24% of all students who responded gave answers related to fixing or making cars. Within the students who participated in the program, 17% of the responses refer to robotics, and 9.5% are related to electricity; students who did not participate did not mention either robotics or electricity in their responses. This is likely due to the hands-on activities, which increase students' awareness of electrical circuits and mechatronics as important tools in engineering.

A quantitative evaluation of the success of the program in reinforcing student learning was performed by testing their knowledge of subjects covered in normal class time and supplemented during the after-class program. Table I reports the detailed performance of the two student groups for questions Q6–Q10. While questions Q6 (ordering the steps of the scientific method), Q8 (number of species discovered to date), and Q9 (identifying the type of energy transformation in using a battery to power a motor) do not reveal a significant difference between the two groups ($p > 0.05$), Q10, which asks what a sensor can be used for, shows weak statistical significance ($p = 0.05$). In addition, answers to Q7, which requires students to rank biological classification, illustrate a strong difference between the two groups ($p < 0.01$). The results of each question are shown in Table I. These findings suggest that their learning is enhanced by, throughout the program, supplementing the subject matter with hands-on activities that relate the learning material to real-world problems.

With respect to students' perception of engineering and its accessibility for them and their peers, Table II displays student agreement or disagreement with six statements at the end of the survey (Q11–Q16). The five response choices—*Agree a lot*, *Agree*, *Neutral*, *Disagree*, and *Disagree a lot*—are first converted to integers ranging from 1 to 5 before using the nonparametric Mann–Whitney U-test for comparing the response of participants to the control group. The results of Q11 ("Engineering is fun.") demonstrate that the students in the after-school program agree significantly more than those who did not ($p < 0.01$) and thus perceived engineering in a more positive way. Q12 ("Engineers are cool.") also exhibits a significantly more positive response from those who participated ($p < 0.01$), showing that, in general, participants have a more favorable opinion toward engineering. Based on these positive results, the use of engaging hands-on activities and the presentation of science topics in real-world applications may have positively altered the students' perception of engineering. Question Q13 assesses if the students feel that they know many engineers. While the group who participated in the program on average answered neutrally, the control group disagreed significantly more ($p = 0.01$). This is likely due to the "scientist in the classroom" element of the program, which allows K–12 students to interact with senior (graduate students) and junior (high school students) DSL members.

TABLE II
STUDENT AGREEMENT PERCENTAGES, ROUNDED TO THE NEAREST HUNDREDTH. AA DENOTES "AGREE A LOT," A DENOTES "AGREE," N DENOTES "NEUTRAL," D DENOTES "DISAGREE," AND DA DENOTES "DISAGREE A LOT"

	AA	A	N	D	DA
Participants					
Q11	19.05	28.57	45.24	2.38	4.76
Q12	9.52	30.95	50.00	4.76	4.76
Q13	11.90	16.67	30.95	26.19	14.29
Q14	4.76	33.33	42.86	14.26	4.76
Q15	9.52	14.29	33.33	30.95	11.90
Q16	9.52	7.14	19.05	23.81	40.48
Non-participants					
Q11	5.36	23.21	42.86	14.29	14.29
Q12	1.79	23.21	39.29	12.50	23.21
Q13	5.36	10.71	25.00	17.86	41.07
Q14	7.14	12.50	42.86	26.79	10.71
Q15	7.14	16.07	42.86	16.07	17.86
Q16	5.36	7.14	21.43	12.50	53.57

The responses from both groups to Q14 ("Many kids in my class could become engineers.") is on average neutral. However, the group who participated in the program agrees more than the other with weak significance ($p = 0.05$). While Q16 ("I want to be an engineer when I grow up.") receives a more positive response from the students who participated in the program, the difference between the two groups fails to reach statistical significance ($p > 0.05$). Even if not supported by compelling statistical significance, the findings related to Q14 and Q16 suggest that students who participated in the program have a more positive inclination toward engineering careers and feel that it is more possible for members of their community to access this profession. This may well be related to the combination of the "scientist in the classroom" aspect of the program and the hands-on interdisciplinary components of the activities. Indeed, while the "scientist in classroom" model, which allows for K–12 students to accept the idea that becoming a scientist is an attainable feat, the engaging elements of the program strengthen the connection of engineering with everyday problems in technology and beyond.

Finally, students who participated in the program disagree more with Q15 ("Engineers don't need to know much about nature.") over those who did not with weak statistical significance ($p = 0.05$). This suggests that by successfully using bioinspiration in the program as a means to elucidate the importance of nature in engineering and vice versa, the students gain a better understanding of the profound relationship between these subjects, which are often independently considered in standard curricula [34].

V. Conclusion

This paper has presented an after-school program for middle school students on bioinspiration. The sessions, focusing on mechatronics, biology, and bioinspiration, are outlined in detail to explain the activities used to foster student interest in STEM subjects and demonstrate the application of these subjects to engineering and biology problems in the real world. The program's final session takes place at the New York Aquarium, where after touring the facility, students perform an engaging hands-on activity involving a bioinspired robotic fish.

A survey administered at the end of the program to both students involved and students not involved shows that those involved in the program are more interested in pursuing STEM-related careers in the future when compared to those who did not participate. Furthermore, students who participated in the program show a better understanding of select STEM topics assessed on the survey, suggesting that the program may increase students' knowledge in these areas. The survey also demonstrates that participants have a more positive perception of engineering and that they are more aware of the relationship between engineering and nature. The interdisciplinary nature of bioinspiration further allows to impact students across a broader range of subject matter, while most typical outreach programs are limited to a particular discipline. The program also allows students to perceive engineering as a career choice that is accessible to them and their peers. Thus, through the use of hand-on mechatronics and biology-based activities and their integration in the emerging area of bioinspiration, the program is effective with respect to its objectives.

In future studies, a larger pool of students, the administration of survey instruments at the beginning and conclusion of the program, and tracking student careers after graduation will be considered to confirm these findings. Future implementations of this program could benefit from direct training of teachers to participate in the implementation of the program, which we expect to eventually transition to an integral part of in-class learning.

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