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Educational Soft Underwater Robot with an Electromagnetic Actuation

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Abstract

As demonstrated by the Soft Robotics Toolkit Platform, compliant robotics pose an exciting educational opportunity. Underwater robotics using soft undulating fins is an expansive research topic with applications such as exploration of underwater life or replicating 3d swarm behavior. To make this research area accessible for education we developed Educational Soft Underwater Robot with Electromagnetic Actuation (ESURMA), a humanoid soft underwater robot. We achieved advances in simplicity, modularity, and performance by implementing electromagnetic actuation into the caudal fin. An electromagnet, including electronics, is placed in a waterproof housing, and permanent magnets are embedded in a soft silicone cast tail. The force from their magnetic interaction results in a bending movement of the tail. The magnetic actuation is simple to implement and requires no mechanical connection between the actuated component and the electrically controlled coil. This enables robust waterproofing and makes the device fully modular. Thanks to the direct and immediate transmission of force, experimental flapping frequencies of 14 Hz were achieved, an order of magnitude higher compared to pneumatically actuated tails. The completely silent actuation of the caudal fin enables a maximum swimming speed of 14.3 cm/s. With its humanoid shape, modular composition, and cost efficiency ESURMA represents an attractive platform for education and demonstrates an alternative method of actuating soft structures.

Keywords: soft robotic, education, injection molding, electromagnetic, underwater locomotion, Fin propulsion

Introduction

The field of soft robotics has great potential in education. Due to the hands-on fabrication experience, use of simple materials, and emphasis on a creative design, it may attract a broader range of students compared to conventional robotic workshops focused on programming and electronics.[1] The Soft Robotics Toolkit (SRT) platform provides an open-access resource to support the development and education of soft robotic devices.[2] The public response shows that there is a huge interest not only as a hub for experienced robotics researchers but also as an educational platform for students

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from middle- and high schools.[3–5] For example, the Shape Deposition Manufacturing Finger, a cable-actuated soft gripper, is an exciting and engaging activity.[1,6] In addition, toolkits like the pneumatic control board set a foundation to explore gas pressure-based actuators like soft artificial muscles and have been replicated by students from both high school and undergraduate levels as a way to rapidly test soft actuators.[2] We discovered opportunities to expand soft robotic education into other domains that are currently being researched.

A large and diverse research field in soft robotics is the biomimetic underwater robotic devices.[7] Especially body-caudal fin (BCF) oscillatory propulsion like thunniform swimming has been studied and replicated.[8,9] In nature tunas and dolphins achieve the highest velocities and efficiencies using this propulsion method. Pneumatically actuated fins are used to study BCF oscillatory propulsion thanks to their similarity with natural fish motion.[10,11] The effect of stiffness, frequency, and co-contractions is investigated, deepening biological understanding. Pneumatically actuated fins can also be used to drive an autonomous acoustically controlled fish mimetic robot as shown by Katzschmann et al.[12] It enables the close-up exploration of underwater life in the ocean without disturbance of natural inhabitants. An interesting alternative actuation method is a magnet-in-coil actuator, enabling an inexpensive and compact propulsion method that can be directly driven by a power supply (battery). Berlinger et al.[13–15] built rigid miniature robots for swarm simulation using this actuation method.

Rigid underwater robots have been successfully applied in Science, Technology, Engineering and Mathematics (STEM) education, especially in the form of competitions.[16–18] There have not been similar efforts for soft underwater robotics using BCF oscillatory propulsion. This could be explained by the significant challenges of providing robust waterproofing in soft robotics while achieving overall cost-effectiveness and simplicity.

This study aims to develop a modular and soft underwater robot that is geared toward advancing the future of STEM education. An electromagnetic actuation method for soft devices was developed, as it does not require a mechanical connection to transmit forces, enabling a modular concept with robust waterproofing implementation. The actuation technology is integrated into a 23 cm long humanoid shape, creating an autonomous underwater vehicle. The functional prototype characteristics and swimming performance are presented, as well as plans for implementation in classrooms. All materials are made available on the SRT website.

Design: Educational Soft Underwater Robot with Electromagnetic Actuation

Our team has conducted 11 workshops and has spoken with over 600 students, parents, and educators as part of previous STEM resource development uncovering a common theme among student interests. We have found there to be an increase in STEM engagement when there are real-world, societal problems integrated with the technology. In one study, a teacher commented, ''We have some pollution problems in our area and the students were very much thinking about how they could build things to solve that problem. So these types of connecting what we are learning to what we're facing in our everyday life, that was very much facilitated by this curriculum.''

This feedback led us to establish a fictional character background story of a superhero set out to tackle marine pollution. In addition, the alignment of the environmental engineering discipline, with increased gender diversity in engineering, may provide additional pathways to create an inclusive curriculum with this proposed toolkit.[19,20] Consequently, we set the goal to design a humanoid character capable of autonomous controlled swimming, which could be used to detect, trace, and pick up trash autonomously.

We determined requirements for a soft underwater robot based on previous workshop experiences and literature. There is a trade-off between functionality and educational usability. The robotic device should swim autonomously in a controllable direction with speeds that match those reported in literature of around 10 cm/s using soft BCF oscillatory propulsion, which as stated earlier, is the best method for achieving this speed. A body length (BL) of 10–30 cm is ideal for making hands-on modifications easy for students while being compact for storage and reuse in classrooms and homes. As an educational device intended for tinkering and modification to allow for creative exploration, a highly robust system is necessary, specifically when it comes to reliable waterproofing. Finally, the overall system should be relatively simple, cost-effective to produce, and easy to assemble and disassemble (Fig. 1).

The actuation method of the fin is investigated to overcome the significant challenge of combining performance with educational applicability. Cable-actuated and pneumatic implementations were considered; however, the magnetic actuation method which was specifically developed had significant advantages. It does not require a mechanical connection between the body and soft tail. This makes it possible to connect the tail with a sleeve design that wraps around the bottom of the main body. This connection simplifies waterproofing drastically and makes it possible to replace the tail within seconds. The tail shape is inspired by the Fin Ray Effect discovered by biologist Leif Kniese (Fig. 2).[21]

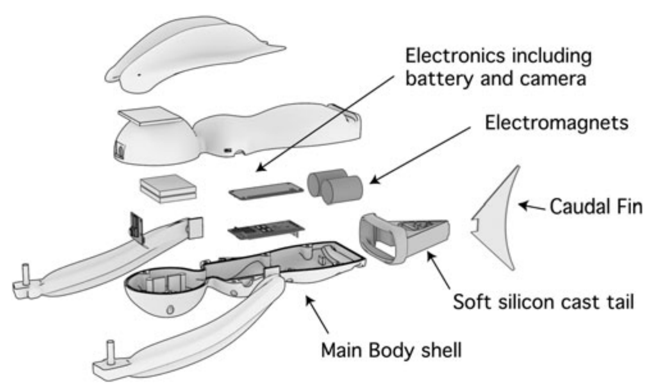


FIG. 1. ESURMA design overview. The soft injection molded tail is attached with a sleeve to the 3d printed main body. The main body includes an upper and lower half, forward facing arms balancing the center of mass, and a dorsal top fin. The main body includes the EM, actuating the soft tail through the main body shell, driving electronics, a camera, and batteries. EM, electromagnet; ESURMA, Educational Soft Underwater Robot with Electromagnetic Actuation.

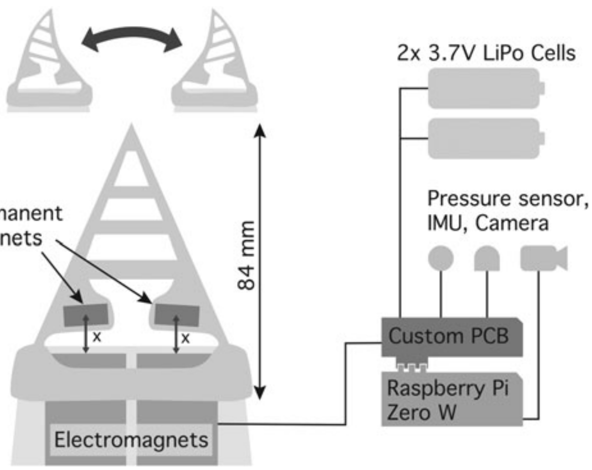


FIG. 2. (*left*) The Fin Ray inspired soft tail design. Attraction and repulsion between the PM embedded in the tail and the EM in the main body cause a flapping motion actuating the underwater robot forward. (*right*) The electrical layout of ESURMA. A custom PCB connects the main microprocessor with Bluetooth and WiFi capability (Raspberry Pi Zero W) with its peripherals. Integrated on the PCB H-bridges drive the EM independently with reversible currents, and two LiPo Cells power the entire device for ca. 50 min. PCB, printed circuit board; PM, permanent magnet.

From within the waterproof main body electromagnets (EMs) apply alternating forces on the permanent magnets (PMs), which are encapsulated in a soft silicone cast tail. Applying a force on the PM at the root of the triangle-shaped tail causes a natural fin-like bend. An undulating movement is achieved when alternating the attractive and repulsive forces on the two PMs. At the tip of the tail, a fin is attached, translating the flapping movement into a forward propulsion.

The main body is a rigid shell, which is sealed with a perimeter gasket and allows easy access to the contained electronics. A fully soft option was discarded, as it would make it more difficult to waterproof the electronics reliably while allowing customization and repairability. The components are 3d printed to allow fast iterations and flexible designs. For high quantity industrial production, molds may be used, to reduce the price per part. The tail, arms, and dorsal fin are independent components that can be interchanged promoting experimentation in swimming behaviors. To maintain a simple design, we avoided the need for active buoyancy control by designing Educational Soft Underwater Robot with Electromagnetic Actuation (ESURMA) with slightly positive buoyancy and adding a rigid dorsal fin that resembles the shape of the hair, ensuring consistency in depth. A stable upright position is achieved by aligning the center of buoyancy straight above the center of mass.

Throughout development, the overall shape stayed consistent. Most iterations focused on improving functionality like waterproofing, opening mechanism, fitting components, and balance.

Methods

Main body

All rigid components are modeled in Autodesk's Fusion 360 CAD software and 3d printed using Stratasys PolyJet printers with Vero filament material. The 1.4 mm thick shell is horizontally split into two parts and held together using eight equidistantly placed screws. A seam around the edge is filled with a sealing gasket ensuring waterproofing. At the top of the head, a window for the raspberry pi camera is created using a glued-on transparent plastic sheet. On the shoulders outside the sealing gasket, a rectangular cavity fits arms, which are locked in position upon closing the two main body shells. To balance the weight of the EM at the thighs of ESURMA, counterweights were attached to the hands of the forward-pointing arms.

Electronics

As shown in Figure 2b the small single-board computer Raspberry Pi Zero W (RasPi) controls ESURMA. Its WIFI connectivity allows remote access, even while floating slightly underneath the surface. A custom printed circuit board was designed, which fits on top of the RasPi, connecting the peripherals, a pressure sensor (TE connectivity MS5803-02BA), a 9DoF inertial measurement unit (MPU-9250), and the EMs. The H-bridge motor driver (L298N) enables precise, immediate and, reversible currents applied to the EMs. Two 3.7 V/850 mAh LiPo batteries are connected in series powering the swimming device for $\sim$50 min under full load (EM draw ca. 1 A at 7.4 V). The Raspberry Pi Camera v2.1 is connected directly to the RasPi. A Python script is used to control the EMs and interface sensors.

Magnetic actuation

A coil (current I; radius r; N loops) generates a magnetic field B_{total} at a distance x along its symmetry axis.

$$H_{single\ loop} = \frac{Ir^2}{2(r^2 + x^2)^{\frac{3}{2}}}$$

$$B_{total} = \mu \cdot \sum_N H_{single\ loop}$$

An attractive or repelling force acts upon a PM placed along its symmetry axis at distance x (Fig. 2 left). Approximating the PM as a magnetic moment based on magnetization M and volume $V, m_{mag} = M \cdot V$, we get:

$$F_x = m_{mag} \cdot \frac{\delta B_{total}}{\delta x} = -m_{mag}\mu \sum_N \frac{3Ir^2 x}{2(r^2 + x^2)^{\frac{5}{2}}} \propto m_{mag}\mu INx^{-4}$$

A coil from 26 AWG enameled copper wire with 800 rounds, an outer/inner diameter of 22/12.7 mm, and a length of 32 mm is placed inside the thighs at the very bottom of the main enclosure. 3D printed guide rails and a turning axis can be used to wind the coil. Through theoretical estimations and practical tests, the values were chosen to maximize forces while respecting the size and input voltage (7.3 V) restrictions. An iron core in the center of the coil increases its magnetic permeability resulting in approximately three times higher forces. Just outside the housing along the axis of the coil an N52 grade cylinder neodymium magnet ($r = h = 6.35$ mm) is encapsulated inside the soft silicon cast tail structure.

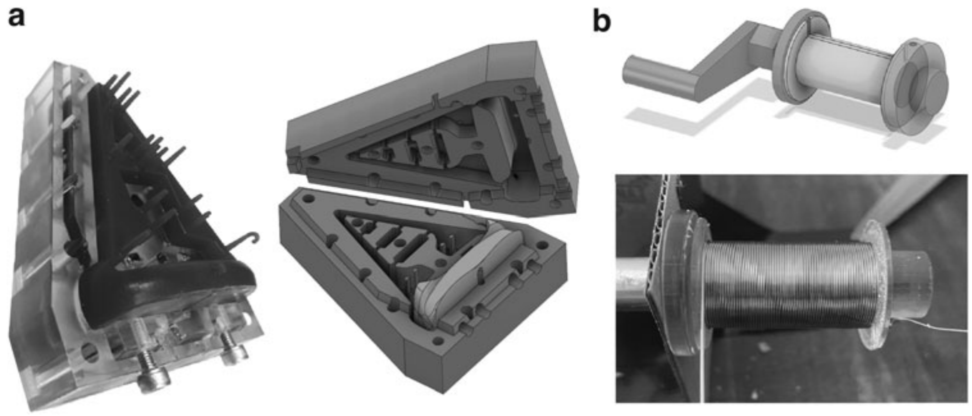


FIG. 3. **(a)** Silicone is injected into the 3d printed mold. The three-part mold is held together using screws, allowing the removal of the cured tail structure. It features vent holes to avoid bubbles formed in the mold and a clamping screw holding the PMs which are then encapsulated by silicone; **(b)** the EMs are wound from enameled copper wire using a custom 3d printed guide.

Soft tail

Smooth Sil 945 with a Hardness Shore A of 45 was used for the final design enabling fine structures while retaining rigidity. A multipart 3d printed injection mold was designed to cast the soft tail structure. The negative of the desired shape forms a cavity in which vent holes were placed at the top. The 3d printed molds and the PMs are held in place with screws (Fig. 3). After injecting silicone with a syringe, it is cured according to its specifications by the manufacturer (4 h at 80°C). Loosening the screws enables one to separate the casted tail from the mold with the magnets resting enclosed in the tail structure. At the end of the tail, a fin is attached, which is cut out from a 1 mm thick acrylic sheet (PMMA). The silicone cast tail wraps around an indentation at the thighs of the main body like a sleeve.

Results

Body

Fitting components into the nonconventional longitudinal humanoid shape posed significant challenges regarding weight distribution, buoyancy, and space. A stable position even while in motion and when actuating different fin sizes is achieved with precise adjustment of counterweights at the forward-pointing hands and inside the waterproof shell. The hair acts as a dorsal fin with the tip sticking out of the water due to overall positive buoyancy. Water leakage did not occur during a 10 h submersion test at 0.5 m depth of only the core main shell. Water leakage did also not occur throughout all speed tests, where the robot swam actively underneath the water surface. No wear or tear was observed after the test sessions. The body is 23 cm long, has a total volume of 780 mL, and weighs ca. 680 g without additional weights (Fig. 4).

Magnet-coil interaction

The force between the coil with an iron core and the PM was investigated (Fig. 5). The Instron 6800 Single Column Series was used to precisely alter their distance while recording forces. When applying no current at the coil an attractive force stemming from the iron core and PM interaction was detected. Applying ±1 A adds additional attractive or repelling force. For small distances below 8.5 mm, only attraction is observed, even for −1 A current applied. To achieve repulsion here the compliant tail structure needs to compensate for the inherent magnetic attractive forces by elastic recoil of the tail elastomer. The crucial parameter causing actuation is the force difference upon applying inverse currents, which increases significantly at lower distances.

Tail response to forces

The detailed design of the tail can significantly change the motion caused due to the force on the PMs. A qualitative preliminary simulation is created to analyze potential structures. The pixels of an image are translated into a 2D node-based spring network. Each node is connected using a virtual spring with its vertical, horizontal, and diagonal neighbors. An external force is applied to the position of the PM, and fixed points are marked. In an iterative approach, the program determines the steady state of the network. Based on the basic triangular Fin Ray shape various design alterations are tested and compared. Results include that reduced side thickness increases bend, increasing horizontal links creates a smoother bend, and connecting the two magnets on the bottom constraints them to stay more horizontal. In addition, abstract new designs can be explored.

With the final design of the tail (Fig. 6) a 20 Hz flapping frequency with full deflection outside the water can be achieved. Higher frequencies of up to 100 Hz were tested and flapping in the respective frequency; however, no full

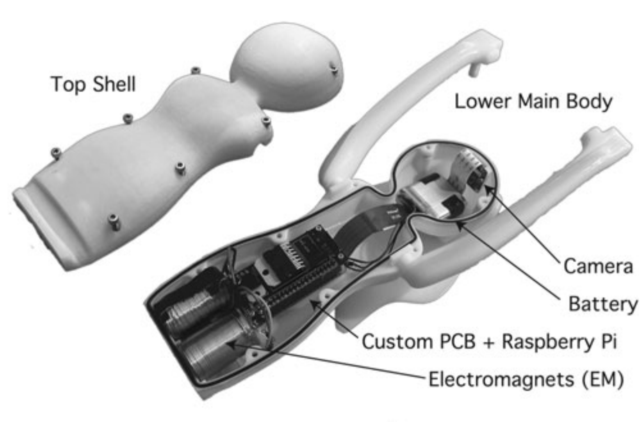


FIG. 4. The main body creates a waterproof compartment housing electronics. It is sealed with a gasket and equidistantly placed screws.

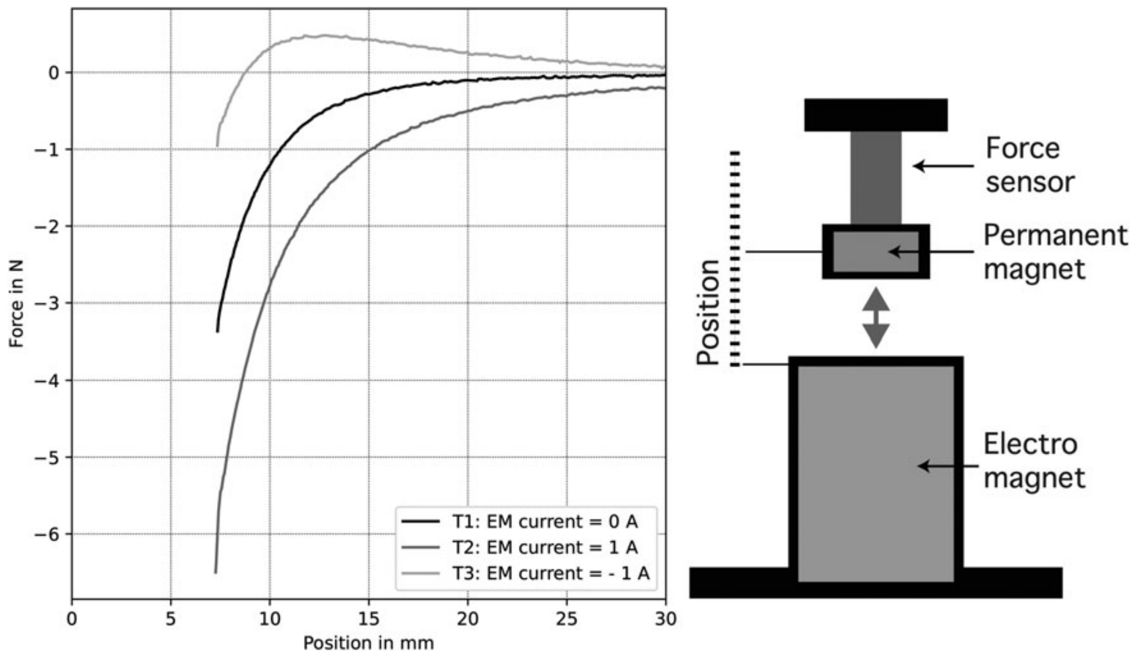


FIG. 5. Force between the permanent magnet and electromagnet at different currents. At lower distance the overall magnitude and the force difference between positive and negative current increase.

deflection of the tail was observed. This confirms that the force transmission between the EM and PM can be considered instantaneously giving a direct and fast response that is only limited by the dynamics of the tail and force applied. This enables optimized efficiency, precision of movement, and control over the exact speed. In water, with a length of tail and Fin 1 at 84 mm and about 70 mm, respectively, we achieved a frequency of 14 Hz, possibly more for smaller fins. This is an order of magnitude higher compared to pneumatically achieved tail frequencies (Table 1). The approximate maximum deflection angle of the fin determined from video footage is 20°.

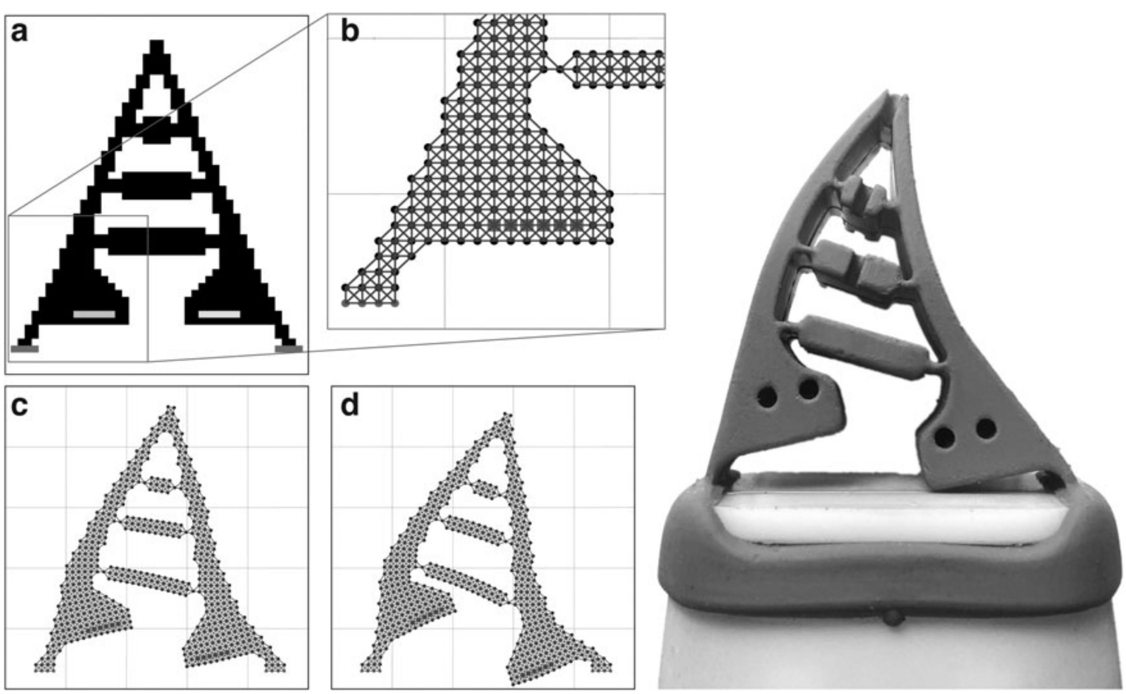


FIG. 6. **(a)** First a 2D bitmap of the tail design is drawn; **(b)** the software interprets each pixel as a node and converts the image into a node-based spring network; **(c, d)** external forces are applied to marked-nodes, indicating the placement of the PM. In **(d)** the force applied is twice the force applied in **(c)**. Through a dynamic iterative approach the response of the structure is determined. (*right*) The final tail design implemented on ESURMA features three horizontal beams.

TABLE 1. PERFORMANCE OF THE UNDERWATER ROBOT AND COMPARISON TO OTHER SOFT UNDERWATER ROBOTS UTILIZING UNDULATORY FIN PROPULSION

	This work	*Berlinger et al.*[13]	*Jusufi et al.*[8]	*Katzschmann et al.*[10]
Actuation type	*Magnetic actuation*	*Magnet in coil*	*External pneumatic*	*Pneumatic*
Full length (mm)	230	160	—	470
Tail length (mm)	84	—	100	150[a]
Fin length (mm)	70	38	70	50[a]
Max undulation frequency (Hz)	14	4.5	1.2	1.5
Max deflection angle (deg)	20	32[a]	45	30
Max speed (cm/s)	14.3	12.2	13	23.5
Cost of transport	7.8	8.2	—	

[a]Rough estimations.

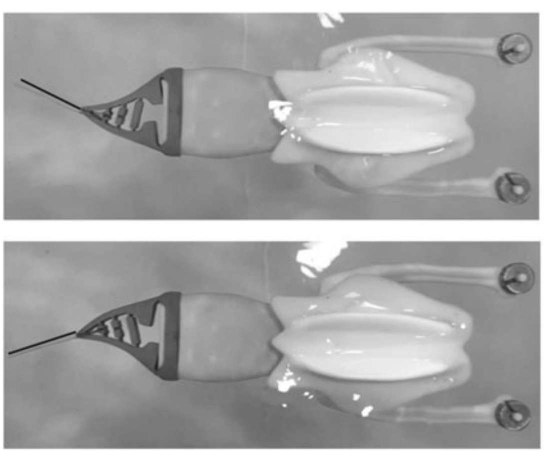
Swimming performance

Swimming performance for a compact (F1) and a tall (F2) fin was measured after an initial acceleration period by manually evaluating footage from a downward-facing camera (Fig. 7, Supplementary Video S1). Both F1 and F2 show an optimum frequency with a maximum speed at 6 Hz, 14.3 cm/s, and 5 Hz, 12.7 cm/s, respectively. The smaller fin is faster with 0.62 BL per second at a higher undulation frequency. No full deflection of the fin is achieved for larger frequencies reducing the propulsion. Maximum power of $1A \cdot 7.4V = 7.4W$ is continuously applied to the coils resulting in a minimum Cost of transport of $CoT = \frac{P}{mg\,v} = 7.8$ at maximum velocity (P = power, v = velocity, mg = body weight). Applying a biased deflection can achieve a turning radius of 30 cm, corresponding to 1.3BL. Berlinger et al. achieved similar characteristics ($v = 12.2$ cm/s; CoT = 8.2) with a smaller turning radius of 0.5 BL due to additional pectoral fins.[13,15] This is on par with other biomimetic robots.[12,22,23] The iSplash-II by Clapham and Hu is significantly faster than this robot and natural fish at 370 cm/s using a rigid multijoint actuation.[24]

Application in the classroom

The modularity of the ESURMA design allows for students to interact with the toolkit at varying entrance points (build, test, and design) based on its curricular placement and grade level. Instructors may also connect multiple courses by combining physics, biology, material science, and computer science aspects (Table 2).

An experiment designed for students to explore ESURMA is called ‘‘Cleaning up the ocean.’’ Figure 8 outlines the activity. Students begin by assembling the aquatic robot according to fabrication guides. Next, students test the ESURMA robot underwater and collect data on its position using cell phone cameras and open-source image tracking software (OpenCV or ImageJ). Next, instructors and students together set the objectives for the design challenge and criteria. Examples may include collecting a set number of markers in a specified time, maneuvering through an obstacle course or an open-ended challenge of the students choosing. The students then spend a few days modifying various components on the robot to achieve the design objective. The modularity of the robot toolkit allows for students at all levels to approach the design from hand cutting fin designs out of acrylic sheets to programming autonomous controls. In one example, the robot collects marked objects, which represent trash. The front facing camera detects the marked objects and steers the robot toward them by changing the bias in the rear fin. A net attached to the robot catches the markers.



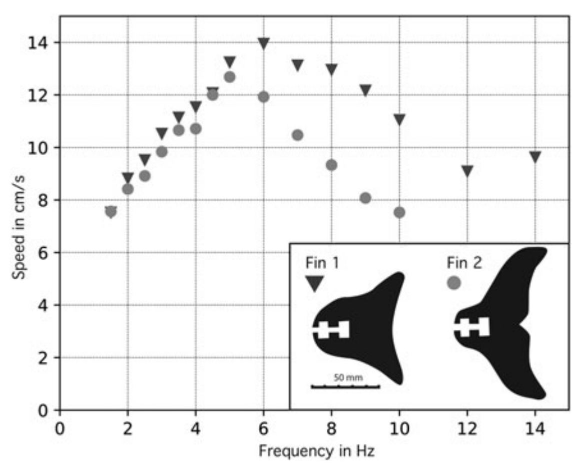


FIG. 7. (*left*) *Top-down* camera footage is used to evaluate the speed and direction of ESURMA. Here, both *right* and *left* tail strokes are shown. (*right*) Two fin shapes were tested thoroughly at various frequencies. The maximum velocity of 14.3 cm/s is achieved with Fin 1. The decrease in speed above 6 Hz indicates that the fin does not reach full deflection and the force is transmitted less efficiently.

Table 2. Educational and Experimental Opportunities for Educational Soft Underwater Robot with Electromagnetic Actuation by Subject

Physics	*Biology*	*Materials science*	*Computer science*
Changing weights and components to understand buoyancy and weight distribution.	Learning about natural underwater locomotion and testing thunniform swimming with ESURMA.	Casting alternative soft tails using custom 3d printed molds. Designs can be based on the simulation provided.	Programming ESURMA using the Raspberry Pi. From simple swimming patterns to autonomous behavior based on the inertial sensor and camera.
Learning about magnetic actuation and working principle of ESURMA	Bioinspiration: Research fish or marine animal properties and replicate them with ESURMA. Recommended examples are fin shape, fin rigidity, or flapping frequency		

ESURMA, Educational Soft Underwater Robot with Electromagnetic Actuation.

Conclusion

Actuation method

The electromagnetic interaction is most prominently present in an electromotor, where cyclic motions in a rigid environment achieve high forces and efficiencies. Translating the technology to soft robotics poses challenges regarding the use of materials and precise placement. In this study, we successfully exploit the fact that magnetic interaction does not require a mechanical connection in the form of a fluidic channel, string, or shaft ensuring a simple and modular implementation. High undulation frequencies demonstrated would require powerful pumps if implemented pneumatically due to the high volume of the liquid pumped. The direct and silent control of the tail enables further biological investigation of fishes with faster tail beats and nondisturbing exploration of marine life.

A critical parameter is the distance between EM and PM. While retaining sufficient range of motion their distance was minimized achieving a Cost of Transport on par with other actuation methods. Changing the design of the EM, optimizing the magnetic permeability, and altering the tail design could increase performance further. Complex, auxetic origami-inspired structures could be explored which translate the low range of motion of the PMs into a higher tail stroke deflection.[25,26]

Educational impact

ESURMA adds a new option for the design of underwater robots with excellent speed, efficiency, and a soft tail design. It is very well suited to be applied in education as it fulfills several unique requirements. The electromagnetic actuation method allows the main body to be fully sealed with a gasket and screws enabling robust waterproofing and complete disassembly. This makes it possible to reuse the kit with multiple students multiplying the experience of assembling and understanding the construction principle. The two arms, soft tail, and fin can be interchanged within seconds allowing high creativity in modifying ESURMA. The humanoid, mermaid robot is built from inexpensive parts adding up to about 80 dollars. Further cost reduction can be achieved by leaving out the sensors reducing the price by half and still enabling autonomous swimming. The most challenging fabrication steps of ESURMA consist of winding EM, soldering the PCB, and casting the soft tail. These steps do not require expensive tools or equipment and

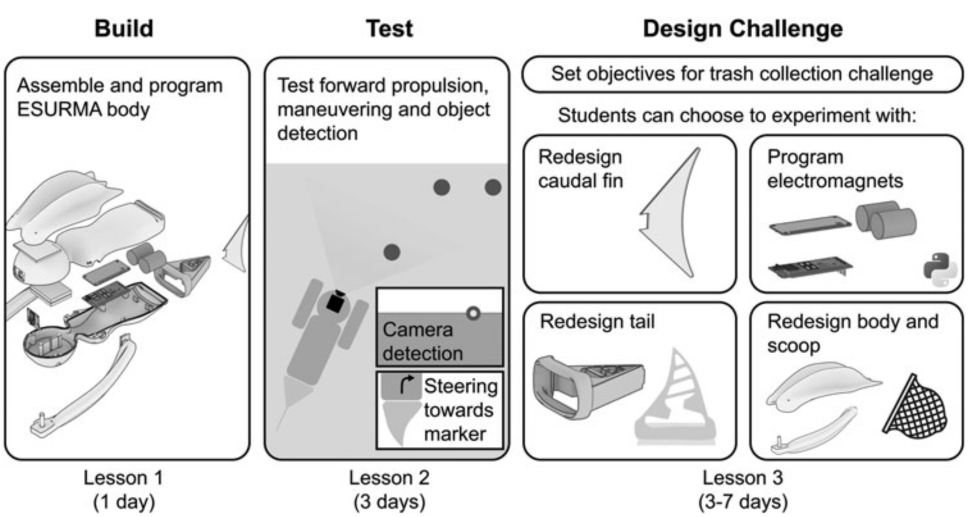


FIG. 8. An example experiment for the classroom, which is divided into three phases. In a first phase the underwater robot is assembled from the individual components. Next, the characteristics of the robot are tested and analyzed. In a final open design challenge, one sets objectives and tries to fulfill them by experimenting with one domain of the robot.

even the soft silicone tail can be cast in a classroom environment if molds are provided.

Outlook

Future developments of ESURMA could include implementing sensors into the tail, providing feedback on deflection, and closed-loop control. Adding an active buoyancy control could make three-dimensional swimming in large open waters like the ocean feasible. This would enable the silent robot to explore marine life or detect plastic material in the ocean using the front-facing camera. The concept of integrating magnetic components in soft structures has large potential for many applications. Thanks to easy, silent, and direct electrical control, many actuators could be used synergistically, utilizing computational design and in-depth simulations, to achieve complex motion with large forces. Such highly responsive, strong, and complex actuators could be applied in all soft robotic applications.

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Authors' Contributions

R.H., A.B., and C.J.W. conceived the work. R.H. and A.B. designed the layout. R.H. fabricated the devices, performed the experiments, and developed the models. H.M.G. developed the curricular framework. All authors participated in writing the article.

Author Disclosure Statement

No competing financial interests exist.

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Supplementary Material

Supplementary Video S1

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