1. Introduction

Locomotion is the essential ability for the survival of animals in nature as it is required to prey on, flee from predators, and even move to their microhabitats. Particularly, underwater locomotion appears to require a tremendous amount of energy because water exerts a counteractive drag force against the progressing direction. However, marine animals are reported to expend a much lower cost of transportation on locomotion than aerial and terrestrial species like birds or humans,[1] largely because they utilize intermittent gliding interspersed with energetic locomotion to reduce energy. Despite their divergent evolutionary background, marine vertebrates actively sway their tails to ascend in water and perform much fewer locomotive activities as they glide downward so that they can simply translate the potential energy into the horizontal traveling distance.[1,2] Notably, it is reported that Weddell seals (Leptonychotes weddellii), for instance, can travel a distance as far as 380 m as they descend 80 m downward during prolonged underwater
gliding. As evidence of convergent evolution, such a generic behavior can be observed in most marine mammals, regardless of the propulsion mechanism and body size to save the aerobic cost of energy for locomotion.\[^1\]

On the other hand, significant efforts have been dedicated to making soft swimming robots and even mimicking marine animals’ propulsive mechanisms.\[^11\]–\[^14\] To freely move in the underwater environment in the presence of antagonistic drag force, the marine species resort to different propulsive mechanisms, which can be classified into three main categories, including 1) body/caudal actuation (BCA) that uses the main body or caudal fins for locomotion; 2) medium/paired actuation (MPA) that utilizes fins other than caudal fins to locomote; and 3) jet propulsion which fills the muscular cavity and forces out water as a means of propulsion just as jellyfish and cephalopods move. The BCA and MPA modes can be subdivided into oscillatory and undulatory modes depending on the swimming mechanisms.\[^15\] The undulatory mode produces a traveling wave along the body or fins to repel water rearward, exemplified by eels and rays. In contrast, the oscillatory mode propels itself largely using a fin that oscillates periodically as tuna and sharks move.\[^11\]–\[^16\]

Several studies on underwater robotics successfully mimicked the propulsive movements of MPA-U\[^6\] and -O\[^12\] while a large number of fish-like robots replicated the locomotion of BCA-O,\[^7\]–\[^11\],\[^13\]–\[^14\],\[^17\]–\[^19\] and BCA-U.\[^56\]–\[^57\] Besides MPA and BCA modes, other studies attempted to imitate the locomotive motion of jellyfish\[^20\] and scallop\[^21\] that represents the jet propulsion mechanism, while other underwater robots included locomotion of the crawling movement of octopus,\[^19\] swimming of turtle,\[^13\] crawling/swimming of starfish,\[^12\] and breaststroke movements of frogs\[^21\] that do not fall into any of three categories of propulsive mechanisms. Most of these underwater robots that mimic MPA, BCA, and jet propulsion rely on soft components because rigid materials limit replicating the natural propulsive locomotion of different marine species with soft exoskeletons. However, none of these soft robots demonstrated the strategic locomotion of marine vertebrates despite their highly effective mechanism (see Table S1, Supporting Information, for comprehensive comparison). Previous literature focused on realizing the intermittent locomotive gliding, but it can also make a turn to steer the direction, demonstrating that it can freely move in all three dimensions in the water by simply controlling localized buoyancy. Finally, to further illustrate the practical applicability, we demonstrated that Flatfishbot can act as a miniature cargo-submarine that delivers the cargo underwater, and we also attached a water-proof camera to Flatfishbot for operation as an underwater spy drone or miniature inspection unit to convey valuable information about the underwater environment.

2. Result and Discussion

2.1. Overview of the Soft Robot Architecture and Its Functional Components

Figure 1a depicts the graphical representation of the locomotive activity of various marine vertebrates to improve transport cost. These species perform a high level of locomotive activities only as they ascend in water and then show notably decreased locomotion as they dive into the depth.\[^1\]–\[^11\] To better reproduce such a locomotion pattern, we designed the soft pneumatic actuator based on the TE effect that enables a substantial reversible volume change with a rapid response time as in Figure 1b as the movement of the marine animals involves an enormous depth change. The TE effect, or Peltier effect, allows the electrons in the n-type TE leg and holes (p-type TE leg) to diffuse toward one side of the junction in the presence of the electrical potential, causing the one side where the electrons and holes are densely populated to heat up while the other side where the charged carriers are sparsely populated to cool down (Supporting Information Note 1). This also implies that we can interchangeably switch between the heating and cooling modes just by reversing the direction of the electrical current because the surface that has been heated up due to the densely populated charged carriers can be cooled down according to the direction of the electrical current. Indeed, the TE actuation can be operated with a semi-permanent lifespan of a minimum of 200 000 h.\[^14\] In addition, the soft pneumatic actuators do not require any auxiliary bulky and heavy pump or air chamber that most of the pneumatic actuators need to exert the force to the subject as actuators
proposed herein thermally induce the reversible phase change of the fluid. Such a pumpless configuration allows the entire system to be lightweight, minimal, and noise free so that it can provide desirable features for underwater applications. Previously, several studies used Joule heaters to fabricate pneumatic actuators.[35–37] Still, these actuators suffer from the slow response time to return to the liquid state because it solely relies on natural convective cooling to induce condensation. To address this issue, we used the bimodal soft TE device capable of heating and cooling the fluid inside the chamber, expediting the vapor-to-liquid transition (deflation of the chamber) by refrigerating the fluid with the active TE cooling mode. In a way, the TPA units resemble the air bladder of a specific fish type of whose volume can freely change by the gas exchange with the blood vessels to control buoyancy when they need to move upward or downward.[38] Prior works report the buoyancy engines, but they could only move up and down without traveling in a 3D space. In addition, they lack the cooling mode just like other pneumatic actuators, relying solely on the natural convection for the vapor–liquid transition and slowing down the response time. [39,40]

Figure 1c shows the overall internal structure of soft TPA that consists of TE legs interconnected by the Cu electrode and an inflatable chamber that is filled with engineered fluid. Boron nitride micropowder was incorporated into polydimethylsiloxane (PDMS) to improve the thermal conductivity of the elastomer so that it enhances the heat transfer between the TE device and the engineered fluid. As depicted in Figure 1d, four inflatable TPA units are added to the front, rear, and sides of the robotic fish to manipulate the localized buoyancy for fine tuning the spatial orientation and net buoyant force of the soft robotic fish. Figure 1e graphically illustrates the functional components (TPA units, printed circuit board, and battery module) and simple

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**Figure 1.** Simplified representation of the intermittent gliding locomotion of the marine vertebrates and overview of soft robot architecture and its functional components. a) Relationship between the locomotive activity of marine vertebrates and corresponding ocean depth where they are situated. Please note that the graphs in the figure are reconstructed illustrations based on the previous study. b) Photographs of the reversible deflation and inflation of TPA by liquid–vapor phase transition. c) Graphical illustration of Flatfishbot with the TPA units switched on and off. d) Internal structure of the soft TPA unit that comprises a soft substrate, copper interconnecting film, TE legs, and elastic chamber. e) Top view of Flatfishbot integrated with its functional components. f) Free-body diagram of the forward ascending, forward gliding, and turning modes of Flatfishbot.
architecture of the soft robotic fish that mimics the body shape of the olive flounder for efficient hydrodynamic locomotion. Detailed information on materials and fabrication method will be discussed in the Experimental Section.

Figure 1f presents the 2D free-body diagram of the cross-sectional Flatfishbot that consists of all applied forces on the system during 1) forward ascending; 2) forward gliding; and 3) making a turn, explaining the basic locomotive mechanics of soft robotic fish. Lift force, which is induced when the external fluids ($V_m$) exert a force on the surface of the robotic fish at motion, mainly participates in the dynamic forward movement both during ascending and gliding. In the case of the forward ascending motion, the rapid TE heating mode vaporizes the engineered fluid inside the chamber and shifts the center of buoyancy (COB) toward the inflated TPA(s), which creates the tilted orientation of the robotic fish. Then, as the net buoyancy of the entire robotic system becomes positive, Flatfishbot starts to float and produces a lift force that is perpendicular to the moving direction, generating $+x$ component force in the $x$-axis and therefore inducing the forward movement as it ascends to the surface. When Flatfishbot glides downward, on the other hand, the front and side TPAs switch to the cooling mode, and the rear TPA is quickly heated with active TE heating, making the soft robot face toward the bottom. Similarly, the net negative buoyancy causes Flatfishbot to sink. However, a certain proportion of lift produces force in $+x$-direction as it moves down, therefore contributing to the forward movement in the course of its gliding motion. Notably, the tilted orientation of the robotic fish plays an essential role in generating forward motion both when it goes up and down because it determines the direction of the lift force. Supporting Information Note 2 compares the physical parameters for Flatfishbot's physical locomotion with numerically calculated values. It indicates that the movement behavior matches well with the numerically simulated result.

Apart from the forward movement, the underwater robot developed herein can change the direction by utilizing the same TPA mechanism. 1) Two TPA units (on the side of the robotic system) and 2) the vertical rudder on the tail play a crucial role in conjunction to make a turn as in the third graphical image of Figure 1f. Please note that activating one of two side TPA units (a left chamber, for instance) creates a difference in buoyancy and therefore tilts its orientation in a roll axis (e.g., tilts toward the right chamber). Yet, without the rudder, simply inflating a single TPA on the side does not enable the robotic fish to make a turn: it rather follows a diagonal path across the fish tank. On the contrary, the vertical plane of the rudder creates a side force in the $y$-axis direction and generates a moment around the $yaw$ axis. This way, the robotic fish can switch its direction depending on which side TPA to activate, thus indicating that it can explore the underwater environment in all three spatial dimensions. We are fully aware that the olive flounder does not have a rudder-like structure to make a turn. The primary focus of this research was to develop a soft robotic fish based on biological inspirations from marine animals, not to replicate the complete anatomy of the marine animal. Therefore, we intentionally incorporated the vertical rudder structure into the design of the soft robotic fish for the additional locomotive functionality so that it can freely make a turn without resorting to other propulsive mechanisms such as mechanical pumps or motors.

2.2. TPA Unit Characterization and Optimization

Taken with visible and infrared (IR) imaging cameras, Figure 2a records transient moments of rapid inflation and deflation that a single TPA module underwent in a unit cycle. We used 3M Novec 7000 engineering fluid with a boiling point of $34^\circ C$, slightly higher than room temperature. Thus, the chamber inflates if the TE device is in the heating mode to vaporize the engineering fluid, and its overall buoyancy increases. The same applies to the cooling mode that induces the vapor–liquid transition and reduces buoyancy. The TPA unit consists of minimal ($28 \text{ mm} \times 28 \text{ mm} \times 5 \text{ mm}$), lightweight (6.9 g), and bimodal hardware because the system does not require an external pump. Such characteristics fully satisfy the purpose of the research, because 1) it would be favorable to control buoyant force if the net buoyancy of the system is close to neutral buoyancy and 2) the capability of TPA to heat and cool fulfills the shortcomings of the conventional thermal pneumatic actuators.

The following thermodynamic process epitomizes the TPA unit cycle of inflation and deflation. The active TE heating mode vaporizes the engineered fluid. It, therefore, leads to a swift rise in the volume of the chamber, which in turn increases buoyancy on a localized region of the underwater robot. The active TE cooling mode of TPA, on the other hand, serves to condensate gas inside the chamber into a liquid, which corresponds to the deflation of TPA. In addition, the rate of inflation, as well as deflation, can be fine turned as in Figure 2b simply by controlling the magnitude and direction of the electrical current in the TE device. [43]

Quite obviously, it indicated that the higher the electrical power is, the faster the TPA module reaches and exceeds the neutral buoyancy. This implies that applying programmed electrical inputs on each TPA unit would enable us to control the 3D locomotion of Flatfishbot.

Furthermore, the thermal pneumatic actuators, despite desirable characteristics such as a pumpless and noise-free nature, suffer from a slow response rate because it relies solely on natural convection cooling for the fluid to return to the liquid state. Such a critical drawback of the thermal pneumatic actuator slows down the response time and hence increases the unintended locomotive error of the soft robots. However, the TE device can directly address the issue of the thermal pneumatic actuators, because it can interchangeably heat/cool with the single device structure depending on the direction of the electrical current. [41]

Therefore, after the complete inflation of the chamber, the TE device can switch to the cooling mode to quickly deflate the chamber. Figure 2c delineates a direct comparison between the TE cooling and natural convection to induce the phase change back to the liquid state by measuring the transient volume difference of the pneumatic chamber with both devices submerged into water. The result suggests that TE cooling substantially accelerated the chamber deflating process by $\approx 6.67$ times faster than natural convection, further implying that the incorporation of the TE device into the underwater robotic design architecture would shorten the response time and allow more accurate control of the final prototype.

TE heat transfer in the particular underwater application also exhibits higher thermal efficiency than conventional Joule heater. We selected Joule heating as a counterpart to be compared with
because it is widely used to induce the liquid–vapor transition in many previous thermal pneumatic actuators. Figure 2d compares the heating performance between the TE device and Joule heater by applying the identical magnitude of electrical power while recording the surface temperature of both devices with the IR camera. The result indicates that TE heating
generates more than twice the higher temperature than Joule heating, and the primary reason for such a large discrepancy lies in how the heat transfer occurs in two thermal models. For the Joule heating case, heat transfer occurs in an isotropic way, so a considerable proportion of heat dissipates into the water, which works as a semi-infinite thermal reservoir. This implies that not all heat generated by Joule heating would be used to contributing to inducing the fluidic phase change. In the TE heat transfer, on the other hand, a heat differential is formed in the cross-plane direction of the device, indicating that the heat is transferred in a highly anisotropic manner because the opposite side of the device would cool down when the heating mode is switched on to inflate the chamber. Thus, instead of dissipating a substantial amount of heat into the water reservoir, the anisotropic heat transfer of the TE device promotes heat flow from the water to the device and further to the engineered fluid inside the chamber. Such a heat flow, as is illustrated in the inset of Figure 2d, explains the reason for the huge difference in thermal efficiency between two thermal devices.

Moreover, the conventional TE system must include the additional heatsink to absorb heat generated on the other heated side of the TE device when it is supposed to cool the arbitrary subject. The absence of the heatsink on the TE system usually causes severe deterioration of the TE cooling performance, which even results in the temperature surge much higher than room temperature even if the original intention was to cool. Yet, operating the TE device in the underwater environment directly settles down this issue, because water possesses a much higher heat transfer coefficient than air ($h_{Hx\text{ water}} \approx 0.01$ W cm$^{-2}$ K, $h_{Hx\text{ air}} \approx 0.0005$ W cm$^{-2}$ K). The absence of the heatsink on the TE system usually causes severe deterioration of the TE cooling performance, which even results in the temperature surge much higher than room temperature even if the original intention was to cool. Yet, operating the TE device in the underwater environment directly settles down this issue, because water possesses a much higher heat transfer coefficient than air ($h_{Hx\text{ water}} \approx 0.01$ W cm$^{-2}$ K, $h_{Hx\text{ air}} \approx 0.0005$ W cm$^{-2}$ K).

Figure 2f explains the reason for the huge difference in thermal efficiency between two thermal devices.

2.3. Outer Shell Design and Untethered Module

To enhance the hydrodynamic efficiency of the robotic fish during its locomotion, we conducted a numerical simulation to compare several soft shell designs as in Figure 3a, as the external structure would significantly affect the lift and drag forces. To make greater use of localized buoyancy for controlling the spatial configuration of the robotic fish, we only considered relatively flat designs for the outer elastomeric shell of the robotic fish because the further away TPAs are from each other, the greater magnitude of torque they would create in the presence of localized buoyancy difference among TPAs. Hence, along with the common geometric models such as triangle (isosceles, right), trapezoid, and rectangle, we also tested the shapes that mimic those of flatfish species in nature, such as flounder and ray-fish because their exteriors would have likely to be evolved in a way that hydrodynamically enhances their swimming effectiveness over time. Since the higher lift-drag (L/D) ratio usually results in efficient locomotion, L/D was numerically computed as a function of angle of attack based on the assumption that water flows at a velocity of $0.2$ m s$^{-1}$ against the subjects. The result shows that the geometrical framework of flounder exhibits the highest L/D value of 3.22, and the angle of attack between 6° and 14° yields the high L/D values, suggesting that the initial orientation of Flatfishbot during forward ascending and gliding must follow the obtained angle of attack to boost its swimming efficiency. To further optimize the outer soft-shell geometry, we calculated L/D with varying a/b ratios, and the result implied that L/D begins to plateau at the range of a/b $> 2$ (Figure 3b). We set the a/b $= 2$ as the optimal design because larger a/b values would unnecessarily enlarge the size of robotic fish and make it less likely to swim into the small cavities in actual strategic applications. Therefore, we applied the optimized design to the robotic fish’s soft outer shell, which resembles the olive flounder as in Figure 3c. Supporting Information Note 3 compares the configuration of Flatfishbot and actual olive flounder in nature.

Furthermore, we implemented the wireless module with multiple sensors to further develop Flatfishbot into a fully untethered robotic unit. However, tethered robotic systems suffer from several limitations that hurt the functionalities of the robotic fish, especially for underwater applications. Primarily, the tethered robots can travel only within the designated distance because it is wired to the rigid power source through the electric cable. In addition, tethering might exert tension force to the robots with relatively small mass and thus might affect their overall locomotion inside water. Finally, supplying power through an electric cable poses a danger to the aquatic ecosystem and might harm the aquatic organisms.

In this regard, to develop the untethered platform for TPAs and the overall system, we designed the board circuit that consists of 1) a microcontroller unit; 2) a heating/cooling relay for each bimodal TPA unit; 4) a sensor module; 5) an antenna...
for wireless communication; and 5) battery modules with the flow chart in Figure 3d. To interchangeably switch between the cooling and heating modes in the course of motion, we used relays to alternate between inflation and deflation of TPA units. Furthermore, the embedded sensor module, which consists of pressure and gyrosensor units, performs an essential task to provide the real-time spatial information of Flatfishbot for human users to pilot the soft underwater robot. The pressure sensor unit delivers data on the water depth at which Flatfishbot is situated at the moment, and it must be noted that the soft body of Flatfishbot enables pressure sensing from the interior of the soft robot because the volume of Flatfishbot changes simultaneously, according to the water depth. Such a system allows facile pressure sensing and even prevents the sensor unit from being damaged by external force because it is situated inside the underwater robot. On the other hand, pressure sensing from the interior of the robot cannot be easily realized on the underwater robot based on rigid materials. It reflects the advantage of soft robotics in the underwater environment. The gyrosensor also conveys meaningful information on the 3D orientation of the robotic fish, such as roll, pitch, and yaw, as its orientation determines the direction of the lift force. Hence, the wirelessly transmitted information on its orientation can then be applied to adjust its position for a desirable angle of attack as it moves forward. To power the TPAs and microcontroller, we used two separate battery modules for constant heating and cooling modes: 7.4 V 2500 mAh LiPo battery for the heating mode (and powering microcontroller via the 3.3 V regulator) and a couple of 1.2 V 2000 mAh NiMH batteries connected in series for the cooling mode (Figure S1, Supporting Information). It is calculated that a single charge would power Flatfishbot for 60 min (equivalent to 36 cycles of continuous forward ascending and gliding alternation and 72 m in distance) owing to the relatively economical locomotion mechanics of Flatfishbot. Finally, we integrated all the components into the soft outer shell fabricated by thermally crosslinking elastomers and commercial brown-color dye inside the 3D-printed polylactic acid (PLA) mold, as shown in Figure 3e.

2.4. Demonstration of Flatfishbot and Its Potential Applications

With the fully assembled prototype based on the previous design factors, we demonstrated the forward movement of Flatfishbot while wirelessly delivering commands to TPAs and collecting data of Flatfishbot in the fish tank with a dimension of 70 mm (width) × 200 mm (length) × 80 mm (height). Figure 4a demonstrates that Flatfishbot moves forward by drawing a sinusoidal trajectory as it ascends and glides (details in Video S1, Supporting Information). Flatfishbot faces upward when the front and side TPA heat the fluid inside the chambers...
Figure 4. Demonstration of Flatfishbot and its potential applications. a) Snapshots of the moving path that the Flatfishbot went through to simulate the forward gliding locomotion of the marine vertebrates and corresponding pressure, gyrodata during locomotion. b) Flatfishbot demonstration of changing direction to make a turn (top and side view) and corresponding sensor data. c) The maximum weight that Flatfishbot is capable of carrying as a submersible miniaturized cargo robot. d) Photographed moving route of the water-proof camera-attached Flatfishbot and corresponding recorded video snapshots during the locomotion to examine its potential to operate as an underwater spy/inspection robot.
to fully inflate, and Flatfishbot ascends forward as the side TPAs start to inflate. As Flatfishbot hits the water surface, the front and side TPAs quickly switch to the cooling mode to deflate while the rear TPA fully inflates the chamber, which serves to tilt the orientation of Flatfishbot downward. Then, Flatfishbot glides down as the front and side TPAs fully deflate. The entire cycle repeats as the rear TPA deflates. Flatfishbot travels at the average velocity of 10.3 cm s\(^{-1}\), equivalent to 0.515 body length per second. Simply using the gliding locomotion by controlling localized buoyancy, Flatfishbot exhibited comparable or even faster velocity than other underwater soft robots that utilize auxiliary components for generating a thrust force such as servomotors, pneumatic pump, dielectric elastomer, and shape memory alloy to mimic the propulsive mechanism of aquatic animal (See Table S1, Supporting Information). In addition, graphs below the series of Flatfishbot snapshots exhibit corresponding sets of real-time data collected by the pressure and gyrosensors, which were in turn used to pilot the locomotion of Flatfishbot. We expect that incorporating thrust components such as a servomotor that produces a thrust force would boost the performance of the robotic fish by far. Nevertheless, we believe that the addition of such components would dilute the original focus of our work, which is to mimic the efficient locomotion behavior to drive the robotic fish in 3D space in the underwater environment without any conventional unit. Future work will incorporate such components into the current system such that it can exceed the swimming speed of other underwater robots. Similarly, turning TPAs on and off all at once make Flatfishbot move only in the vertical direction as in Figure S2 and Video S2, Supporting Information. Please note that we could control the spatial orientation of the robotic fish when it moved up by activating all TPAs in the video. At first, the pitch values turned slightly negative as it ascended vertically to the water surface because inflating rate differed between the front and rear TPA. Then, we increased the electrical input value of the rear TPA to balance the orientation of Flatfishbot, as shown in the video and the transient pitch graph.

Figure 4b, on the other hand, demonstrates that the underwater robot can also make a turn to steer the direction of progress, owing to the side TPAs and a rudder structure as they collectively produce the side force, which is translated into torque and makes the underwater robot rotate about the z-axis around its center of mass (COM) (Video S3, Supporting Information). As can be seen from the yaw value in Figure 4b, it rotates by 70° in a clockwise direction until it hits the glass wall of the fish tank. We believe that the soft robotic fish can rotate further and even make a full U-turn with a bigger tank. For other values obtained from the pressure and gyrosensors, please refer to Figure S3, S4, and S5, Supporting Information, (forward movement, vertical movement, and making a turn, respectively). Capable of moving forward, vertically, and making a turn, the Flatfishbot is expected to travel in all three dimensions inside the water freely. For example, Flatfishbot can also operate as a miniaturized submersible cargo submarine as it can generate buoyant force that is large enough to load the additional object. Figure 4c and video S4, Supporting Information, show a series of scenarios in which 1) Flatfishbot approaches the dyed elastomer block; 2) makes magnetic contact; and 3) carries the elastomer block to the destination. We adhered the magnets both on the abdomen of Flatfishbot and elastomer block so that the elastomer block does not fall off the robotic fish in the course of the journey (the dimension and mass of the elastomer block were 77 mm × 86 mm × 11 mm and 70 g, respectively). Flatfishbot does not travel as far as it can move without the cargo because the cargo itself increases the overall weight of robotic fish and affects drag force. Still, the demonstration corroborated the practical usage of Flatfishbot as a miniaturized cargo submarine.

Furthermore, to demonstrate that the identical structure can be adapted to an underwater spy drone, we attached the commercial waterproof camera (the total camera mass of 31 g) to Flatfishbot with the camera facing toward its right so that it can record the ex situ video during the course of its journey (See Figure S6, Supporting Information, for the experimental setup). This way, Flatfishbot can act as an aquatic exploration or spy drone and thus be deployed to record a video to inspect the underwater environment (Figure 4d and Video S5, Supporting Information). It is expected that Flatfishbot is especially appropriate for such an application as it does not generate noise, unlike bulky motors or engines that usually would propagate undesirable vibration inside water and agitate marine animals. In this regard, future work will include formulating a collective swarm of multiple Flatfishbots wirelessly connected to exchange information due to a simple and scalable fabrication process to manufacture a single unit of Flatfishbot such that a swarming unit can inspect a much wider space and perhaps open up possibilities for more strategic actions.

However, one of the significant limitations of wireless control originates from its short communication range, as electromagnetic properties of water inhibit its propagation and induce critical attenuation.\(^{[47]}\) Future work will replace the current Bluetooth wireless communications with the acoustic communication platform for long-range application as the previous literature demonstrated that the acoustic communication is capable of communicating within hundreds of kilometers.\(^{[48]}\) In addition, we will add the TPA operation in the underwater about the water depth. Figure S7. Supporting Information, shows the relationship between the buoyant force and water depth of a single TPA unit. It suggests that the deeper the water depth gets, the smaller the TPA generates with identical electrical input. The reason is that water exerts counteractive pressure against the TPA, and water pressure heightens as the water depth increases. Thus, to generate the same buoyant force regardless of water depth, we will incorporate a deformable strain sensor into the inflatable chamber of the TPA. This sensor will provide sensory feedback for the TPA to control the buoyant force depending on the water depth.

3. Conclusion

This article reports an untethered soft robotic fish that can mimic effective gliding locomotion inspired by marine vertebrates saving aerobic energy based on selective manipulation of localized buoyancy. The bimodal TPA units reversibly change the fluid phase with a rapid response time to control localized buoyancy, facilitating the robot’s gliding locomotion. The integrated wireless module allows bidirectional communication with an operator while receiving real-time physical information from
the pressure and gyrosensors. With an integrated soft structure, the robot could simulate the sinusoidal locomotion of the marine vertebrates and make steer turns. As a result, the fishbot moves faster than most previous fish robots, even without thrust force generation, showing the energy efficiency of the intermittent gliding mechanism. Finally, this work demonstrates the robot's practical usage as a cargosubmarine or underwater inspector to examine the aquatic environment. We expect that the presented soft robotic structure with miniaturized pneumatic actuators can be used to develop various types of underwater robots.

4. Experimental Section

Material Preparation: PDMS (Dow Corning), Ecoflex 00-30, Dragon Skin 10, Sil-poxy silicon adhesive and Silc Pig color dye (Smooth-On), Bi$_2$Te$_3$ TE legs (Wuhan XinRong New Materials Co., Ltd), 25 μm thick Cu foil (Alfa-Aesar), and boron nitride powder (Graphene Supermarket) were used. All materials were used as received without purification. 0.25 μm Ni wire (Sigma Aldrich) was used.

Fabrication of TE Actuator: Boron nitride powder was incorporated into PDMS in a weight ratio of 1:5 to boost the thermal conductivity of the silicone elastomer, and the mixture was spin coated at 350 r.p.m, followed by 60 °C electric oven curing for 30 min. After curing, a copper foil was placed on the thermally conductive elastomer substrate and then laser ablated (Nano Air 355-3-V, Innolas, λ = 355 nm) to form an interconnection electrode, on which the boron nitride/PDMS slurry mixture was successively spin coated at 1000 rpm and cured at 60 °C for 30 min to encapsulate the Cu electrode. Afterward, rectangular holes of thermally conductive elastomer were laser ablated without affecting Cu electrodes and then carefully peeled off to expose the Cu electrode for interconnection. The counterpart-encapsulated Cu electrode was fabricated using the same process. Cream solder was screen printed on the exposed Cu electrode so that alternating p-type and n-type TE Bi$_2$Te$_3$ legs could be mechanically soldered to the Cu electrode at 260 °C for 15 min with mechanical pressure. Now, Bi$_2$Te$_3$ was soldered to the other counterpart Cu electrode so that the TE legs were connected in series. Then, the TE device was placed in a Petri dish filled with slurry PDMS paste in the vacuum environment so that voids among TE legs were completely infiltrated with PDMS. Finally, the TPA was fabricated after the rectangular Ecoflex 00-30 chamber, which was cured on the 3D-printed PLA mold and was attached to the top of the TE device. The graphical schematic on the fabrication process is provided in Figure S8, Supporting Information, for better understanding.

Characterization of TE Actuator: Buoyant force in this work was calculated by placing the TPA unit inside water and then measuring the water level difference while applying electrical input to the TPA, unit as illustrated in Figure S9, Supporting Information. Comparing the heating performance between a TE device and Joule heater in Figure 2d was done by measuring the surface temperature (with the chamber removed) of two thermal devices with IR camera (FLIR A645), while their opposite sides were in contact with water to simulate the underwater environment (the Joule heater was made up of a commercial Ni wire with 250 μm diameter in a multilowered form inside a thin film of PDMS block). Likewise, the TE cooling performance comparison operating between 1) underwater and 2) in air was conducted by measuring the surface temperature with the IR camera, while the opposite side of the device was either in contact with water or air, as illustrated in Figure S10, Supporting Information.

Simulation for the Soft Robot, Circuit Design of TPA, and Integration: COMSOL simulation was used to calculate the I/D and angle of attack first to determine the shape and further optimize the design of the robotic after the shape was decided with the assumption that water flowed at the constant velocity of 0.2 m s$^{-1}$. About the TPA circuit design, a single 7.4 V battery and two 2.4 V batteries were used to power four units of TPAs and microprocessors. As TPAs in this study must interchangeably alternate in between the TE heating and cooling mode, the single-pole, single-throw (SPST) relays were used to switch between two thermal modes. The 7.4 V battery was responsible for relaying the heating mode and powering the microprocessor at 3.3 V using a regulator. Two 2.4 V batteries connected in series were used to relay the cooling mode of the device. The RF wireless communication was used because a longer wavelength ensures communication for a longer distance. Finally, the outer framework of the soft robotic fish to integrate all the functional components was made by curing Dragon Skin 10 on 3D-printed PLA molds at room temperature (because the heat treatment thermally deformed the PLA molds) with a small addition of brown Silc Pig dye into the Ecoflex 00-35 to mimic the actual color of olive flounder.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

J.L., Y.Y., and S.K. conceived the idea. J.L., Y.Y., H.P., J.C., and Y.J. conducted experiments and developed software. Y.J. designed 3D rendered images. S.K. and W.Y. funded the project and guided the research. J.L., W.Y., and S.K. wrote the paper.

Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.

Keywords

biomimetics, locomotion, pneumatic actuators, soft robots, thermoelectric devices, untethered electronics

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