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Development of a Fish Robot Equipped with Novel 3D Printed Soft Bending Actuators

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Abstract—**This paper reports on design and fabrication of a novel soft fish robot. Application of soft actuators for the fish tail will generates continuum bending motion which resembles the natural motion of the fish. However, most soft actuator mechanisms are complex and have low efficiency. Thus, to address this issue we have developed a 3D printed soft bending actuator which can be actuated with an electromotor. The basic design idea of the soft bending actuator is explained, and iteration of the design showed to create the desired motion for the soft tail. The soft actuator has been successfully integrated with fish body and it has been shown that the fish can swim.**

Keywords: Soft Actuator, Fish Robot, 3D printing

I. INTRODUCTION

Soft robotics is an emerging field of research that studies biomimetic design of robots [1]. Over the past decade, researchers have developed several soft actuators including ionic [2], thermal [3], chemical [4], and pneumatic soft actuators [5]. Most of these actuators suffers from issues such as limited lifetime, slow response, and low efficiency [1]. Although soft pneumatic actuators are efficient and durable, the compressor requirement makes their application limited. In the current work we will integrate electromotors with soft structure to design a novel soft bending actuator. Since electromotors are durable and efficient the proposed soft actuator has the potential to improve the performance of soft robotic systems.

The evolution of human aquatic propulsion has alway fallen short to the evolution of aquatic life. While humans have progressed from paddles to more advanced forms of motion such as noisy and disruptive propellers and water jets; Fish and other nekton have mastered a sophisticated carangiform of swimming. This interconnected dance of muscle movements is remarkably efficient while simultaneously allowing fish to achieve a greater maneuverability and creating little to no disturbance in the environment. In a juxtaposition, current forms of human aquatic propulsion systems create damaging turbulence and disruptive noise pollution to marine environments. These disturbances in the environment impact communication, orientation, feeding, and parental care of marine life, as noise can result in abnormal development, hearing loss, or injured vital organs[6]. In order to create a more harmonious human relationship with aquatic environments, robotic fish are created to mimic the naturally engineered design of a fish's structural and locomotive blueprint perfected over eons of natural selection and evolution.

There are two main types of fish swimming propulsion; body and caudal fin (BCF), and median paired fin (MPF) [7] 85% of aquatic animals use BCF propulsion[8] and it is believed that MPF swimmers undergo a gait transition with increasing speeds to a BCF gait [9]. Due to this or simplicity's sake, most Robotic fish have been designed using BCF propulsion designs. Multiple approaches to the design of Robotic fishes have been created in the past, the first being the Robotuna created by MIT researchers that were inspired by wanting to study the efficiency of using an underwater vehicle with fishlike propulsion [10].

A multitude of approaches have been taken to designing a robotic fish tail actuation, MIT's "Sophie" used a displacement pump to actuate the soft fishtail [11]. Often robotic fish tails are actuated by using motors connected to joints [12], [13]. Another approach taken was by researchers at Beihang University in which they used two servo motors to move links connected to the caudal fin[14]. The JX-DC5821LV from [15] used a wire tension driven fish tail.

The construction and manufacturing of robotic fish depends on the drive type as well as body style desired. Hard body robotic fish such as [14] implement a rigid hull fabricated with carbon fiber and aluminum alloys which function as an exoskeleton. Rigid hard body robotic fish are typically designed to perform in harsher environments than soft body fish with the goal of reaching greater depths and pressures. However they sacrifice the maneuverability and full BCF motion that occurs with soft body robotic fish. Soft robotic fish with an interior rigid skeleton structure also tend to use light but strong materials such as aluminum and carbon fiber. The skin and body can that is molded around the skeleton can be made out of plastic, reticulated foam,conformal lycra, and/or flexible polymers such as silicon. Soft body fish without a ridged interior skeleton are typically molded from a more stiff but somewhat elastic silicone structure more closely resembling the cartilage based body of sharks. Additional materials such as low density crush resistant glass microbubbles to achieve an equivalent or slightly higher density than water to maintain a proper buoyancy as seen in [11] Mechanically simple components such as the head and casual fin have been manufactured using 3-D printing in a similar manner to [16]. This paper focuses on the design of a fish robot that, with the exception of a few parts and mechanisms such as motors, screws, etc., is entirely 3D printed. The other design focus is that the drive motor operates in a single direction, maintaining angular velocity and momentum.

II. FISH ROBOT DESIGN

The basic idea for design of the soft fish robot will be discussed here. From basic mechanics one knows that the bending deformation in the beam will happen when there is a variation of strain across the beam layers increasing from top to bottom or vice versa. This mechanism can be used to create a soft bending actuator. Let us assume we have a beam which comprised of two layers according to Figure 1. Now, if we push one layer upward its length increase compared to the other layer and as a result the whole structure will bend. This bending mechanism can be improved by fixing the relative distance between the layers. In the next section we will explain how we can improve the bending motion and integrated the soft actuator with an electromotor.

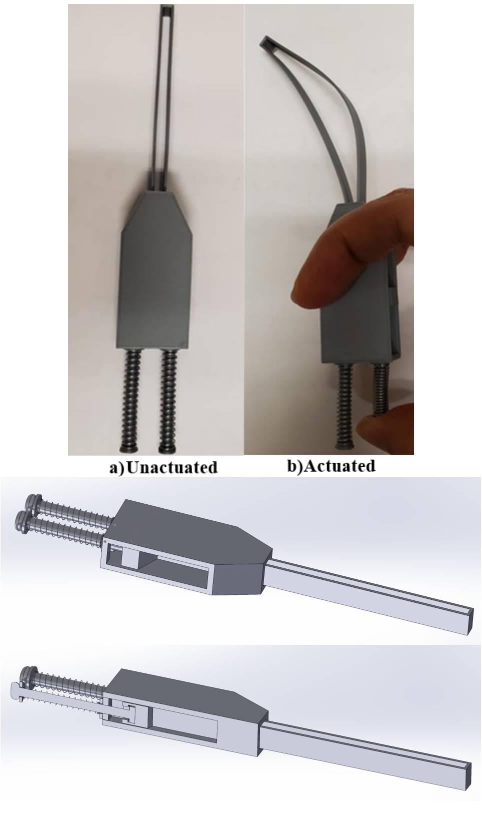

a)Unactuated b)Actuated

Fig. 1: Spring-loaded actuator proof of concept.

A. Soft Tail Initial Design

This mechanism went through a great deal of iterations before arriving at the current version. With the one of the goals of this project being that it must be mostly 3D printed using a FDM (Fusion Deposition Modeling) printer, some geometric constraints were placed on the design, for example, the design must limit the amount of the model are floating in free space or overhanging the edges. While it is possible overcome this constraint by printing the model with supports, sometimes the supports are ineffective or become a hindrance. The first design of the tail encountered this problem. The parts must be able to be printed so that the optimal orientation for printing does not create weak points in the part, such as what happened to the spring shafts in another iteration.

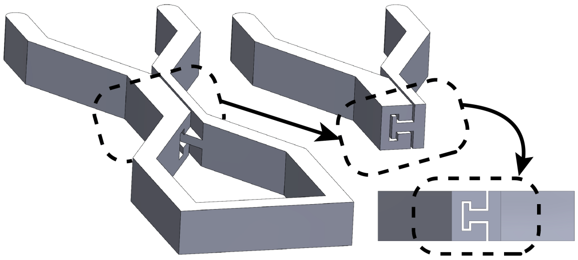
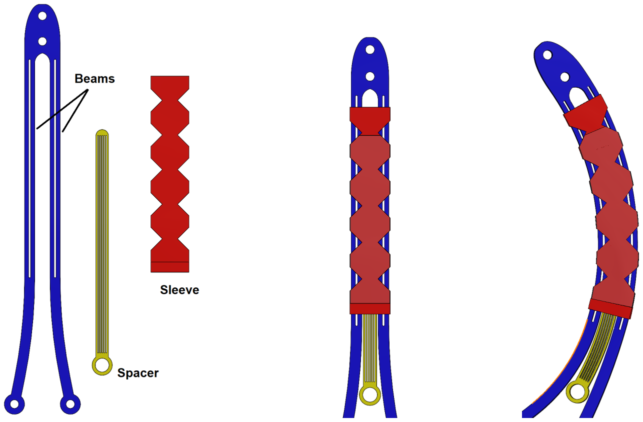


Fig. 2: Early design of 3D printed soft actuator.

The first attempt at a 3D printed thermoplastic polyurethane (TPU) tail was a failure. The beams of the tail intersected each other as in Figure 2. This design was intended to allow for the beams to slide along each other as they flexed. The design fails in the manufacturing stage. Printing this part became exceedingly difficult, as the gaps along the rail section required a support interface. The support structure fused with the part, or caused some other failures. Many attempts were made to rectify this error, including using water soluble support material, but those had their own issues. In the next design, this self-intersecting rail concept was abandoned.

The next attempt creating the tail mechanism was a successful proof of concept, as it is seen in Figure 1. The flexible portion of the tail consists of two beams that are only connected at the tail end. When the two beams are moved in opposing directions along the length of the part, the tail flexed as it was meant to. The next step of this design was to print and assemble all the parts. The parts were assembled during the printing process. The tail sits within a housing and spring loaded push rods are inserted into the base of the tail. Pushing on one rod causes the tail to flex in one direction, while pushing the other causes the tail to flex in the other direction, as seen in Figure 1. Despite this being an effective demonstration of the concept the actuation method for the fish, it did have its flaws. The push rods were printed upright, so that they could be assembled during the print. The print was paused at the top of the 5mm shaft so that the washers and springs could be placed on, then the print was allowed to finish. Due to these parts being printed vertically, the layer lines along the shaft were horizontal, causing the shaft to be highly susceptible to sheer stresses. Many of these ended up breaking. Despite that minor failure, the basic design worked.

Aside from the weakness of the push rods, there were only



(a) Parts (b) Assembled (c) Bent

Fig. 3: Tail beams with spacer and sleeve.

two issues of note that detracted from the performance of the system. The beams had a gap between them and could also move apart form one another, allowing for flexing in undesirable locations and directions. This was solved by adding a flexible spacer between them. The spacer also allowed for a greater difference in radii of the two beams as they flex, creating a more pronounced overall displacement. The other issue was that the beams were able to move apart from one another, which also reduced the displacement and force that the actuator was able to produce. To solve this problem a flexible sheath, as seen in Figure 3, was added around the length of the tail to restrict the separation of the beams which was used, with some variation, in all of the designs going forward.

Having established a working general design for the soft tail, the next step was to drive the device with an electric motor. One of the principle concepts of this fish design is that the motion of the tail is driven by a single motor that only rotates in one direction, preferably at a single speed. Some designs for the drive were considered and dismissed before reaching the modeling stage. For example, an elliptical cam was considered as a means to manipulate either of the spring-loaded push rods seen in Figure 1. Such a design would not allow for enough displacement of the beams to be practical. The design that did end up getting printed was a lever driven oscillator. As seen in Figure 4, this design had many moving parts. Due to the number of moving parts, the material the parts were constructed of, the lack of torque in the motor, and the tolerance in fittings, this design failed to produce the desired movement. A simpler solution with less moving parts had to be considered.

B. Current Design

1) Drive: In an effort to create a simpler and more resilient drive system, existing oscillating drives were considered. After examining many designs, the Scotch Yoke was chosen as the simplest and most easily implemented system. This type of oscillator works by using a rotating crank placed in a slot on a yoke, as seen in Figure 5. Such a drive provides linear oscillating motion along a single plane, however, in order to generate maximum displacement of the flexible actuator, two planes if linear movement are required. Each side of the fish actuator must be pushed or pulled in the opposite direction as the other. To do this, a secondary yoke is placed on an extension of the crank 180°out of phase with the first. Placing these yokes in a housing that guides their movement and turning the crank with the same electric motor as the previous designs yielded the desired movement of the fish tail.. Renderings of the current drive system can be seen in Figure 6. In this configuration, the drive motor reaches 179 RPM, or 179 complete oscillations, when outside of the water. This drive is not without issues, however. Being made of PLA, certain components are prone to mechanical failure, such as the crank.

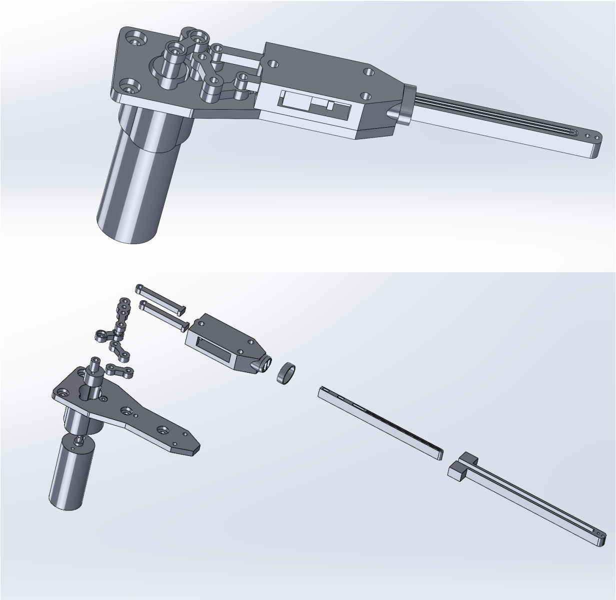
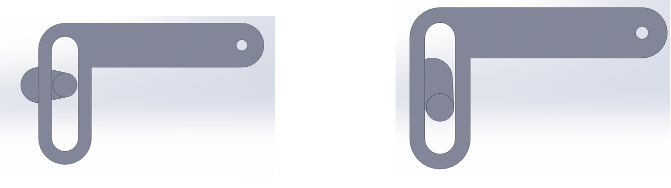
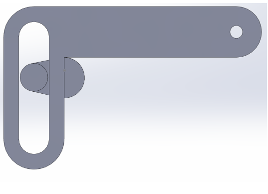


Fig. 4: Lever driven design.



(a) 0°Rotation (b) -75°Rotation



(c) -180°Rotation

Fig. 5: Movement of a scotch yoke.

The crank is thin component that is subject to comparatively large mechanical stresses, which causes plastic deformation over time and eventualy falier of the part. Being a hygroscopic material, PLA is also subject to changes in material properties when exposed to water. Solutions to this will be explored in the future.

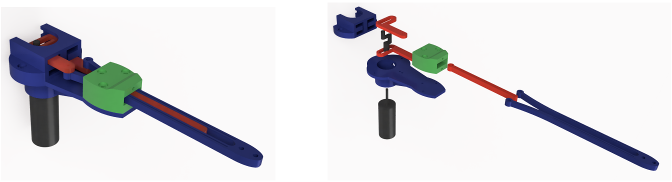

(a) Isometric view (b) Exploded view

Fig. 6: CAD model of current drive system.

2) *Tail and Caudal Fin:* Once the drive and the tail actuator were designed, a caudal fin had to be developed in order to propel the fish through the water. In nature, every fish has specific requirements for speed and agility. The geometry of the caudal fin one of the primary factors in reaching those specifications. For this iteration of the design, a forked fin was chosen, as many fast swimming fish utilize this geometry of caudal fin. Initially a shorter fin was used, but testing showed that a longer caudal fin was more able to conform to an undulating motion along its length, enabling greater speed. The cycle of movement of the tail and caudal fin can be seen in Figure 7. Being that this iteration of the fish design is a proof of concept, optimization thus-far has been limited to some trial and error. Much greater improvements will be made in future iterations, including moving the design toward thunniform movement with a lunate tail. [17]

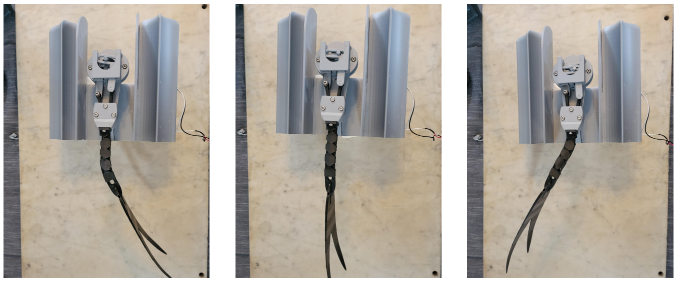
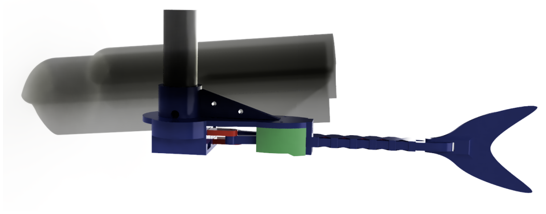

(a) Right stroke (b) Center Stroke (c) Left Stroke

Fig. 7: Tail actuator movement

3) *Body:* In order to test the operation of the swimming mechanism, a floating platform had to be created. This testing platform is a simple catamaran style flotation device with mounts for the swimming mechanism on the underside. Each of the two pontoons incorporates a shallow full keel in order to alleviate yaw and side slipping. The test body was was 3D printed in in PLA-Pro a single piece and coated with several coats of weather proof clear coat. The clear coat seals any gaps in the print, making it watertight. This design also allows for a batter pack to be affixed to the top of the device, enabling untethered movement. An exploded view of the complete assembly can be seen in Figure 8. As a test platform, this body performs adequately, but there is much room for improvement.


(a) Side view

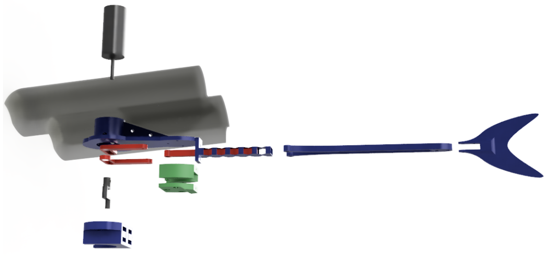

(b) Exploded view

Fig. 8: CAD model of complete fish robot (Current design renderings).

III. RIGID FINITE ELEMENT MODEL

This section will discuss the modeling of the soft tail using rigid finite element method (RFEM). The soft fish tail can bend both clockwise and counterclockwise providing propulsion for the fish. Thus, modeling the fish tail can provide insight for further development and optimization of the fish robot. While application of finite element software packages will be investigated in our future works. In the current study will use the method of RFEM to capture the basic bending deformation of the tail. This model can be used to optimize the length and size of the tail considering a required bending angle. We have explained the method of RFEM in our previous works [18] [19]. According to this method the tail can be discretized into several elements where each element connected to the consecutive one through a revolute joint and a rotary spring. Where the rotation in z-direction is θ_i. At each revolute joint there will be a rotary spring

$$k_i = \frac{nEI}{L} \tag{1}$$

where EI, and L are the flexural rigidity, and length of the tail and, and n is the total number of elements used for simulation. By pulling and pushing the soft beams in the structure of the tail a constant moment Mi will be applied along the tail. Thus, considering the LaGrange equation the tail model can be defined as:

$$\{M\} = [K]\{\phi\} \tag{2}$$

where

$$\{M_2, M_2, ...M_n\}, \{\phi\} = \{\theta_1, \theta_2, ..., \theta_n\}, [K] = diag(k_i) \tag{3}$$

After defining the tail model to assemble the element and obtain the tail position the following kinematic model will be used.

According to Figure 9 to model the kinematics of the robot tail, it is discretized into n elements where they are connected through revolute joints. The transformation matrix for each joint can be defined as:

$$T^i = \begin{bmatrix} cos(\theta_i) & sin(\theta_i) & \frac{L}{n}cos(\theta_i) \\ -sin(\theta_i) & cos(\theta_i) & \frac{L}{n}sin(\theta_i) \\ 0 & 0 & 1 \end{bmatrix} \tag{4}$$

Thus, the overall transformation between base and tail can be defined as $T = T^1T^2...T^n$.

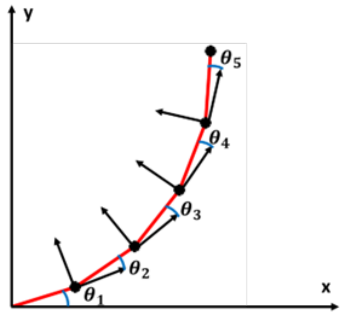


Fig. 9: Frame assignment for kinematic model of the tail

Figure 10 compares the bending defomation of the tail outside the water with the model. It can be seen that the assumption of the constant bending moment across the length of the tail (pure bending) can predict the bending deformation very well. However, this assumption is not valid inside the water due to existence of the distributed external hydrodynamic forces, and the caudal fin force [20]. While our future work considers development of more complex model and optimization of the fish performance, we will show that the hydrodynamic forces can be easily added to the RFEM model using the method of virtual work. Consider the potential energy of the fish tail to be as

$$V = \frac{1}{2}(k_1\theta_1^2 + k_2\theta_2^2 + ... + k_n\theta_n^2) \tag{5}$$

According to Figure 11 for a virtual displacement the work done by external hydrodynamic forces (F) and the applied bending moment (M) from electromotor can be defined as:

$$\delta w = M(\delta\theta_1 + \delta\theta_2 + ... + \delta\theta_n) + F_1.\delta r_1 + F_2.\delta r_2 + ... + F_n.\delta r_n \tag{6}$$

Where the δr_i is the virtual displacement of the force F_i. Finally, the equation of motion can be obtained using the LaGrange method as $\partial V/\partial\theta_i = Q_i$, where Q_i are the generalized force vectors which will be obtained from Eq. 6.

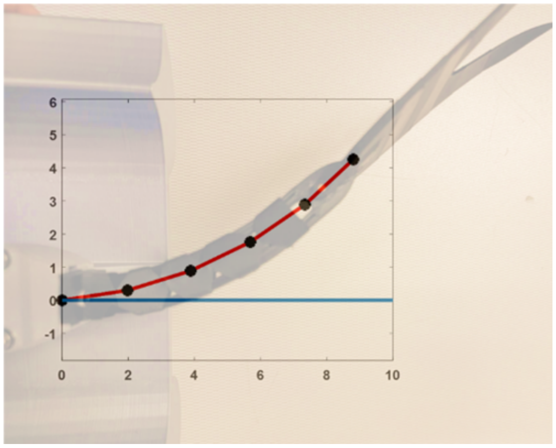


Fig. 10: Comparison of the model and experimental bending deformation of the tail

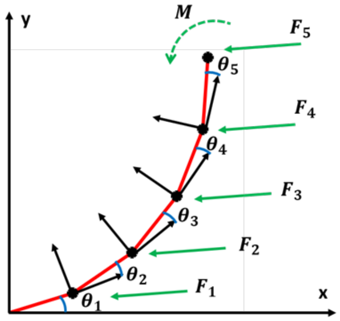


Fig. 11: Application of virtual work principal to include the hydrodynamics forces

IV. RESULTS

The 3D printed soft actuator and fish robot performed well as the proof of concept for the first iteration of the device, which will undergo optimization and further improvement in our future designs. In water and laden with the power source, consisting of four AA batteries, the fish was able to reach a speed of 17.4 cm/s by flapping the tail at 2.8 Hz. That equates to 0.6 body lengths per second, bl/s, as swimming speed is often measured. Figure 12 shows the swimming sequence of the fish as it moves through the water. For reference, RoboTuna [10] can swim at nearly 1 bl/s, while the fastest swimmer currently known is the stingray-like robot discussed in[21] can swim roughly 3 bl/s. Both of these devices are much more advanced and developed than the one discussed in this paper.

V. FUTURE DESIGNS

As previously mentioned, there are a great deal of ways in which the current device can be improved as a simple swimming device. The whole of the device needs to be made of material that is less affected by water. The drive, tail, and body all need to be optimized in various ways. Beyond that, the end goal is to create programmable robotic fish that is able to swim on its own and able to move about freely in three dimensions in an aquatic environment.

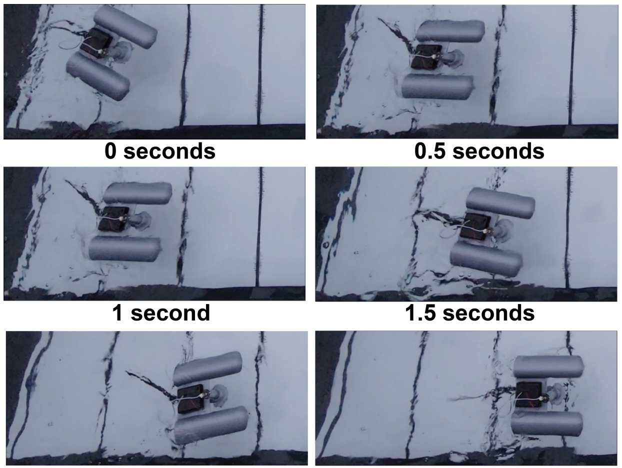

0 seconds
0.5 seconds
1 second
1.5 seconds
2 seconds
2.5 seconds

Fig. 12: Swimming sequence of the fish robot

A. Drive Improvements

The problems with the current drive are far from insurmountable. As discussed the crank can be improved. It can be made more resilient by making it from metal, carbon fiber infused PLA, or other higher performing material. The yokes could be improved by using more robust geometry and redesigning the yoke housing to reduce torsion. The drive motor will be replaced with a more powerful, faster, and smaller motor.

B. Tail Improvements

Currently the tail is functional, but there is some room for improvement. The TPU used to print the fish tail worked very well and was easy to work with, unlike some flexible materials that were tried. However, it does tend to hold its shape when flexed (plastic deformation observed) and it is somewhat stiff. A less stiff and and possibly more elastic material will probably be tested in the future. The caudel fin also needs to be redesigned to be more efficient. As mentioned previously, a lunate fin would very likely perform better than the current elongated fork design, so it will definitely be Incorporated into the next iteration. Fluid–structure interaction (FSI) simulation will be used to optimized the structure of the fish.

C. Body Improvements

Though the body of the fish performed admirably as a test bed for the system, it is a major source of inefficiency for the device. As the tail moves side to side, the body yaws and slips to the side. This recoil [17] causes energy to be diverted from pushing the fish in the intended direction. By reducing the recoil, the fish can be made to swim much faster. One way to do this in the next iteration is to increase the underwater profile of the body. The next body will not be a mere test bed. It will be designed to be a functional component of the system itself.

VI. Conclusion and Future Works

The current work serves as a proof of concept for a fish robot equipped with novel 3D printed soft actuators. There are several advantages in application of the proposed soft actuators in comparison to existing soft actuators based on thermal, chemical, or ionic actuation mechanism including, simplicity of design, efficiency, fast responses and durability. RFEM has been successfully used to capture the bending deformation of the soft actuator and can be used to optimized the fish tail design in our future work. The fish obtained the speed of 0.6 body lengths per second in the first iteration which is a acceptable result compared to existing results. Our future work includes optimization of the soft actuator and fish body as well as addition of extra fins for steering and position control of the fish.

VII. Acknowledgement

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References

[1] A. A. Amiri Moghadam, S. Alaie, S. Deb Nath, M. Aghasizade Shaarbaf, J. K. Min, S. Dunham, and B. Mosadegh, “Laser cutting as a rapid method for fabricating thin soft pneumatic actuators and robots,” *Soft Robot.*, vol. 5, no. 4, pp. 443–451, aug 2018.

[2] A. A. Amiri Moghadam, K. Torabi, A. Kaynak, M. N. H. Zainal Alam, A. Kouzani, and B. Mosadegh, “Control-oriented modeling of a polymeric soft robot,” *Soft Robot.*, vol. 3, no. 2, pp. 82–97, jun 2016.

[3] S. Wu, G. L. Baker, J. Yin, and Y. Zhu, “Fast thermal actuators for soft robotics,” *Soft Robot.*, vol. 9, no. 6, pp. 1031–1039, dec 2022.

[4] “Equivalent dynamic thermoviscoelastic modeling of ionic polymers", author = "amiri moghadam, amir ali and alizadeh, vahidreza and tahani, masoud and kouzani, abbas and kaynak, akif,” *Polym. Adv. Technol.*, vol. 26, no. 4, pp. 385–391, apr 2015.

[5] B. Mosadegh, P. Polygerinos, C. Keplinger, S. Wennstedt, R. F. Shepherd, U. Gupta, J. Shim, K. Bertoldi, C. J. Walsh, and G. M. Whitesides, “Pneumatic networks for soft robotics that actuate rapidly,” *Adv. Funct. Mater.*, vol. 24, no. 15, pp. 2163–2170, apr 2014.

[6] L. Weilgart, “The impact of ocean noise pollution on fish and invertebrates,” *Report for OceanCare, Switzerland*, 2018.

[7] A. A. M. Faudzi, M. R. M. Razif, N. A. M. Nordin, E. Natarajan, and O. Yaakob, “A review on development of robotic fish,” *Journal of Transport System Engineering*, vol. 1, no. 1, pp. 12–22, 2014.

[8] D. Zhang, K. Low, H. Xie, and L. Shen, “Advances and trends of bionic underwater propulsors,” in *2009 WRI Global Congress on Intelligent Systems*, vol. 1. IEEE, 2009, pp. 13–19.

[9] A. B. George and M. W. Westneat, “Functional morphology of endurance swimming performance and gait transition strategies in balistoid fishes,” *Journal of Experimental Biology*, vol. 222, no. 8, p. jeb194704, 2019.

[10] P. Anderson, D. Barrett, and M. Triantafyllou, “A force sensor system for the robotuna project.” MASSACHUSETTS INST OF TECH CAMBRIDGE DEPT OF OCEAN ENGINEERING, Tech. Rep., 1996.

[11] R. K. Katzschmann, J. DelPreto, R. MacCurdy, and D. Rus, “Exploration of underwater life with an acoustically controlled soft robotic fish,” *Science Robotics*, vol. 3, no. 16, p. eaar3449, 2018.

[12] H. Hu, J. Liu, I. Dukes, and G. Francis, “Design of 3d swim patterns for autonomous robotic fish,” in *2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2006, pp. 2406–2411.

[13] J. Liu, I. Dukes, and H. Hu, “Novel mechatronics design for a robotic fish,” in *2005 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2005, pp. 807–812.

[14] J. Liang, T. Wang, and L. Wen, “Development of a two-joint robotic fish for real-world exploration,” *Journal of Field Robotics*, vol. 28, no. 1, pp. 70–79, 2011.

[15] I. Mitin, R. Korotaev, A. Ermolaev, V. Mironov, S. A. Lobov, and V. B. Kazantsev, “Bioinspired propulsion system for a thunniform robotic fish,” *Biomimetics*, vol. 7, no. 4, p. 215, 2022.

[16] A. C.-E. C. T. A. T. Nikhil Pai, Amir Ali Amiri Moghadam, “Design and development of a fish-like, soft biomimetic robo,” *IMECE*, 2022.

[17] M. Sfakiotakis, D. M. Lane, and J. B. C. Davies, “Review of fish swimming modes for aquatic locomotion,” *IEEE J. Ocean. Eng.*, vol. 24, no. 2, pp. 237–252, apr 1999.

[18] A. A. Amiri Moghadam, W. Hong, A. Kouzani, A. Kaynak, R. Zamani, and R. Montazami, “Nonlinear dynamic modeling of ionic polymer conductive network composite actuators using rigid finite element method,” *Sens. Actuators A Phys.*, vol. 217, pp. 168–182, sep 2014.

[19] A. A. A. Moghadam, A. Kouzani, R. Zamani, K. Magniez, and A. Kaynak, “Nonlinear large deformation dynamic analysis of electroactive polymer actuators,” *Smart Struct. Syst.*, vol. 15, no. 6, pp. 1601–1623, jun 2015.

[20] Y. Zhong, Z. Li, and R. Du, “A novel robot fish with wire-driven active body and compliant tail,” *IEEE ASME Trans. Mechatron.*, vol. 22, no. 4, pp. 1633–1643, aug 2017.

[21] A. M. Karelin, Y. D. Orekhov, I. K. Khmelnitskiy, V. M. Aivazyan, and D. O. Testov, “Biomimetic stingray-like robotic fish with propulsors based on IPMC actuators,” in *2021 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (ElConRus)*. IEEE, Jan 2021.