

Investigating the Effect of Variable Stiffness Caudal Fins on MuBot Swimming Speed

Arnab Gupta
College of Engineering
Pennsylvania State University
University Park, PA
apg5799@psu.edu

Micah DeLattre
College of Engineering
Pennsylvania State University
University Park, PA
mwd5376@psu.edu

Austin Giordano
College of Engineering
Pennsylvania State University
University Park, PA
kmr6714@psu.edu

Abstract— This paper presents an investigation into the effectiveness of utilizing advanced additive manufacturing technologies to create caudal fins of variable stiffness for a bio-inspired swimming robot (MuBot). In this study, a method was developed to manufacture caudal fins that closely resemble those on real fish by mixing resins of various elasticity to create spines and gradients. The Stratasys J55 printer was used to produce prints with variable elasticity at an extremely fine resolution. The effectiveness of the caudal fins was measured based on their forward straight-line swimming speed. Their performance was compared to a single elasticity control caudal fin. As a result, some of the caudal fins performed better than what was previously accepted as the optimal material for a caudal fin as it relates to maximum forward swimming speed.

Keywords—fish caudal fins, variable stiffness, embodied intelligence, bioinspired robotics, additive manufacturing

I. INTRODUCTION

A. Motivation and Background

Though fish are simple creatures, they have mastered the art of quick and agile motion through highly complicated underwater environments. There are several thousand different species of fish, meaning there are many ways in which they swim. This leads to the caudal (tail) fin of fish performing differently depending on the environment the fish lives. Many species of fish use undulatory movement that relies on the effectiveness of the caudal fin to maximize efficiency when swimming [1]. Caudal fins can range widely in shape and texture, influencing how the fish propels itself through the water. In this study, different designs of variable stiffness 3D printed caudal fins for a bio-inspired fish robot were tested for improvement in swimming speed compared to a single-rigidity fin [2].

The field of bio-inspired robotics aims to push the limits of technology that resembles and functions similarly to living things. Bio-inspired fish robots have been around for decades, but as additive manufacturing techniques become more advanced, there is still much research to be done as to how 3D printing can be used to more closely mimic life. In this study, we utilized the Stratasys J55 polyjet resin printer to create caudal fins that resemble the structure of the fins on real fish. This printer can print in materials ranging from a shore hardness of 45A to full rigidity, and a single print can have bodies of various stiffnesses that are combined cohesively.

The caudal fins that were created for this study vary in many ways. The three main designs are the lamprey tail, the pike tail, and the lunate tail. For the lamprey and the pike tails, there are 2 variations: spined and gradient. Gradient tails have sections ranging from the most rigid to the least

rigid material, allowing for variations in the way the caudal fin bends at different points along it. Spined tails attempt to replicate the bone structure of real fish, adding rigid “bones” to an otherwise fully elastic caudal fin.

The overall goal of this study is to evaluate whether using these variable stiffness caudal fins enhances the performance of MuBot swimming at various speeds.

B. Literature Review

There have been many studies over the years on different methods of developing robots for underwater locomotion. Many of these include other types of bionic fish robots, as robots with fish traits were found to be extremely efficient in underwater motion compared to more traditionally modeled robots [3]. There have been many different species of fish that robots have been modeled after, such as tuna, boxfish, pike, and dolphins. Due to differences in physical traits, there are many ways that these robots have been designed to generate movement. One common way is tail-actuated motion combined with body-actuated motion, which the MuBot is designed for. Specifically, MuBot utilizes anguilliform locomotion, meaning that the entire body of the robot moves in waves to generate motion [4].

Utilizing additive manufacturing techniques for the development of such robots is not a new idea. Many fish robots are created using materials that attempt to mimic the frictionless surface of fish, which allows for their efficient swimming [5]. Additionally, when it comes to hydrodynamics, precision down to the micrometer can impact the effectiveness of swimming, so high-end 3D printers such as the Stratasys J55 are ideal for this sort of application [6]. The J55 also allows for multiple bodies within a single part to have different stiffnesses without post-assembly being required, making it a viable option for seamlessly replicating traits found in the caudal fins of real fish.

Caudal fins serve various purposes for fish, such as dampening undulatory motion, thrust production, and spinal cord protection. The exact formation of the caudal fin between species varies, but many of them contain the cartilaginous notochord, which is a stiffer structure compared to the surrounding caudal fin membrane [1]. By adding rigid bodies in the shape of spines to the 3D printed caudal fins, we can more closely replicate this essential structure. There have also been studies done that incorporate actuated movement of these individual spines within a caudal fin that have been shown to more precisely generate movement [7].

II. METHODS AND MATERIALS

A. Design of Variable Stiffness Caudal Fins

The design of the caudal fins was a biomimetic process, taking direct inspiration from real-life fish and how their tails or caudal fins have rigid spines connected to a more elastic and pliable membrane. As previously mentioned in the literature review, research conducted at the lab has already given us some insight into how a less rigid and more elastic material is more likely to improve thrust generation in the MuBot and increase swimming speed [2]. Two main approaches were used to incorporate variable stiffness designs into the caudal fins: first, using a constant gradient of decreasing stiffness starting with the most rigid at the base or chord and going down to the least or 2nd lowest stiffness. Second, the bio-inspired approach of using rigid spines with decreasing thickness travelling down towards the end of the caudal fin, wherein the spine is the most rigid material, and the remainder base of the fin is fully elastic.

The modelling of the actual fins was done on SolidWorks, and the changes between each iteration were decided by discussing as a group and seeing which fin we thought would perform the best. Ideally, this should have been more quantitative and measured, but this is something that is expanded upon in the future work section, as it was slightly outside the scope of the project for this class. Each caudal fin was bioinspired, and 3 main types of fish were used to mimic their caudal fin: Pike, Lamprey, and Lunate.

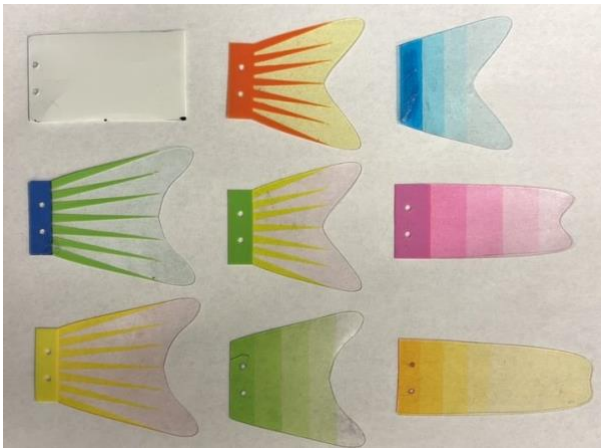


Figure 1. Caudal Fins for Session One of Experiments

Figure 1 demonstrates both these types of fins along with the constant baseline tale used, captured in the top left of the image. Again, this is the caudal fin that Deng et al.'s research found to be closest to optimum, in terms of maximum swimming speed, out of all the materials tested [2]. This first round of experiments was used to gauge which tail geometry worked best and to understand which variable stiffness arrangement leads to the best results. As the discussion section will solidify later, it was uncovered that the gradient stiffness fins were not effective. Poor structural integrity, from this style of stiffness array, resulted in the MuBot swimming into the walls of the tank instead of straight. Therefore, the 2nd session of experiments only used the spine tails and aimed to further investigate some new kinds of fins.

The fabrication of the caudal fins involved using the Stratasys J55 printer, which allows variable stiffness prints. The range is from 45 to 95 on the Shore Hardness (A) scale in 6 increments of 5 or 10. Although the stiffness feels quite

uniform in going up or down a level, during the experimentation phase it was realized that changing the level even once has a drastic impact on the stiffness of the fins and as our results will go on to show, had huge impacts on MuBot swimming speed and overall performance as well.

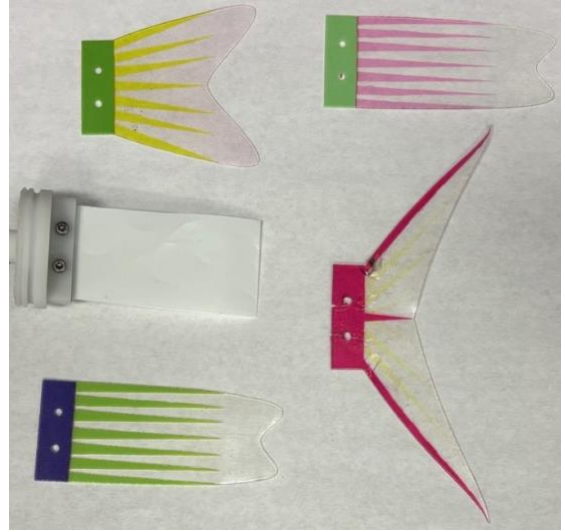


Figure 2. Caudal Fins for Session Two of Experiments

Similar to Figure 1, Figure 2 shows the lunate tail, a caudal fin with a much larger chord angle and a much longer and wider fin compared to the pike or lamprey fins previously tested. Another purpose of testing the lunate fin was the test the limits or range of parameters for the tails when the artificial evolution study will be conducted, more about that in the future scope section.

Two additional, new caudal fins were also tested in session 2 of the experiments. These were two tails of the lamprey variety and included spines this time, instead of a gradient. The level of spine stiffness varied between the two.

Two caudal fins were repeated to firstly validate previously found results, and just to use as a reference, as many variables changed between the two experiments. The changed variables start from the water level of the tank, the trajectory tracking algorithm, to internal differences in the actuation and sealing of the MuBot. The two repeated fins were the baseline, Polyolefin, and the fastest tail from experiment one, the pike with the second-most-rigid spines.

B. Experimental Setup

The experimental setup and experimental procedure were crucial aspects to ensure the experiments were conducted efficiently and correctly. Thanks to the BioRob InFL lab, we had the 3-meter-long, 58 by 25 cm tank at our disposal, which made data collection very easy. The tank is equipped with 6 IR lights and an overhead IR camera to capture a top view of the MuBot from the tank. Figure 3 displays a diagram of the experimental setup that was used for collecting data for this project. As illustrated, the setup includes a linear stage connected to an Arduino-controlled stepper motor for autonomous use. Unfortunately, the motor no longer works, and therefore, the tether connected to the MuBot must be manually pulled to follow the MuBot as it swims in the tank.

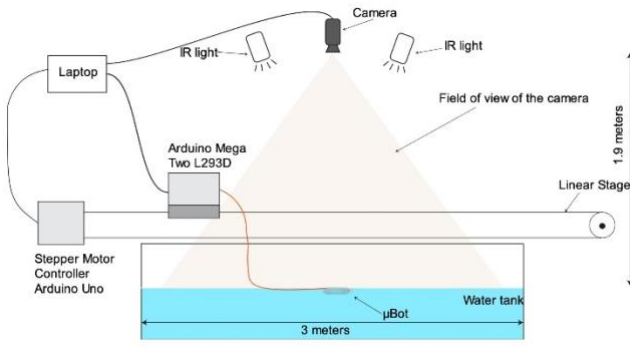


Figure 3. Diagram of Experimental Setup used for Data Collection

The tether, attached to the robot, is used for power and communication between the swimmer and the laptop used for the controls. The IR camera and lights set up allowed motion tracking and 0° heading regulation of the swimming MuBot. Figure 4 also shows the tether as it connects the MuBot to the linear stage, which allows for the needed communication.



Figure 4. Image of MuBot in Water Tank

Another important note is addressing the float, which can be seen in Figure 4. This generation and particular version of the robot is negatively buoyant, and therefore, a float is used to keep the robot at a constant depth to ensure all of the tail is underwater. Although this slightly decreases overall swimming speed due to increased drag forces, this ensures all-sized caudal fins, like the lunate, for example, can stay completely underwater during the testing.

The experimental procedure included conducting a frequency sweep for each caudal fin, which ranged from 3 to 9 Hz. 3 iterations were conducted at each frequency, and an average of the forward swimming speeds was recorded and graphed. The velocity was calculated by taking the difference in displacement from 4 to 7 seconds and then dividing this value by 3, to get the swimming speed in centimeters per second. Each caudal fin experiment took roughly 45 minutes to complete, then the caudal fin was changed before moving on to the next one.

III. RESULTS

To reiterate the experimental procedure, we aimed to collect an average swimming speed for all caudal fins at 7 different frequencies. The frequency sweep results could then be compared between individual fins and, importantly, against the baseline or constant caudal fin, the Polyolefin fin, previously thought to be the optimal stiffness [2].

Figure 5 below shows the results from our first set of experiments, session 1, of the variable stiffness caudal fins. As annotated in the legend, this session consisted of 5 variable stiffness fins and our one baseline.

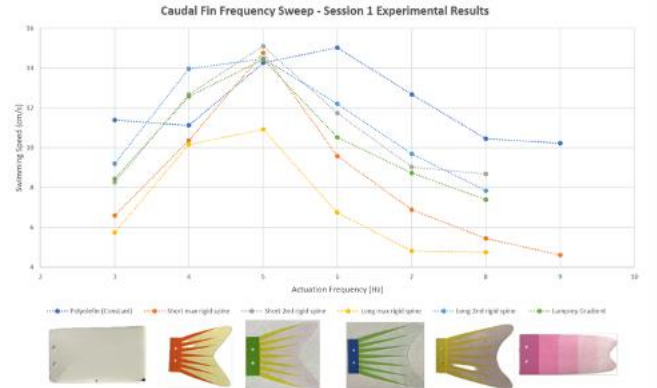


Figure 5. Session 1 Caudal Fins Frequency Sweep Results

As shown in the graph, the baseline, Polyolefin, was still the fastest at almost all frequencies, apart from 5 Hz, which was the same frequency at which all the printed variable stiffness fins peaked. The overall fastest average swimming speed was, however, the short variation of the pike fin with the 2nd most rigid spines. Narrowly beating Polyolefin at 6 Hz, which recorded an average speed of 15.02 cm/s, with a speed of 15.09 cm/s at 5 Hz. The order of performance for the variable stiffness tails was short pike with 2nd rigid spines, then short pike with the most rigid spines, followed by the lamprey gradient and the long variation of the pike with the 2nd most rigid spines. The lowest performing by a large margin was the long pike with the most rigid spines.

Furthermore, Figure 6 shows a screenshot from a side-by-side video of three of the fins captured by the IR camera. The image demonstrates how, at this certain time step, the short second rigid spine is just slightly ahead of the Polyolefin fin, which in turn is ahead of the slowest variable stiffness fin, the long max rigid spines.

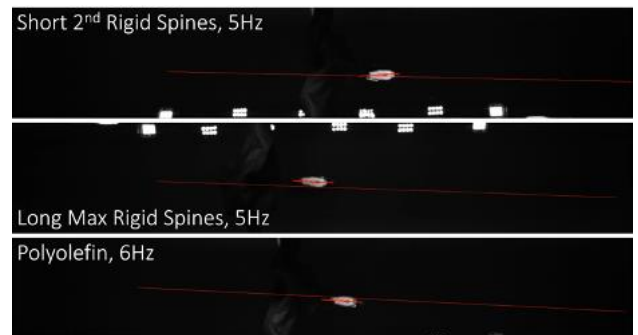


Figure 6. Side-by-side IR Video of 3 Caudal Fins Swimming

Finally, the experimental results from session 2, using the modified lamprey spine fins and lunate caudal fin, can be seen below in Figure 7. An important note to make is, due to changed variables between these sessions, it is difficult for

direct comparisons to be made. These variables range from the depth of the water changing due to evaporation over the time between sessions, to internal changes in the electronics and sealing of the robot, to minor changes in the path planning and tracking software, which eventually gave us different, and seemingly lower speeds. For this reason, two caudal fins were repeated and tested again in the 2nd session, namely the two fastest ones from the first session, the short pike variation with the 2nd most rigid spines, and the Polyolefin caudal fin.

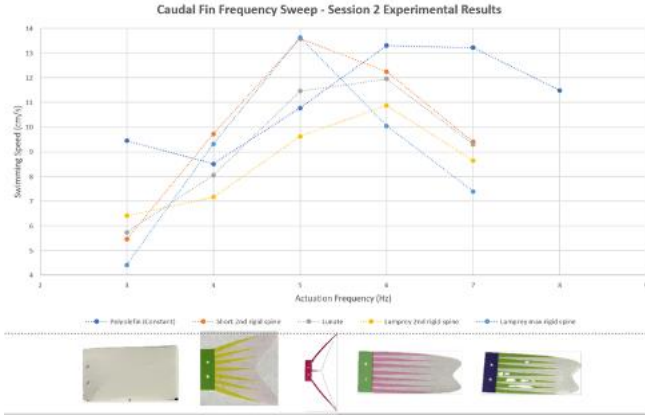


Figure 7. Session 2 Caudal Fins Frequency Sweep Results

The second session verified and validated our initial experiment and confirmed that the short variation of the Pike with the second most rigid spines is indeed faster at 5 Hz than Polyolefin is at 6 Hz. Additionally, as shown on the graph, a second caudal fin was found to be faster than Polyolefin's highest swimming speed of 13.3 cm/s (for this session), both the short second rigid spines (again) at 13.58 cm/s and the lamprey with the most rigid spines at 13.64 cm/s outperformed the baseline handily. The lamprey with the most rigid spines turned out to be the fastest caudal fin overall, and unfortunately, we could not recreate the higher speeds from the first experiment due to the aforementioned variables, but it did beat the two fastest fins from the first session quite convincingly.

Additionally, it is worth mentioning that the lunate tail performed better than expected. Figure 2 does a good job of showing just how much bigger it is than the other tails. We expected the much larger surface area relative to MuBot size would greatly hinder swimming performance, but that did not turn out to be the case. On the other hand, the lamprey with the 2nd most rigid spines turned out to perform poorly, closely contesting the long pike fin with the most rigid spines for the worst fin performance.

IV. CONCLUSION

Through the experiments conducted, we concluded that 2 of our designed and manufactured variable stiffness caudal fins were able to outperform the previously accepted baseline or optimal stiffness caudal fin. The two caudal fins, which outperformed the Polyolefin fin, were the short Pike variation with the 2nd most rigid spines and the Lamprey with the most rigid spines.

A. Discussion

We found that our results seemed to resonate with previous literature and research done at the lab, including Deng et al., work, suggesting that less stiff materials are

generally better and result in faster swimming caudal fins [2]. This was verified as we had many scenarios where we would have 2 identical fins geometrically, with the only difference being one tail was with the most rigid spines and one was with the 2nd most rigid spines. For the most part, we discovered that the less rigid tails were able to outperform their stiffer counterparts. The only exception to this was the lamprey, which was best with the most rigid spines, but we suspect this is due to a much longer and larger surface area and moment of inertia.

Similarly, during the experimentation and data collection phase, we noticed that the different caudal fins resulted in drastically different swimming gaits executed by the MuBot. More specifically, some changes in the geometry or stiffness of the tails also resulted in major changes in the gait. Although the scope of this work did not include analyzing these different gaits, we did want to mention this as it also correlates to previous research in this field and work done in our lab. Moreover, this correlates to embodied intelligence, as this combination of morphological change and the controls applied to a robot is the very essence of embodied intelligence. Additionally, this resonates with biology as we know in nature, different fish showcase different kinds of swimming gaits, which correlate to their sizes and roles in their environment.

Another interesting finding of this work, as it relates to embodied intelligence, is the change in midline kinematics of the MuBot with these variable stiffness caudal fins. Although not numerically quantified, we observed much more elastic midline kinematics, especially in the caudal fin region, which closely resembled the kinematics observed in real fish. This was achieved simply by attempting to mimic the morphology and stiffness array of biological swimmers.

B. Limitations and Scope for Improvement

During the research process, we also realized multiple limitations and weaknesses of the work, which we feel are important to state and acknowledge in this section. Firstly, for more thorough and rigorous testing, we could decrease the increment size for the frequency sweep to something like 0.1 to get a precise idea of which exact frequency results in the best speed; this would also give us much more data and populate the graph more. Also, the motion tracking software follows and calculates the speed of the float and not the MuBot itself. Because the connecting tether is so short and taut, we don't think their velocities vary greatly, but there is some error or uncertainty in this process. However, switching to a positively buoyant MuBot comes with its complications, as certain fins, like the Lunate, for example, would be sticking out of the water and therefore could not be compared to a Lamprey tail directly.

Another potential source of error arises from the motion tracking algorithm. During the data collection process, we felt that the tracking was less precise for the extremely fast trials. This could have to do with the brightness values of the IR camera not being tuned correctly, or just the fact that it was unable to keep up with some quicker speeds, but regardless, the motion tracking was less accurate for higher speeds. Additionally, another variable that we could not control but that we felt affected our results was the coil heat in the actuators. Other variables and factors of the MuBot cannot be quantified easily, but this is one factor for which we noticed a lot of correlation. Repeatedly, the second or third iteration for each frequency would result in a higher swimming speed, and during the experimentation, we

hypothesized that this was caused by the heat produced in the coils, making the actuation faster and more fluid. This would also introduce other uncertainty, as if coil heat is indeed a major variable, the heating up and cooling of the coil should be tracked and measured to verify this.

For instance, as previously mentioned, one of the major reasons for not comparing session 1 and session 2 of our experiments is because of the water level of the tank changes. This is something relatively easier to measure and double-check, and we confirmed that this caused major discrepancies in the velocity readings, with a difference of almost 0.6 cm/s with an increased water level. The reason for this difference is again that the algorithm takes the difference in displacement to calculate velocity, which changes based on the depth of the tank, as the distance from the MuBot/float to the camera also changes.

C. Future Work

This work produced a lot of interesting results, and as mentioned in the results, with a preliminary or pilot experimentation phase, two variable stiffness caudal fins were already able to outperform the previously accepted optimal caudal fin stiffness material. An important note for future work is to quantitatively make measured changes in the caudal fins based on measured responses and make the process more objective. For the scope of this project, the adjusting and optimizing of the designs was done purely by us conversing with one another and just going off our feel and experience for what we think would work best.

In the near future, a complete artificial evolution study will be conducted based on the principles observed in this paper. To be more precise, we plan to conduct artificial evolution, mimicking biological evolution, to find an ‘optimal’ morphological caudal fin. This process will entail establishing an ecological niche, which, relating to embodied intelligence, involves keeping a steady environment between generations and iterations. Next, a design space must be established for the caudal fin, which parametrizes all the potential variables for designing the fin.

This includes the shape of the spline curve, chord angle, aspect ratio, thickness, and the other variable stiffness parameters. Next, code will be written to spawn random caudal fin shapes with varying parameters, which will act as the base or seed generation. After carrying out tests on all these fins, slight modifications will be made, methodically, using the code to design a more efficient fin which will act as a child generation. This process will continue until a complete evolutionary tree is formed, which would most likely result in an objectively optimized morphological caudal fin, which could end up mimicking biology, or it could result in a completely novel shape or geometry. Additionally, there are potential changes to be made in the reward function to incorporate acceleration and not just velocity, or to change the task and involve some tandem swimming task or a race-type game instead of just a straight swim, if we notice very marginal improvements.

Finally, one other area that was briefly explored was applying these advanced AM techniques and variable stiffness to other parts of the MuBot, more specifically, the actuator arms. The caudal fin is the most important part of

thrust generation, but a close second would be the actuators, which cause the undulation in the robot. If these traditionally rigid actuators are replaced with more elastic and less stiff actuators, it could potentially result in a much higher bend angle, which in turn could increase the undulation and overall swimming performance of the robot. Figure 8 shows the results of a brief study conducted with a ‘dummy’ test robot, which displays the improved deflection angles and bending abilities of the robot.



Figure 8. Direct Comparison of the Variable Stiffness Actuator Arms

As shown in the figure, there is a massive increase in the bend angle, and this is something worth exploring further. To add context, Flexible 80A is a fully flexible material which is still quite elastic, but the variable stiffness one shown above is from the same Elastico material mentioned before, and it is much more plastic, which is partially why the angle is so much higher. However, it is important to emphasize that these preliminary tests were conducted on dummy robots, which did not include any electronics or magnets. A real test must be conducted to test feasibility, as a lot of factors would come into play, such as the heat from the coil potentially damaging or even melting the elastic actuator arms.

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