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Additive Manufacturing Materials and Design Considerations for Thunniform Propulsion

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ABSTRACT: A series of polymer fins were designed and made using additive manufacturing techniques, to be tested by the Human Powered Submarine team at UCSD in a wet submarine that utilizes a thunniform method of propulsion. A 3D printer was also constructed in order to print these fins efficiently. Designs were inspired by the shape and semi-flexible properties of fish caudal fins. Materials utilized included polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polycarbonate (PC), PC-ABS blends, Nylon, and thermoplastic urethane (TPU) polymers. Of these materials, polycarbonate proved most practical for this application. Factors that were qualitatively considered during the practical testing were the material properties of a specific polymer, the surface area of the propulsive fin, and the shape of the fin. The low-cost polycarbonate processing techniques used in this project are also applicable to the additive manufacturing field in general.

Introduction

Thunniform swimming, one of the types of locomotion utilized by fish, potentially presents advantages over more conventional propeller-driven underwater locomotion, primarily in terms of greater propulsive efficiency. For the past several years, the Human Powered Submarine team at UC San Diego, inspired by these facts as well as research into the subject performed by various institutions around the world, has produced a series of submarines propelled by an oscillating hydrofoil, emulating this thunniform propulsion method (see *Figure 1 and 2*). Previously, propulsion fins have been handmade, typically shaped out of wood with a layer of fiberglass overlaid on top. While this has proved sufficient in the past, it is limited by imperfection in shaping the fins by hand, as well as the great amount of time and effort required to produce a fin in this manner.

Recently, growth of the additive manufacturing industry has allowed for much wider access to high quality 3D printing. This greater access, as well as developments of a wide variety of plastics for 3D printing, has made 3D printing a viable method of production for the propulsion fins required for this application. The greatly reduced production time, higher precision, and ability to change material properties now allow for a variety of fin configurations to be tested relatively easily. Thus for this application, the significant advantage that 3D printing provides in terms of design iteration capabilities is very beneficial, allowing for a large degree of qualitative testing, as the huge number of variables at play makes quantitative testing prohibitively difficult.

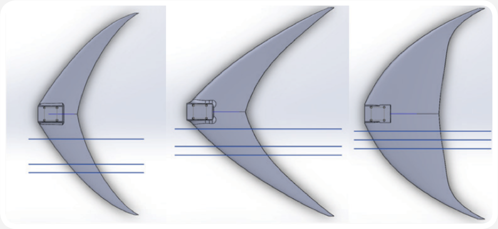
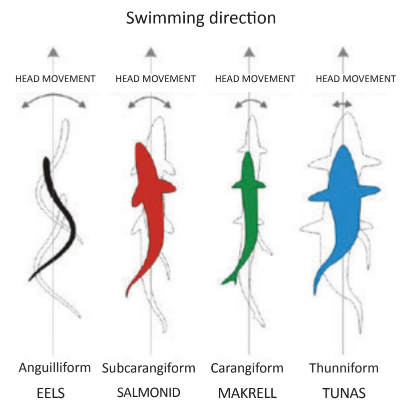


Figure 1. A sample of the variety of fin shapes that were considered



Redrawn from FIsh Physiology, 1978

Figure 2. A variety of fish propulsion methods; thunniform is illustrated on the far right

Figure 3 shows a table with some typical mechanical property values for materials considered in this project. Note that these values are for injection molded parts; 3D printed parts are typically around 10-20% weaker than similar injection molded parts due to the imperfect layer adhesion inherent in additive manufacturing. Information comes from datasheets for some of the specific polymers obtained for use in this project. From left to right, as they appear in the table, these resins are Sabic MG94, Ertalon 66 SA, Makrolon 2458, Stratasys PC-ABS, Ingeo 4043D, and Elastollan C85A.

Biological Inspiration

Thunniform swimming is characterized by a relatively rigid head and body, with a wide tail sweep (as opposed to an eel, for example, where the head moves as much as the tail). This model fits well with that of the human powered submarine team's boat, as the rigid fiberglass hull stays relatively stationary while propulsive thrust is generated with the sweeping of the rear boom and fin. Thus, the majority of fins produced for this project were inspired by the lunate caudal fins of fish that swim in a similar thunniform manner, such as tuna and marlin. These fins exhibit a high aspect ratio that is advantageous for high-speed tail fin oscillations.3 Additionally, the diminishing area towards the fin tips is advantageous for design purposes, as it reduces the moments imposed on the fin due to the reactive stress of the water.

Another desirable biological quality of fish caudal fins is their degree of flexibility. The composite nature of a fish fin, with a flexible membrane of tissue over a bone structure that provides some rigidity, allows for semi-flexible properties. This elasticity allows for an induced twist along the caudal fin, with varying levels of elasticity influencing the degree of twist and thus the swimming speed.4,5 This varying elasticity can be emulated in 3D printing through changes in the infill and shells of printed model, as well as the material with which it is made. While different in form, it allows for biomimicry of the functional properties of fish fins.

Equipment

Printer: In order to produce the fins for this project efficiently, a custom modified printer was required. The two key requirements for the printer were high working temperatures to handle all consumer 3D printing plastics, as well as a large build area to reduce the amount of separate sections required for a relatively large (about 3 feet or 0.9 meters) fin. To meet the size requirement, the base 3D printer that was acquired was a Folger Tech FT-5 printer kit, one of the largest commercially available consumer printers with a 300x300x410 millimeter (12x12x16 inch) build area. The base kit was then modified to support dual extrusion and higher processing temperatures, with aftermarket extruders, hot ends, cooling, and build platform. Additionally, a ventilated enclosure system was constructed to limit fume emission and to maintain a higher ambient temperature around the items being printed.

Filament Extruder: A 3D printing filament extruder allowed for a cost effective means of producing large quantities of filament, as well as experimenting with the composition of the filament. The filament extruding setup consisted of a modified Filastruder kit used to make the filament, and a filament winder. As was the case with the 3D printer, the modifications to the Filastruder were necessary for the processing of thermoplastics with higher melting points, such as polycarbonate and nylon. These modifications include an upgraded power supply to reach these temperatures, a larger nozzle bore, and a more effective filament cooling system. Advantages of a filament extruder over purchasing pre-made filament include knowledge of the specific resin (and thus the properties of that resin) used to make the filament, as well as the fact that purchasing plastic pellets is much cheaper than extruded plastic filament. Additionally, with a plastic shredder, it becomes possible to recycle failed prints using a filament extruder, which is advantageous for expensive plastics such as those with carbon fiber reinforcement.

Property	Unit	Values					
		ABS	Nylon	PC	PC-ABS	PLA	TPU
Transile Yield Strength	MPa	45	93	65	41	60	41
Tensile Strength at Break	MPa	34	90	65	41	53	41
Tensile Modulus	MPa	2471	3550	2400	1900	3600	345
Notched Izod Impact	kJ/m^2	16	33	75	14	5	N/A
Flexural Strength	MPa	70	178	97	68	83	7
Flexural Modulus	MPa	2500	6700	2350	1900	3800	24
Glass Transition Temperature	°C	105	70	145	125	55	-40

Figure 3. Typical mechanical properties of polymers

Printing Procedures

The production procedure of the fins varied based on the material and the shape of the fin. Initially, fins made of PLA and of TPU were printed vertically with the ends on the print bed. This orientation was easiest to manufacture, as it allowed the fins to be printed in fewer sections. However, it with other materials, warping became a problem, making such orientations difficult. Additionally, having the layers stacked along the z-axis made fins printed in this orientation more prone to shearing along print lines in response to stresses encountered in the water. Later revisions were therefore printed flat on the print bed. *Figure* 4 shows a table containing general printing settings used for the plastics in this project. After printing, fin sections were then fixed together, typically using Amazing Goop brand styrene-butadiene adhesive (some fins were welded successfully welded together, namely those made of PLA and TPU).

Of particular interest is the printing method for polycarbonate, as it is relatively new in consumer printing. Polycarbonate filament is also relatively difficult to print with, due to issues with bed adhesion, warping, and high processing temperatures. Numerous bed adhesion methods were tried, including common 3D printing adhesive coatings (PVA glue stick, ABS-acetone solution, and hairspray) and various surfaces (painter's tape, polyimide tape, smooth glass, and sanded glass). Ultimately, the most successful surface was found to be smooth glass with Airwolf Wolfbite Mega, a newly developed adhesive specifically for 3D printing polycarbonate, but even this required an exceptionally high bed temperature. The most cost effective solution to attain these high temperatures was through a 750-watt silicone heater mat affixed to an aluminum build platform and powered via a solid-state relay. To aid with bed adhesion and combat warping, polycarbonate fins were printed with a significant first layer brim (upwards of 15 perimeters). Additionally, a partial enclosure allowed for higher ambient temperatures around the printed object, in order to reduce further the problems posed by warping. After compensating for these issues imposed by polycarbonate, it proved to print comparably to ABS, with finished parts being significantly stronger.

Polymer Extrusion Procedures

Essentially, the polymer extrusion process for producing filament consists of feeding plastic granules through the extruder, which melts them together into a continuous strand. Similar to printing, different plastics required different procedures for extruding into filament. Since the process is much simpler than printing though, the differences in procedure are generally less complex, with the major differences being the processing temperature and the amount of cooling required. Additionally, some plastics required pre-processing in order to remove moisture, which was accomplished by placing the pellets in a food dehydrator for several hours before extrusion. *Figure* 5 shows a table with some of the processing information for plastic filament produced for this project. Some variation in these values occurs based on the specific resin being used, as well as the presence of any additives, such as dyes.

Material	Print Surface Preparation	Nozzle Temp (°C)	Bed Temp (°C)
ABS	Heated glass with PVA glue stick	235	110
Nylon	Heated glass with PVA glue stick	255	45
PC	Heated glass with Wolfbite Mega adhesive	280	145
PC-ABS	Heated glass with Wolfbite Mega adhesive	265	120
PLA	Blue painter's tape	220	N/A
TPU	Heated Glass with PVA glue stick	220	50

Figure 4. General print settings

Material	Processing Temp (°C)	Fan speed/ cooling airflow	Pre-processing
ABS	185	Low	None
PC	250	High	Dehydration
PC-ABS	230	High	Dehydration of PC
PLA	150	Low	Dehydration

Figure 5. General processing settings for filament production

Testing and Design Iteration

Fins for this project were designed iteratively, with results of previous tests altering the design goals of future tests. The first round of tests consisted of small-scale fins, to get an idea of the properties exhibited by fins made of a variety of materials. From these tests, TPU and Nylon were found to be too flexible, and thus were not utilized in later tests. Additionally, PLA was found to be too rigid and brittle for thin lunate shapes, but was found to be suitable for producing simple, straight hydrofoils.

After this preliminary phase, further testing of fins was conducted underwater on the full-scale submarine, in UCSD's Canyon View pool. This second round of testing was conducted with the aforementioned simple rigid hydrofoils in order to determine general dimensions and cross section that would be suitable for testing with shapes with a greater complexity. Taking into account pilot feedback, a surface area of about 120 square inches (775 square centimeters) was found to provide a suitable balance between oscillation speed and hydrodynamic resistance imposed by the fin. Additionally, a span of about 3 feet (0.9 meters) proved to be a practical length due to concerns of damaging fins on the bottom of the pool, and provided for a favorable aspect ratio. The cross section of the fin was chosen to be a NACA 0012 shape, as it was narrow enough to allow for a degree of elasticity, while not narrow enough for failure under load to be a major concern.

Once the general base dimensions were found, three simple lunate fins were constructed out of polycarbonate, ABS, and a PC-ABS blend in order to test the induced twist in thunniform motion. ABS, while sufficiently flexible for use as a fin, exhibited wear lines at the points of deflection after some use, and cracked along these lines after continued testing. PC-ABS and pure polycarbonate performed similarly to each other, and both were found to be suitable for use as a propulsion fin. Ultimately, polycarbonate was chosen as the material for the final fin, as it was simpler and more cost effective to acquire and process. Additionally, pure polycarbonate offers better material properties for this application than those of ABS blends. The main advantage of ABS blends is easier processing, with reduced warping and lower temperatures. As there were minimal difficulties processing polycarbonate, there was no reason to sacrifice the higher impact resistance, wear resistance, and elasticity of polycarbonate.

Conclusion

The final fin design combined these findings, being a lunate design measuring 33 inches (838 mm) in span, with a maximum length of 5.125 inches at the center, tapering down to a point at the ends (see *Figure* 6). An aspect ratio of 9.1 was calculated for the fin, and induced twist during propulsion was estimated to be about 30 degrees of rotation at the tips of the fin. The fin was printed from Makrolon 2458 polycarbonate filament, produced on the modified Filastruder extruder. Further variants of this fin will be examined with different numbers of layers and different infill patterns in order to increase durability and optimize the level of elasticity. Another further goal is to attain near-neutral buoyancy, as this would simplify the balance the submarine's overall buoyancy.

Figure 6. A printed iteration of the final fin design.

Acknowledgements

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References

Harper, K., Berkemeier, M., & Grace, S. (1998). Modeling the dynamics of spring-driven oscillating-foil propulsion. *IEEE Journal of Oceanic Engineering*, 23(3), 285-296. doi:10.1109/48.701206

Pedro, G., Suleman, A., & Djilali, N. (2003). A numerical study of the propulsive efficienc of a flapping hydrofoil. *International Journal for Numerical Methods in Fluids*, 42(5), 493-526. doi:10.1002/fld.525

Lindsey, C.C. 1978. Form, function, and locomotory habits in fish, p. 1-100. In W.S. Hoar and D.J. Randall (eds.) Fish physiology. Vol. II. Academic Press, New York.

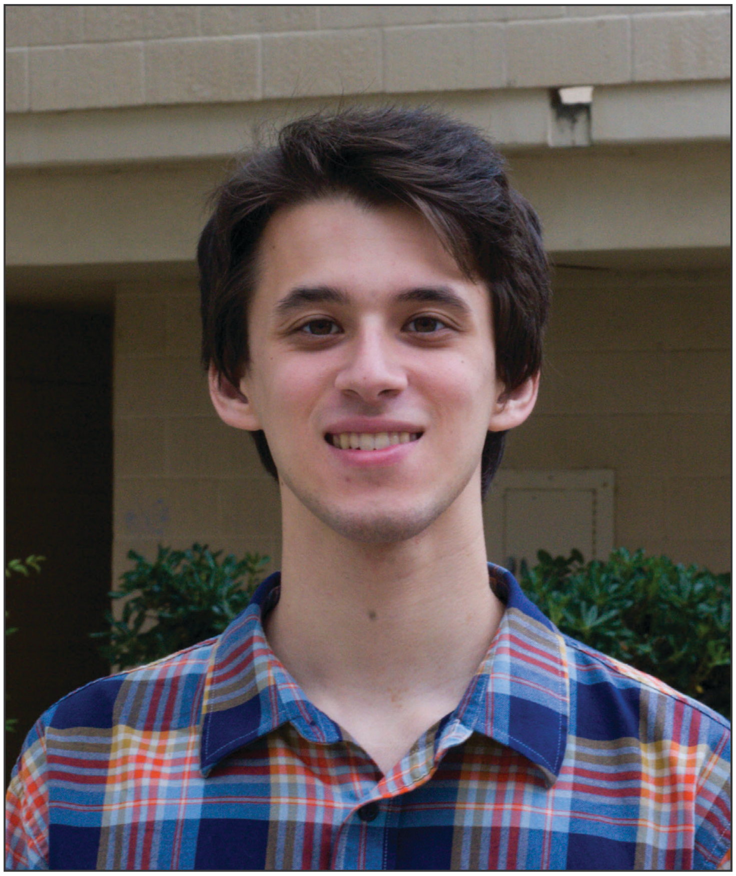
Ziegler M., Pfeifer R. (2013) Sensory Feedback of a Fish Robot with Tunable Elastic Tail Fin. In: Lepora N.F., Mura A., Krapp H.G., Verschure P.F.M.J., Prescott T.J. (eds) *Biomimetic and Biohybrid Systems. Living Machines 2013. Lecture Notes in Computer Science, vol* 8064. Springer, Berlin, Heidelberg

Morikawa H, Nakao S, Kobayashi S-I, Wada H. 2001. Experimental study on oscillating wing for propulsor with bending mechanism modeled on caudal muscle–skeletal structure of tuna. *JSME Int. J. C Mech. Syst.* 44: 1117-1124

Fish Swimming Styles [Photograph found in *Stanford Environmental Science Investigation*]. (n.d.). Retrieved from https://esi.stanford.edu/exercise/exercise4.htm

Burgess, G. (n.d.). A close-up of the lunate caudal fin [Photograph found in Xiphias gladius, *Florida Museum*]. Retrieved from https://www.floridamuseum.ufl.edu/fish/discover/species-profiles/xiphias-gladius

Cain, P. (n.d.). 3D Printing Infill [Photograph found in Selecting optimal shell and infill parameters for FDM 3D Printing, *3D Hubs*]. Retrieved from https://www.3dhubs.com/knowledge-base/selecting-optimal-shell-and-infill-parameters fdm-3d-printing



Thomas Spencer

Aerospace Engineering

Thomas Spencer is a second year aerospace engineering student at UCSD from Santa Ana, California. He is heavily involved in the Human Powered Submarine team at UCSD, for which he designs and manufactures propulsion and control systems; this involvement provided the inspiration for this particular research project. He plans to develop future iterations of the fin to improve the desgin. In addition, he volunteers in a structural engineering laboratory that studies shocks and impacts. In the coming years, he hopes to continue research in the field of 3D printing, as well as other topics of interest such as material development and electronic controls, with the ultimate goal of working in the aerospace industry.

In his free time, Thomas enjoys hiking, reading, and playing video games. He looks forward to going home on breaks in order to visit his dog, two cats, turtle, chameleon, and fish.

How did you get involved with research at UCSD?

I know that sometimes it takes a while to find a lab position on campus, especially one that aligns with your interests. I however, got quite lucky. I received an email from the Aerospace Engineering department stating there was an available undergraduate research position at a lab. I decided to apply for the position since the research being done at the lab seemed very intriguing. I was interviewed by the PI, and fortunately, I got the position at the lab. I am very grateful that my first research experience has been so enriching and has helped me acquire essential research skills, and I am very glad that I decided to apply for that position.

If you were a PI, what research would your lab focus on? And why?

If I were a PI, my lab would focus on material research. I want to learn more about the different processes making items with different materials. In particular, I would like to delve deeper into 3-D printing and polymer research.

What has been your greatest challenge in research?”

I think my greatest challenge with research was how to keep track of all the tiny details that are involved. These tiny details are very crucial, and I initially struggled with it. I received a lot of help from my mentors who guided me throughout the entire process conducting research. I hadn’t been exposed to working at a research lab before, so I really had to understand and learn about the scientific method and all the various stages of conducting research.

What’s the coolest research project project you’ve seen/ heard of, and where did you see it?”

I think the research being done on robotics is very fascinating. I know that there are some projects with robotics going on in the Nanoengineering department, but I’m not completely sure. I don’t know much about the research being done on robotics and other Artificial Intelligence, but I do know that AI is our future and I would really love to be able to learn more, and perhaps get involved with some research about these topics.