3-D Printed Metal and Plastic Propeller Design and Manufacturing for Small-scale Underwater Thrusters

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Abstract

The use of additive manufacturing technology in a senior Capstone project setting is increasing. In this paper, effective examples of additive manufacturing are presented, which was used in a Capstone project. Moreover, the design challenges for prototyping by metal 3D printing are discussed. Examples of plastic or metal thruster propellers are presented. These propellers are designed for an underwater thruster, which is one of the key elements in underwater robots. A thruster consists of a propeller, brushless motor, ducted enclosure, and electronic speed control (ESC) unit. This paper includes a design and manufacturing case of the small-scale thrusters. Moreover, the assembly of the thruster is presented, which meets 2019 Marine Advanced Technology Education (MATE) competition safety requirements. Furthermore, the Remotely Operated Vehicle (ROV) robot example is presented.

I. Introduction

Ocean exploration is a topic where real-world needs, engineering technology, education, and novel manufacturing methods can converge. The exploration of the ocean makes it possible to discover and search for underwater resources that have not yet been actively used. For ocean exploration, it is important to collect various data sets from the underwater environment, usually supported by sensors and electronics. Underwater areas that pose potentially hazardous locations give way to robotic, unmanned platforms for performing data collection missions.

One of the key elements in these underwater robots is a thruster. It is the collection of parts including a propeller, brushless motor, ducted enclosure, and electronic speed control (ESC) unit. The propeller design and manufacturing is an important task for the thruster development. In this paper, the challenges of 3D printing an in-house thruster for underwater propellers are presented. For the propellers, there are two types of additive manufacturing techniques that are applied and the design, build, and implementation are discussed.

First, Fused Deposition Modeling (FDM) machines were used. The material choice was an acrylonitrile butadiene styrene (ABS) plastic. The roughness of the propeller is known to have a significant impact on efficiency in moving water. Ridges left on the part from the layer deposition in plastic FDM create a roughness much greater than desired for this type of part. Therefore, post processing for the FDM was performed. Rather than using a mechanical polishing method such as sanding, a vapor treatment with acetone was used and found to drastically improve the surface quality of the blades. As a second method, the propellers were manufactured by a Selective Laser Melting (SLM) process using powdered 316L stainless steel. The limitations in geometry, cost, strength, and resulting performance are discussed in this paper. Six in-house custom thrusters were fabricated and they have been applied in an example remotely operated vehicle (ROV).

II. Educational benefits in using additive manufacturing technology in Capstone projects

One of the authors, David Malawey, has been teaching capstone-enrolled students closely to meet the various needs in capstone projects as a Technical Laboratory Coordinator in Engineering Technology Department at Texas A&M University. He has assisted students in conceptual design, selection of materials, selection of manufacturing processes and designing for manufacturing. Through the experience, he has observed that the additive manufacturing (AM) tools have taken on specific roles in prototyping projects. Student teams often require specific instruction and consultation regarding the use of additive manufacturing tools in order to benefit from the AM tools available in the labs.

Plastic AM repeatedly adds high value in projects that have modular designs. The students in Texas A&M Engineering Technology Department build applied electronics projects in their capstone course. One previous project was an automated gardening system that used a microcontroller circuit board, power adapter, and water valves, which were integrated in a monolithic CAD design at stage one. Before attempting to 3D print the system, the design was improved by modularizing. The final version used a strong waterproof off-the-shelf enclosure, with brackets for each component individually modeled, printed, and fastened into the enclosure with epoxy. Each bracket was printed in plastic. This reduced total print time by more than 50%, allowed iteration of designs for each feature without discarding the whole prototype, and allowed designs to be validated piecewise. Piecewise design also gives an advantage of dividing tasks into parallel efforts among team members. This concept and similar strategies have developed with time and trials.

Another team prototyped most parts in plastic. This is NT^2 (Neptune's Trident Nautical Technologies) capstone team [2]. They focused on developing underwater robotics and ROVs (remotely operated vehicles). This was a team with four students and two faculty mentors. This Capstone project was carried for two semesters (Fall of 2017 ~ Spring 2018). The team has designed a thruster by modification of an open source model and printed them in plastic. To pursue a better quality and to protect the propellers underwater, it was decided to create a metal 3D print using stainless steel 316L. Therefore, a new propeller for metal printing was designed and the propellers successfully were printed in metal. However, these initial metal propellers were not used in a thruster assembly since they required some modifications in other thruster assembly parts.

The NT^2 team's propellers were eligible for metal printing based on the following criteria: First, using metal adds real value - in this case by improving durability. Second, the design naturally had good "printability" with its small envelope, thin cross sections, and minimal overhangs. This example is shown in Section IV. To achieve the build, minor design changes were introduced including reduction of mass and changing the pitch of the blades to keep the surfaces above the "overhang" threshold of 45 degrees. Metal 3D printing, unlike FDM printing, requires higher consideration for detrimental design features and potential failure-modes. Most of the design features of concern are described in detail in the following section.

III. Design feature issues in Metal 3D printing

In designing for metal AM (specifically in the SLM process), a number of design features must be eliminated before starting a build job [3]. Due to incompatibility with the powder melting

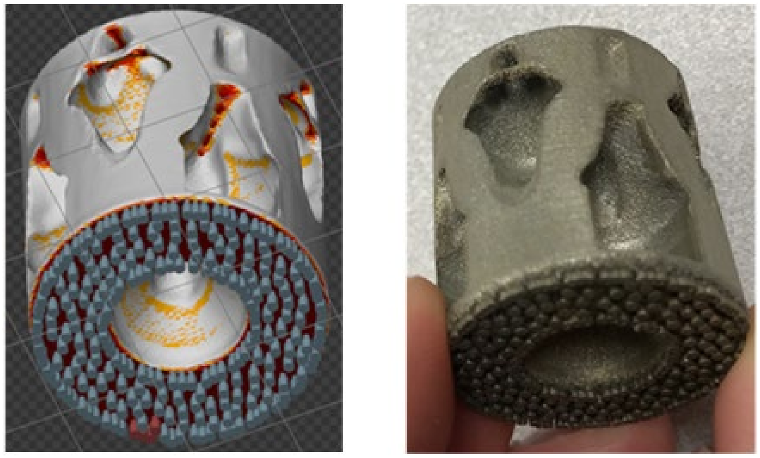

Figure 1. Highlighted overhanging regions and resulting rough surfaces

process, parts with these features cause manufacturing problems which can cascade along build, part removal, and post processing [4][5].

A. Overhanging surfaces

Overhanging surfaces may be the largest challenge of a metal SLM process. A flat-lying part that is not built directly to the build plate may use more than a thousand small pillar supports. Matrix-style supports may replace the pillars but they come with their own challenges in software and CAD processing power, as well as recovery of unused powder. After the supports are removed, the downward facing surface of an overhang still has an undesirable rough surface finish in the range of 80 grit sandpaper, which corresponds to 8 to 15 micron Ra value. Some slicing software such as quantAM offer visual highlighting of the regions of parts hanging below the set threshold (usually 45 degrees) to help with choosing part orientation and planning design modifications. An iterative placement, orientation, and design modification process usually precedes the actual build.

B. Warping

Parts with large contiguous masses, and more specifically a rapid increase of cross-sectional area from lower to higher z heights cause problems in SLM. These parts tend to warp significantly unless countermeasures are implemented. Most businesses that build large parts use post-build heat treatments as a standard process to relieve internal stresses. Heat treatment is applied before even removing the part from the build plate. Warping is hard to predict but one key is that parts that are not heavily anchored to the build plate tend to contract in the direction of the center of mass. Evidence of this is found in leaning support tips that point towards the center of the part and indicate contraction, as shown in Figure 2.

Planning geometry for metal AM is helpful, but even perfectly symmetrical parts will warp if the support structure is not designed for the part, orientation, material, and build environment. To date, no reliable simulations for the SLM process have surfaced, and perfecting the supports involves iterations of building and re-engineering support structures. Alternatively, parts may be built directly to the build plate, without supports. These parts leave more material on the build

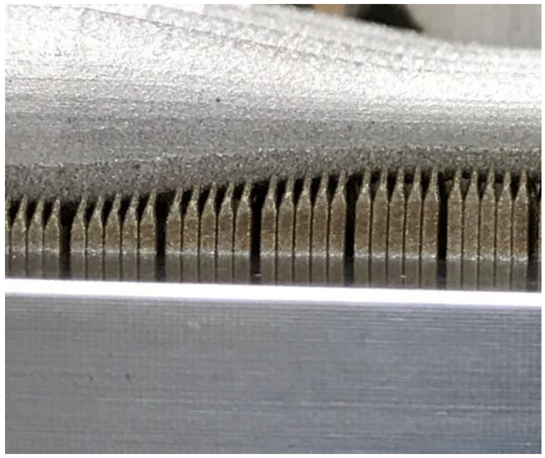

Figure 2. Tips of supports pointing in direction of contraction

plate after cutting them free (shown in Figure 3), and add cost in re-machining the plates in preparation for reuse. Since the part material is usually a strong alloy and the build plate is usually mild steel, tool wear is an added factor. In the ideal case, parts have a small footprint, gradual growth of cross-section along the z-axis, and a few heavy-gauge supports that can be broken off by hand after the build.

C. Supports falling

When a part has a large overhanging surface, the internal stresses that build up in the part can sever the connection between the support and the part. Figure 4 shows an example of a part that warped and detached from supports. If the support connection is increased, it remedies detachment but the supports become very hard to remove from the part. Strong supports that are densely placed often require manual removal with a grinding wheel. If the support connection is weakened, the support is easier to remove but it is likely to detach during the build and allow the part to lose its net shape.

A common method for cutting metal AM parts free of the build plate is by using a wire electrical discharge machine (EDM) [6]. Supports which detach then drop into the wire EDM water bath during the cutting process. This creates a need for more cleaning of the bath which contains purified, deionized water. Cutting a full build plate sized area would take more than an 8-hour workday and it requires technician supervision due to broken EDM wires from the very interrupted cut. Broken wires require restringing. The cutting of the supports also relieves some internal stress which causes the part to move and occasionally pinch and break the wire.

D. Rust

When the plate spends more time in the wire EDM, it causes rust which must be buffed or otherwise cleaned from the plate. A plate that was rust-free could be corroded. Fine rust particles clog the EDM machine filters more rapidly than other impurities that are normally introduced, and reduce the filters lifespans. The takeaway from this issue is that parts of small footprint and short cutting times are most suitable for metal AM.

Figure 3. Steel buildup from parts built directly to the build plate

Figure 4. A large part broken free from the supports

E. Parameter Variation

Many researchers wish to vary laser parameters on metal AM parts as part of their experiment, but this must be done with caution. Sometimes as little as 20% deviation from the parameters developed by the manufacturer can ruin a build and put the machine in danger of damage. Parameter deviation can effectively change power densities, which can result in poor melting and can create a buildup of semi-melted powder and damage the wiper which passes over the build plate to distribute each powder layer. A part with poor melting is shown in Figure 5 on the left next to a part with manufacturer-recommended parameters on the right. In this case the buildup of semi-melted material began to scrape and erode the aluminum wiper holder and the part was cancelled mid-build to protect the machine.

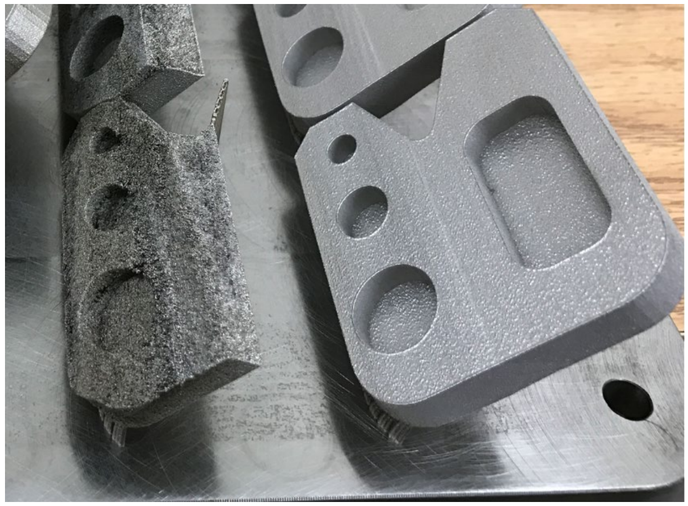

Figure 5. Poor melting due to improper parameters

E. Insufficient supports

A large part mass translates to a large amount of heat input. Massive parts must be especially well supported (regardless of overhangs) to avoid tearing free from the supports when the build reaches the timing of heavy heat input. At this time the partially built part lying under the powder bed surface can curl upwards and can crash the machine or slowly file away the wiper arm without the machine detecting any fault.

The limitations of metal AM create a strong need to carefully select projects that should be implemented on an SLM machine, and a need to make design adjustments before "printing" a part. The technology is still young and it is truly an achievement to build a functional part on the first or second trial. As the students and faculty become more familiar with the design conditions best suited for metal AM, it is easier to identify projects that add noteworthy value and build with ease, such as the propellers presented in this paper.

IV. 3D printed propellers in ABS and Metal

The authors printed an initial customized propeller in plastic and metal as shown in Figure 6. This effort was carried out through a capstone project. It was designed to fit a Turnigy 1100KV brushless outrunner motor. These propellers have not been used in the ROV. The plastic propeller on the left side was printed in a high resolution 3D printer, and the same design was printed in a Renishaw AM400 metal 3D printer using stainless steel 316L, shown on the right side. During this metal printing process, several lessons were learned. For instance, there were slight differences in printed qualities among the six propellers on the same build. In order to expedite the process, it was attempted to remove supports using a nipper and saw. This turned out to be a non-recommended practice, as it requires too much manual labor and risks bending of the blades. It is suggested to schedule a cut with wire EDM.

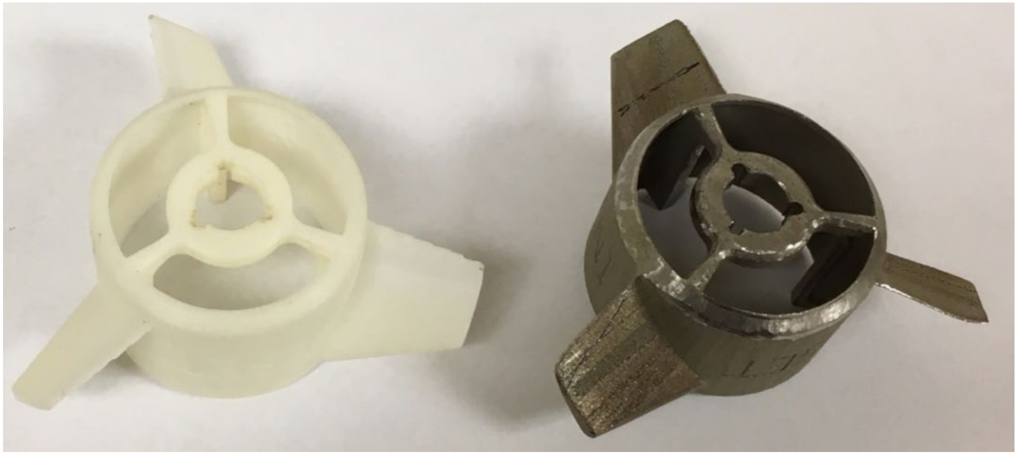

Figure 6. Initial plastic (left) and metal (right) 3D printed propellers for a turnigy outrunner motor.

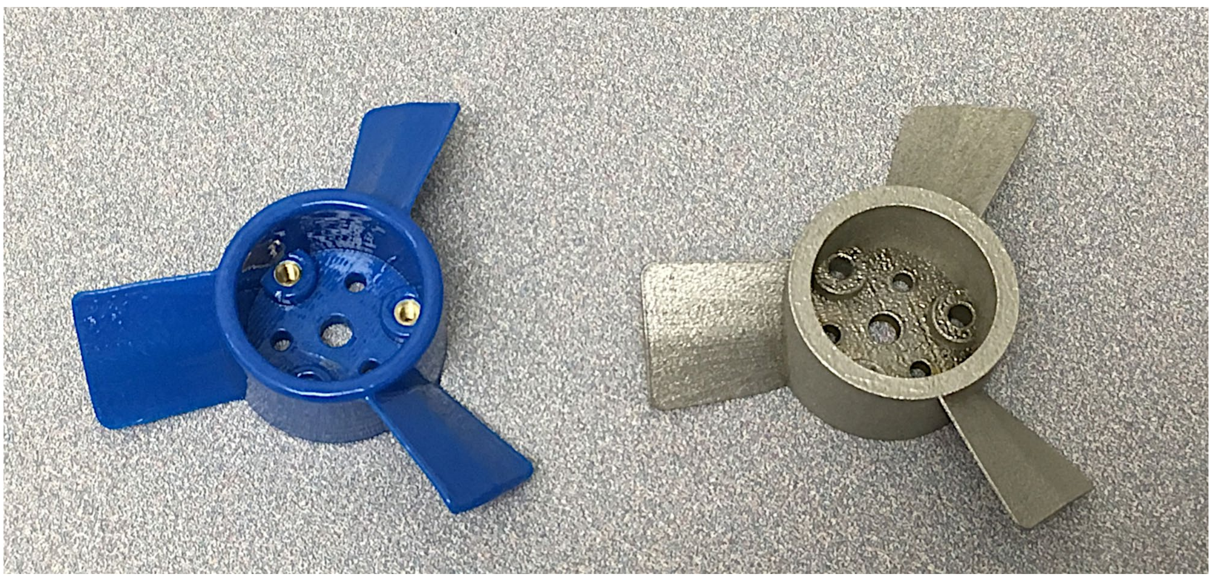

Figure 7. New version of the plastic (left) and metal (right) 3D printed propellers for T-Motor F40 Pro II

A new propeller was designed for T-Motor F40 Pro II motor as shown in Figure 7. In this version, the design is slightly more complicated since the height of the motor is less than the previous motor. Therefore, the bottom layer was placed low, and the top shows empty but, a separate propeller cover printed in plastic will be assembled on top. On the left side, the propeller printed in ABS plastic was shown. On the right side, the propeller printed in metal was shown. For this metal propeller fabrication, the design has been slightly modified to support manual threading instead of heat-set threaded inserts.

In order to further increase the propeller efficiency, the propellers were twisted slightly. This triggers the manufacturability issues. As the angle of the propellers stays around 45 degree, it has been smooth process in both plastic and metal 3D printers. However, due to the twist of the

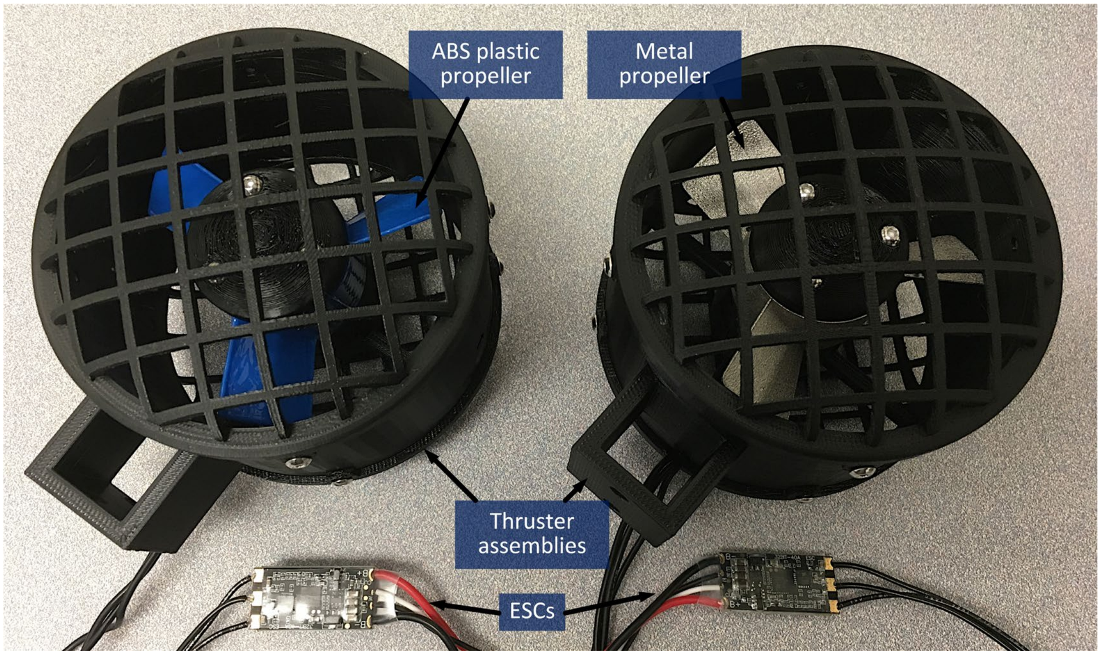

Figure 8. Thruster assemblies. Plastic propeller was used on the left side, and the metal propeller was used on the right side

propeller wings, it requires a significant amount of support. This is a manageable amount of support in plastics however, in a metal 3D printer, this amount of support was manageable but not negligible. It is worthy to mention that this propeller is a bidirectional propeller. It is typical for ROV to change the direction of the motor, and it would be desirable to have the balanced thruster efficiency between forward and reverse rotations. Now, regarding the surface quality of the propellers, the post process of acetone treatment was applied to the plastic propellers. As it can be seen from Figure 7, the texture of the surface is smooth rather than rough and striated. This turns out to be effective technique to create smooth finish on plastic 3D printed models, which is a good fit for a propeller model.

V. Thruster assembly and ROV application

Figure 8 shows the full assembly of the thruster. On the left side, it shows the thruster assembly using the acetone treated plastic propeller. The black propeller cover was used on top of the propeller. On the left side, it shows the thruster assembly using a metal printer, and the thruster using a metal propeller was shown on the right side. The motor is a brushless motor, and the ESCs are attached to these thruster assemblies. For the safety requirement of 2019 Marine Advanced Technology Education (MATE) competition, the thrusters must have propeller guard with the given specification [7]. These thruster assemblies were designed to meet the 2019 MATE competition requirement that has propeller guards on both sides. Other than propellers, all parts were printed using ecoABS [8] which was a type of PLA but stronger than a typical PLA material. The ESC was shown on the bottom of Figure 8. It is a typical BLHeli ESC. Depending on the model, it may be necessary to flash the firmware in order to support the bidirectional mode, which is central to the operation of this kind of thruster.

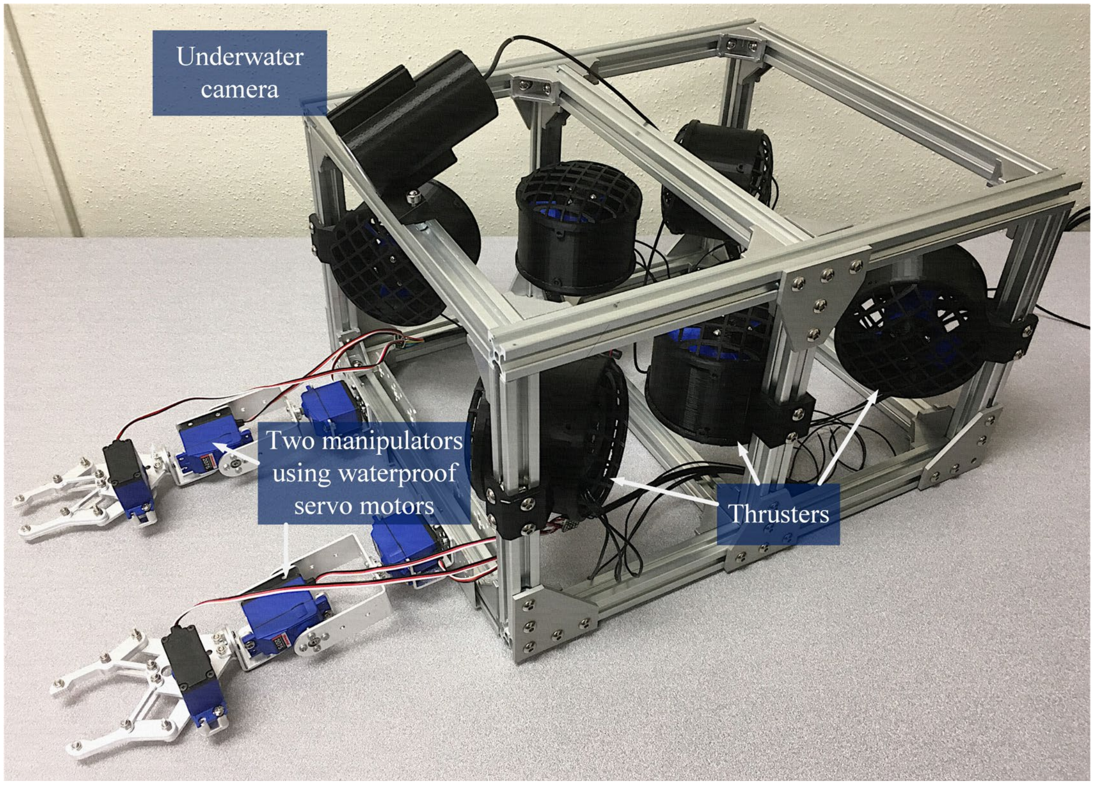

Figure 9. ROV application example using the custom built six thrusters for 2019 MATE competition.

The ROV application is shown in Figure 9. It has six thrusters. Four thrusters were faced forward and backward. Two thrusters were faced top and bottom. The underwater camera is mounted on the top, and two manipulators are attached. This is a ROV frame that can be used in creating an underwater robot as well as to create a ROV for a MATE competition. For the 2019 MATE competition, it is recommended have two manipulators for the various tasks.

VI. Discussion & Conclusions

The introduction of additive manufacturing technology created an impact in both industry and academia. In Capstone projects, this 3D printing technology has been actively used in a wide range of applications. In this paper, the 3D printed propellers for thrusters both in plastic and metal were presented. The instructional guideline of the design issues for the metal 3D print technology were discussed. The 3D plastic and metal prints for an initial model were shown, and the new version model for T-Motor F40 Pro II was presented. The thruster assembly was shown, and the ROV application was presented. The authors plan to continue to perform research and development on a wide range of thruster applications.

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References

[1] T. Duda, L. Venkat Raghavan, "3D metal printing technology," *IFAC-PapersOnLine* 49.29, pp. 103-110, 2016

[2] Neptune's Trident Nautical Technologies, available: https://capstone.tamu.edu/capstone-term-fall-2017-spring-2018/neptunes-trident-nautical-technologies

[3] Z. Weng,et al. "Mechanical and thermal properties of ABS/montmorillonite nanocomposites for fused deposition modeling 3D printing." *Materials & Design* 102, pp. 276-283, 2016.

[4] L. E. Murr, et al. "Fabrication of metal and alloy components by additive manufacturing: examples of 3D materials science." *Journal of Materials Research and technology* 1.1, pp. 42-54, 2012.

[5] Dept. of ETID, "Failure Causes in Metal Additive Manufacturing.", available: https://youtu.be/bq_6DYyZPBQ

[6] E. Sachs, et al. "Progress on tooling by 3D printing; conformal cooling, dimensional control, surface finish and hardness." Proceedings of Solid Freeform Fabrication Symposium, 1997.

[7] Marine Advanced Technology Education, "Underwater Robotics Competitions", available: https://www.marinetech.org/rov-competition-2

[8] Dremel Digilab, "ECO-ABS Filament.", available: https://digilab.dremel.com/service-3d45-filament-ecoabs