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Additive Manufacturing of Robot Components for a Capstone Senior Design Experience

Dr. Wesley B. Williams P.E., University of North Carolina, Charlotte

Dr. Williams is an assistant professor in the department of Engineering Technology and Construction Management, where he teaches courses in the areas of instrumentation and controls, technical programming, and mechanical design. He is active in the area of robotics, serving for three years as a faculty mentor for the UNC Charlotte Astrobotics team competing in the NASA Robotic Mining Competition.

Mr. Eric J Schaus, Georgia Institude of Technology

Graduated from the University of North Carolina at Charlotte in 2014 with a Bachelors of Science in Mechanical Engineering. Currently attending graduate school at Georgia Institute of Technology perusing a PhD in Aerospace Engineering.

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Abstract

The University of North Carolina at Charlotte competed in the 5th Annual NASA Robotic Mining Competition with a robot that included several additively manufactured (AM) parts. The team used a design-build-test approach throughout their project and were drawn to additive manufacturing (or rapid prototyping) to help them to reduce the cycle time on each iteration of the design-build-test process. Two different technologies, fused deposition modeling (FDM) and film transfer imaging (FTI), were used to additively manufacture these parts, using a Stratasys Dimension and 3D Systems VFlash respectively. These technologies provided some significant advantages in producing complex parts for the robot, but it did come with some limitations as well. Several students started the project with the mainstream notion that additive manufacturing allowed effortless printing of any part you desired from a CAD file. Through both successes and failures, they came to realize both the limitations and appropriate application of both the FDM and FTI process and their associated materials. The AM parts that ultimately made it on to the robot included replacement aperture covers for a photomultiplier tube (PMT), a custom gimbal used to orient the PMT, a latch used to secure a deployed arm, enclosures to protect sensors mounted on the robot exterior, and custom enclosures for the laser beacon system used for navigation. Notable disappointments for the AM parts included issues with part warpage, inappropriate application of sparse internal structures, and restrictions related to discrete layer thicknesses. These setbacks were ultimately resolved by either redesigning the parts, additional post processing, or shifting to alternative manufacturing approaches. The key success for the AM parts included the desired reduction in cycle time, effective matching of existing complex geometry, efficient mass reduction, and increased productivity by allowing students to move on to other tasks while parts were being printed. Once final embodiments were settled on for the various AM parts, they performed their intended functions without incident throughout the testing and competition at Kennedy Space Center.

Introduction

Students at the UNC Charlotte designed and built a robot to compete in the 5th annual NASA robotic mining competition [1]. The six wheeled robot, which weighed in at 167 lbs, included ten motors/actuators, numerous sensors, mechanisms, and an off board navigation system. While the load bearing components were almost exclusively aluminum or steel, additive manufacturing was used to produce several components for that robot that were used both for prototyping, testing, and competition. Additive manufacturing was used effectively in these cases to match difficult geometry on existing components, experiment with fixture geometries and to minimize the weight and lead times on other components.

Additive manufacturing processes

The additively manufactured parts all went went through a design, build, test process just like the conventionally manufactured components on the robot. The design phase included geometry generation in CAD software and file preparation for additive manufacture. The build phase consisted of production on one of the two available additive technologies, and the appropriate post processing to prepare the part for installation. The testing for the components consisted of fit and function tests, making sure that the tolerances were appropriate for the desired fits and that the components functioned as intended.

The parts were initially modeled in Solidworks to both generate the geometry and insure fits with mating components and that it could be successfully integrated into the overall assembly. The parts were then exported as STL files, using the high preset resolution. Like students at many other universities, the students had access and experience with some low and medium cost additive manufacturing technologies [2]. These STL files were then loaded into the Catalysts software if it was going to be produced on the Stratasys Dimension machine or loaded into the VFlash software for production on the VFlash.

The Stratasys Dimension is a fused deposition modeler (FDM) that produces parts in an acrylonitrile butadiene styrene (ABS) material [3]. This thermoplastic gives the produced components sufficient strength and toughness for use in many low stress applications. The machine is deposits material in .010” layers, which limits its application to parts requiring fine layer resolution. The Catalyst software allowed students to choose the orientation of the build to ensure the best representation of critical features. It also allowed the parts to be produced as either a full density part or a part with a sparse interior, consisting of a lattice structure. The lattice structure offers the benefits of lower material usage as well as a lower weight, while maintaining stiffness in the part. As the thermoplastic is deposited by a nozzle which is rastered across the build area, the build time is strongly dependent on the total volume of the part (including areas filled with dissolvable support material). Students were directed to estimate the manufacturing cost for the FDM parts using $5 per cubic inch for material and $5 per build plate.

The VFlash printer from 3D Systems uses digital light processing (DLP) to selectively cure an entire layer of photocurable acrylate epoxy in a process known as film transfer imaging [4]. Given that the entire layer is cured at once, the build time scales with the vertical build dimension instead of the overall volume of the part, allowing for quicker build times compared to the FDM. The layer thickness of .004” allows for much greater layer resolution than the dimension machine, but the material is significantly more brittle. The VFlash is somewhat unusual in that the part is built in an inverted orientation, so orientation of the STL is important to avoid distortions or defects arising from support contacts to the part geometry. Cost estimates for the the VFlash included $9 per cubic inch of material and $5 per build platform.

Once the build process is finished on both the Dimension and VFlash systems, the parts require some post processing before they are ready for use. The post processing of the FDM parts involved removing the parts from the build plate, then immersion in a solvent bath to dissolve the soluble support material, which is used in the build process, but not part of the final build. Parts produced on the VFlash were cleaned in a solvent bath to remove uncured resin, rinsed, and then placed in a UV chamber for final curing. Once the final curing was complete, the supports connecting the part to the build plate were clipped to remove the part. Despite using flush cutters to remove the supports, residual nubs remained on the surfaces oriented toward the build platform as shown in Figure 1 below, which had to be sanded down if the surface was critical. This is in contrast to the soluble support technology used in the FDM process where the surfaces do not require any post processing once they have been removed from the solvent bath and rinsed.

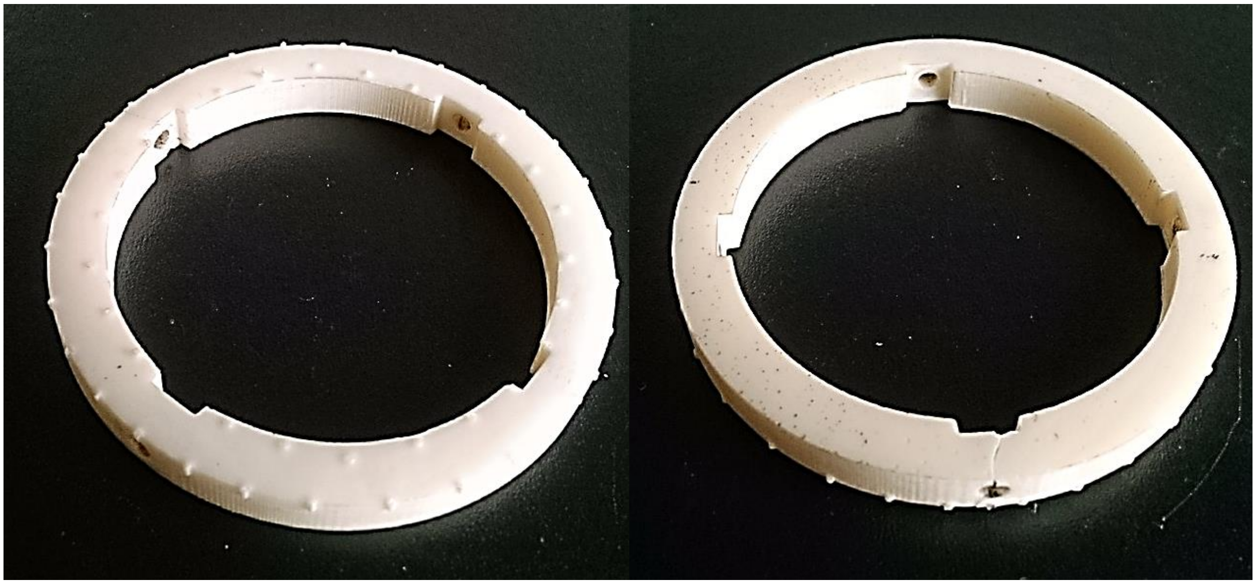
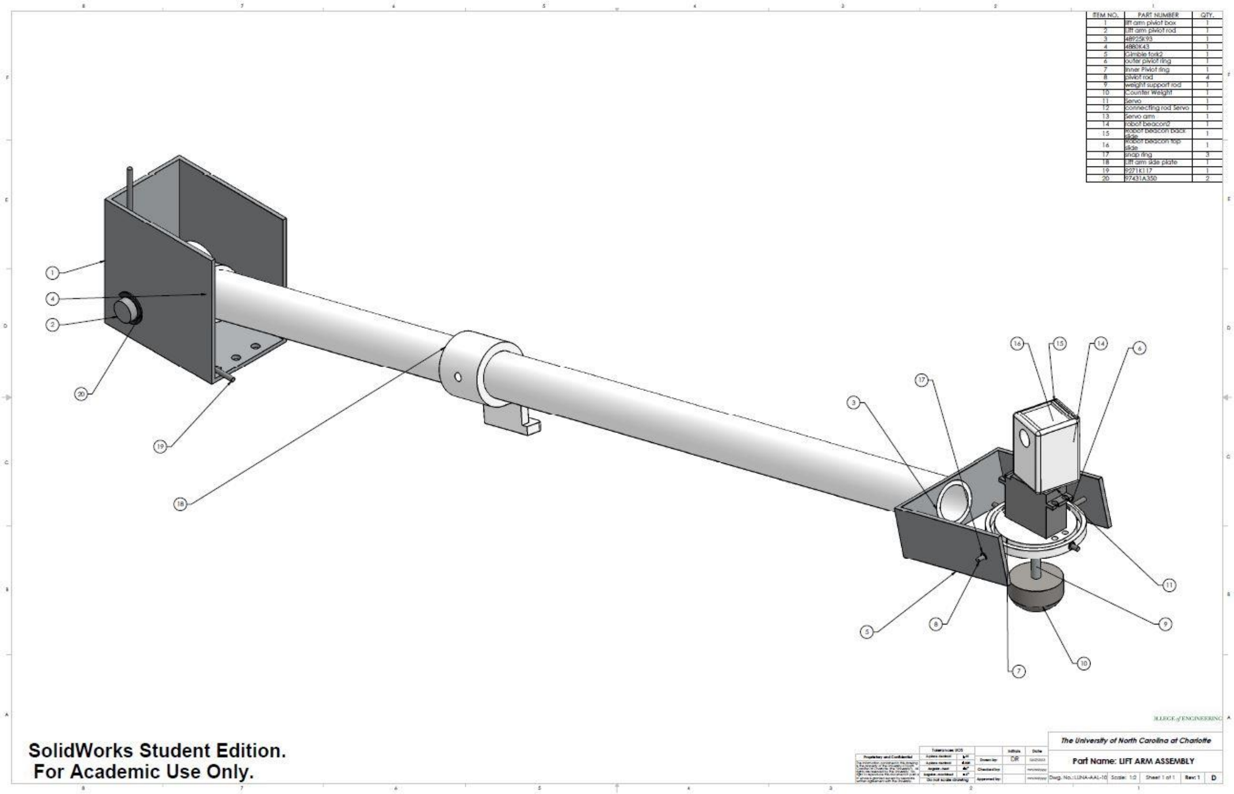


Figure 1. Gimbal assembly produced on the VFlash FTI system showing residual nubs from the support structure on surfaces facing the build plate (left) and the smooth surfaces which were oriented away from the build platform.

The additively manufactured parts

Several parts on the robot were chosen to be additive manufactured. These included a gimbal for a location detector, a cover and mounting for a photomultiplier tube (PMT), accelerometer housings, and enclosures for the laser assemblies used for the navigation beacon. In each case, there were certain desirable attributes that biased the design towards additive manufacturing.

A key component in the scheme for robot navigation was a gimbal mounted PMT on the robot, which was rotated to pick up modulated laser signals for stationary beacons in the competition arena. The PMT gimbal assembly was mounted to an arm that was deployed as soon as the match started, moving from a horizontal position (as shown in Figure 2) to vertical position.



ITEM NO.	PART NUMBER	QTY.
1	lift arm pivot box	1
2	Lift arm pivot rod	1
3	48925K93	1
4	4880K43	1
5	Gimble fork2	1
6	outer pivot ring	1
7	inner Pivot ring	1
8	pivot rod	4
9	weight support rod	1
10	Counter Weight	1
11	Servo	1
12	connecting rod Servo	1
13	Servo arm	1
14	robot beacon2	1
15	robot beacon back slide	1
16	robot beacon top slide	1
17	snap ring	3
18	Lift arm side plate	1
19	9271K117	1
20	97431A350	2

Figure 2. PMT lift arm and gimbal assembly.

The gimbal as shown in Figure 1 was key to insure that the PMT aperture was oriented parallel to the nominal surface so that signals from the lasers would be captured. While CNC machining of aluminum disks was considered for the production of the gimbal ring, the students ultimately opted for production on the VFlash due to the rapid turnaround (a 5 hour build instead of waiting several days to get through the CNC queue) and the ability to produce the desired geometry without the restriction of machining toolpaths, fixtures, and clearances.

The VFlash also enabled the production of a lightweight part, which was critical given the scoring rubric for the competition which penalized robots based on their overall mass. Attempts to achieve similar weights in aluminum resulted in more complex geometry for the aluminum gimbals which would have increased the manufacturing time, expenses, and expertise required. The students recognized that the resin part would not be as strong as aluminum, but in the event that it deflected unacceptably, they felt that they would at least get valuable information about the function of the gimbal design.

The PMT required a cover to exclude extraneous light from the sensor and to hold the optical bandpass filter. While the team was fortunate to source a low cost, working PMT through EBay, it did mean that the PMT came with limited documentation. The boss around the aperture (as seen in Figure 3 below) was measured, and the corresponding rectangular recess on the cover was sized to slide over the boss. The PMT also required some fixturing in order to mount it to the gimbal assembly. Once again, measurements of the PMT were made as well as best estimates for fits, given the lack of documentation detailing the geometry. The VFlash was also used for the PMT cover given the tight tolerances that were required and the fact that it was not a component expected to carry any load or suffer any impact.

Figure 2. Photomultiplier tube showing the aperture without bandpass filter or filter cover.

While the PMT was essential for the navigational design, it would ultimately be useless without laser signals from the mounted rotating beacons (Figure 3). Unlike the PMT where the students had to build around specific geometry without valuable documentation, the laser enclosure designs involved commercial, off the shelf parts with datasheets that were readily available. The Enclosures needed to house the laser and line spread lens assembly as well as the electronics and battery packs, while mounting to servo motors that would rotate the lasers during the ten minute run. As the mass of the lasers and housings counted against the overall mass of the robot, it was key to minimize the weight within the design, while providing a reliable housing that oriented the optical components and protected the electronics from regolith infiltration.

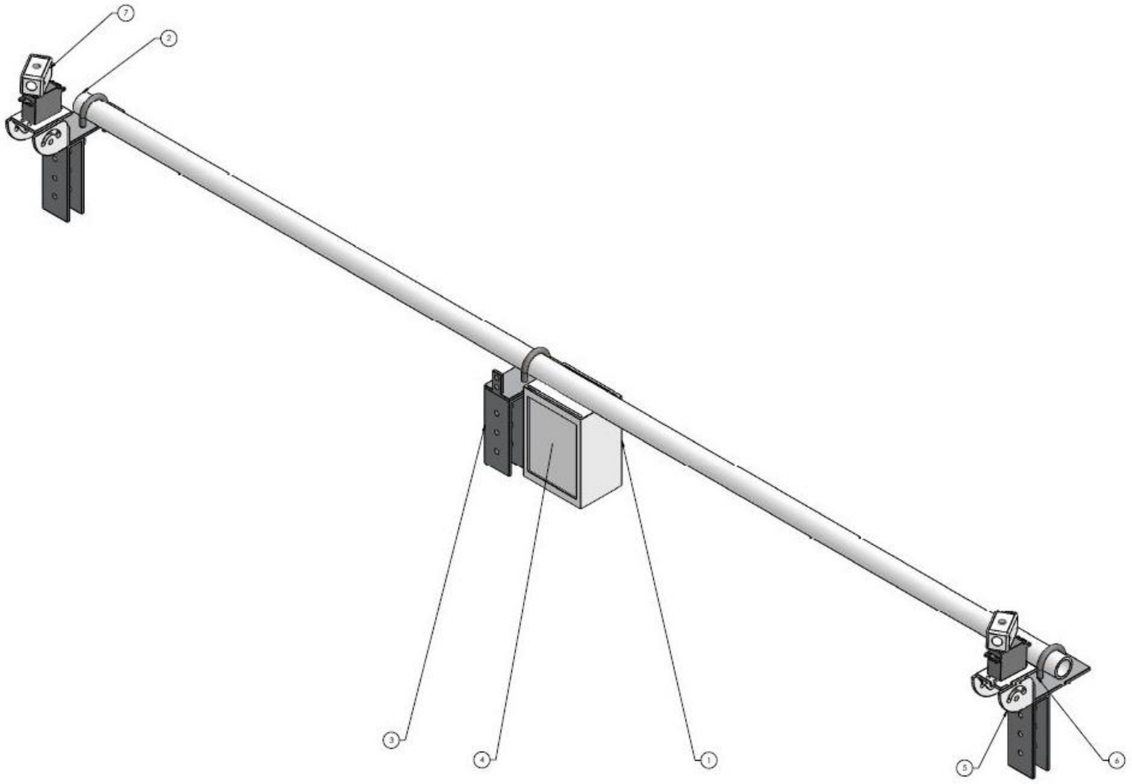


Figure 3. The laser beacon assembly designed to mount to the collection bin, featuring servo mounted lasers (ends) and an electronics enclosure (center) to house the control unit.

Given the larger dimensions and the desire to minimize weight, the laser enclosures were produced on the Dimension machine, using the FDM process and ABS plastic. This allowed the students to specify a sparse build, which shelled the thicker walls and filled it with a sparse lattice structure, which maintains the dimensional stability while reducing the mass. This was also key for the beacon control box which housed the requisite electronics to control the motion and modulated signal of the laser beacons. The design of laser mounts consisted of a common bore that maintained the alignment of the lasers and line spreader lens assembly while mounting to the servo (Figure 4 below). The enclosure design consisted of a section for batteries and a section for the electronics, both of which were accessible by removable panels and holes for routing the wires (Figure 5 below).

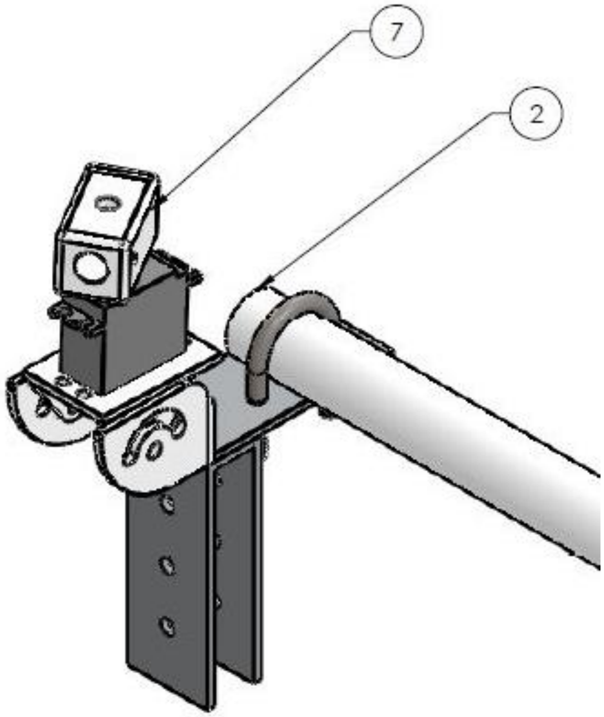


Figure 4. Laser beacon detail

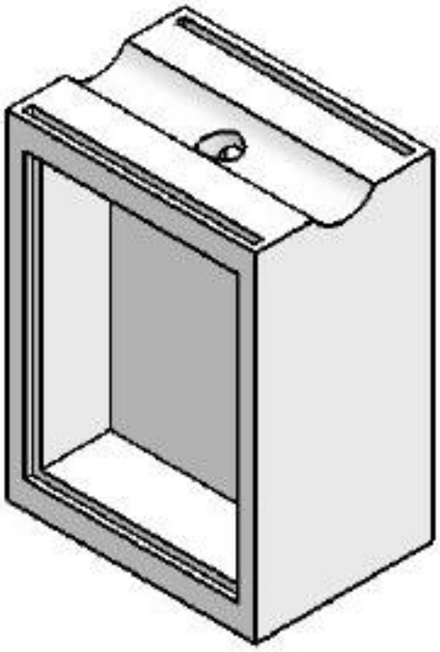


Figure 5. Beacon control enclosure detail

Sensors and feedback were key to the robot build, providing critical information on the position and performance of various components of the design. Accelerometers were used on the lift arm to determine the position of the excavation bucket, as it needed to be low enough to excavate regolith during mining, high enough to clear obstacles while traversing the course, and raised to its highest angle to deposit the mined regolith into the collection bin. In order to protect the accelerometers and associated circuits from the abrasive regolith, accelerometer housings were designed. In addition to dust protection, these housings provided geometry to secure the sensor and circuits, while providing separate mounting features to secure the sensor to the lift arm on the robot. Given the housing would be mounted to a moving arm and collisions were a possibility during excavation or travel, the Dimension FDM process and ABS material were selected for the higher impact strength compared to the VFlash. As with the beacon housings, weight was a concern, so the accelerometer housings were pocketed where appropriate to reduce weight while meeting the geometric requirements.

The final robot components that were produced additively were latch components used to secure the detector arm once it was deployed. In order to have the PMT reliably detect signals from the laser beacons, it needed to be higher than the surrounding structures on the robot. Given the rules of competition and the existing elements in the robot design, this would have a static beacon arm extending outside the permitted initial starting volume [5]. To address this, the students designed a simple mechanism that folded the detector arm down into a horizontal position. Once the competition round began, and the operating volume restrictions were relaxed, an actuator released the arm, allowing a spring to snap it into an operational vertical position. To insure that the arm stayed in a vertical orientation as the robot traversed the undulating terrain, it needed to be secured against the robot frame (electronics housing). The latches were designed in Solidworks, where the deflection of the barbed leaf was calculated with Solidworks Simulation. Adjustability was also designed into the latches to allow for fine tuning once they were produced to get the right balance between reliably actuation and robustly securing the beacon arm. As with prior components, the students took care to minimize weight in the latch components. These weight reduction efforts resulted in a design that would have required some difficult setups for the students, but were easily realized on the Dimension machine, which was selected for the ABS material, as the bending stresses were calculated to be problematic for the epoxy resin.

Performance of the additively manufactured parts

The production of the gimbal design was a measured success initially. After curing and removing the build supports, the parts were found to have distorted radial holes which were used for the pivots. The parts also exhibited some slight warping from the designed flat geometry. The likely culprits in the production processed were hypothesized to be a) insufficient removal of uncured resin, which clogged and distorted the holes and b) warping of the part due to removal of build supports before it was fully cured. With some additional post processing (drilling out the holes and sanding down the warped surfaces, the gimbal rings were successfully deployed on the robot for testing. Under load, the gimbal rings were seen to sag over several weeks of testing, so prior to the competition new rings (which had been redesigned for added rigidity) were manufactured as well as a set of spares.

In the course of testing, the gimbal design for the PMT also changed to reduce the weight and volume of the assembly. The counterweight and servo were replaced with a stepper motor that served both to rotate the PMT and to provide the counterweight. The PMT enclosure also underwent a redesign, being reduced to a simple gimbal mount for the PMT and the associated electronics being moved off the arm as shown in Figure 6 below.

Figure 6. Photomultiplier Tube (PMT) mounted on the gimbal and stepper motor

The PMT mount was ready for use after similar preparation (slight sanding) to ensure a good fit. The mounting posts aligned exactly as intended with the mounting holes as shown in Figure 7 below. The central bore of the mount also provided sufficient clearance for the connector to mate to the bottom of the PMT (as shown in Figure 7).

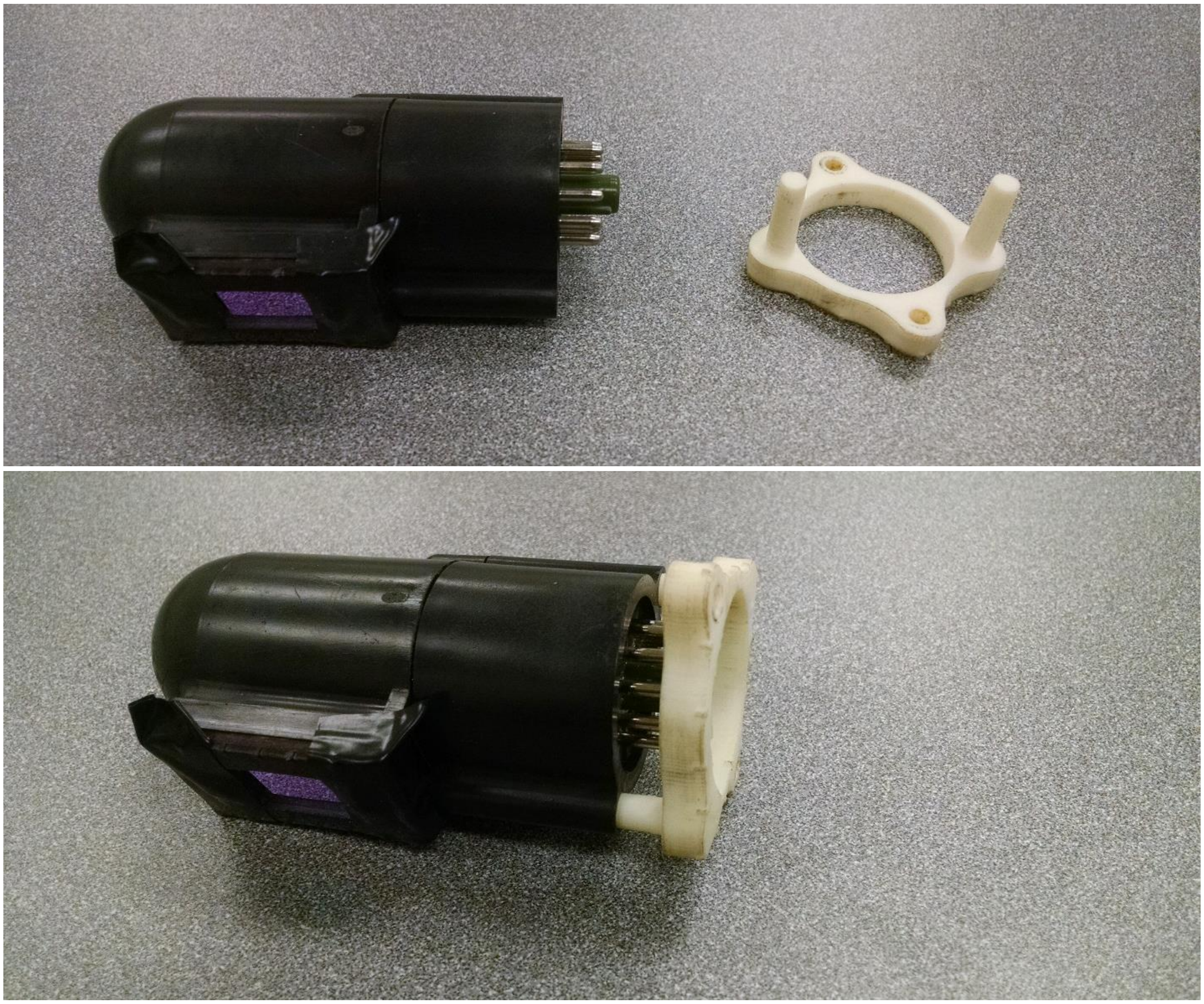


Figure 7. The PMT and gimbal mount separate (top) and assembled (bottom)

The first PMT lens cap that was printed did not fit as securely as intended, so that part was rebuilt. In fact, several versions of that part were built in the same run so that they could each be tested and the best fitting part selected. Given the small volume (and associated material cost) this seemed a reasonable approach to get the part in the students' hands quickly. The nature of the VFlash build process, also meant that there wasn't a time cost associated with the additional versions to test, since the build time for the VFlash scales with the height being built, not the pack density of individual layers. One of the design variants provided a suitable fit to the front of the PMT while holding the lens, and was added to the assembly after the surface was darkened with paint marker to prevent any stray light passing through the filter housing and distorting the signal (the cure FTI-GN resin was not fully opaque at the given thicknesses without the coating).

Results from the FDM processes were similar in that they were generally positive, with some tweaks required to achieve the desired functionality. The sliding panels on both the laser housings and the beacon control enclosure however would not fit as printed. The students reviewed the CAD files and verified that the panels should be sufficiently undersized to slide into the slots on both enclosures. Upon measuring the parts, they found that panel thickness was the same as the slot width, leaving no room for clearance. After further reflection and discussion with the faculty mentors, the students realized that the specified clearances were less than the .012” minimum layer thickness of the Dimension machine. In slicing the STL into individual cross sections, the slight difference was not captured as in effect it “rounded up” and printed another .012” layer when only a fraction of that thickness was specified by the CAD file. This was remedied by using a deburring knife and razor to slightly trim the guide slots until the panel was able to slide in with reasonable effort.

A second challenge with the FDM parts was related to the sparse fill used to save weight. The students planned (but had not indicated on the drawings) to drill and tap into the sides of the enclosures for mounting purposes. The sparse lattice fill within the hollow walls however was not strong enough to hold threads and the screws pulled out almost immediately. As a quick remedy, the students drilled out the failed holes and plugged them with polycaprolactone (PCL). Commercially sold as Shapelock or Instamorph [6,7], PCL is a plastic that is moldable at temperatures as low as 140 F, but hardens to a nylon like consistency when cooled. While heated, the PCL was pressed such that it infiltrated the voids in the lattice structure and bonded to the existing plastic when it cooled. The plugs were then drilled and tapped, without any problems in the resulting mounting.

Outside of those issues however, the FDM parts worked as intended and largely met the design criteria. The custom enclosures for circuitry worked to protect the components from both bumps and impacts as well as infiltration of the abrasive regolith simulant. The accuracy of the parts was also sufficient for the laser beacons, keeping the lasers and optics securely aligned as they were rotated by the servos as shown in Figure 8.

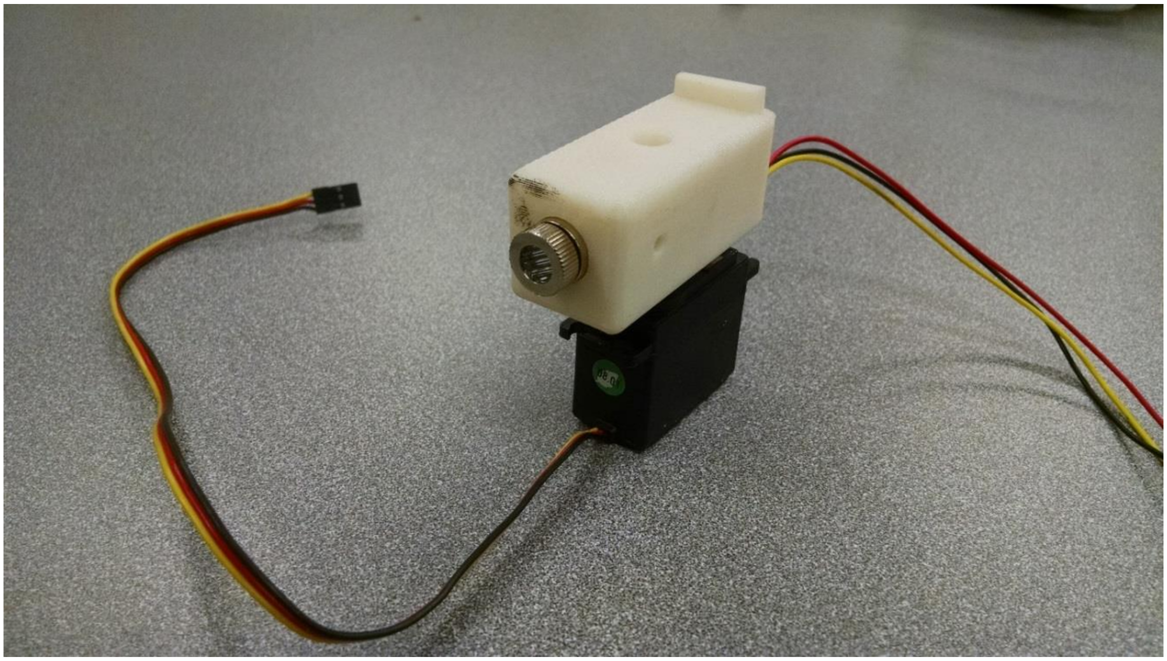


Figure 8, Laser beacon enclosure mounted to the servo

In addition to the qualitative testing, the additively manufactured parts were measured to determine how closely they matched the prescribed dimensions. Selected measurements (performed with Mitutoyo calipers and micrometers) from the parts are shown in Table 1 below.

Table 1. Comparison of selected part measurements to the design dimensions

Part/Dimension	**Designed Value**	**Measured Value**	**Difference**
Bin Beacon (produced on the Stratasys Dimension)			
Overall X (length)	2.25”	2.250” max 2.244” min	+0.000” -0.006”
Overall Y (width)	1.00”	1.000” max 0.998” min	+0.000” -0.002”
Overall Z (height)	1.00”	1.012” max 1.008” min	+0.012” +0.008”
Gimbal Outer Ring (produced on the VFlash)			
Inner Diameter	2.50”	2.508” max 2.494” min	+0.008” -0.006”
Outer Diameter	3.16”	3.171” max 3.142” min	+0.011” -0.018”
Thickness	0.325”	0.340” max 0.320” min	+0.015” -0.005”
Notch Width	0.30”	0.308” max 0.302” min	+0.008” +0.002”

Educational outcomes

As a result of this capstone senior design project, the students became acquainted with many of the strengths of additive manufacturing. They were impressed with the quick turnaround on parts, in that once the parts were started, they were done within a day or less. Additive manufacturing also shined in the ability to produce multiple variants of parts to mate with existing geometry that was difficult to measure. Finally, students observed the weight saving potential of using a sparse fill for interior regions of a part.

More importantly, students learned some of the limitations or concerns associated with additive manufacturing. The first of those being the need to understand how the resolution and layer thickness of the machine affect the achievable tolerances for the parts. Students also came to realize that the weight savings of sparse filling interiors came at a price and they would need to consider the implications on future builds to ensure that they parts had sufficient strength/density at mounting points. The last insight was how parts can distort or warp due to the material properties or the post production processing. Some of these warping issues with the VFlash could be mitigated if the parts were produced on the Form 1+ from Formlabs, which features greater control over the creation of supports in their Preform software and advice for best practices on minimizing warping [8].

The additively manufactured parts were also relatively economical to produce. The parts produced via FDM ranged from $10 per part to $30 per part, while the VFlash parts ranged from $5 to $10 per part as they tended to be smaller builds. Several of the VFlash parts had to be iterated to meet the design requirements, which commonly resulted in $10 to $20 to produce a functional part with the VFlash. Given the set build costs of $5 per build plate for each setup, the students also learned to group several smaller builds into a single operation to distribute that fixed cost across several parts.

These outcomes and observations are largely consistent with earlier studies [9] that found students needed a greater exposure to the limitations of additive manufacturing. While many of the more egregious mistakes were avoided by this student team, in the future the mentors plan to implement formal design guides to assist students in selecting appropriate technologies for manufacturing their parts.

Acknowledgements

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