# LOCKHEED MARTIN GPS SATELLITE BRACKET – MANUFACTURING TEAM

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## Abstract

For our senior design project, CU Denver partnered with Lockheed Martin in order to improve upon their current GPS satellite bracket design. It had been determined that it would be very beneficial to create a bracket that would reduce the cost, weight, and production time of the current design by taking advantage of additive manufacturing. In order to do this most effectively, our team of thirteen students divided into four sub-teams, each of which focused on a separate aspect of the project: software, manufacturing, testing, and design innovation. The collaboration between Lockheed Martin and the university resulted in the addition of an EOS M290 Direct Metal Laser Sintering (DMLS) machine to the downtown campus in the fall of 2019. DMLS is the process of which a thin layer of metal powder is deposited across a platform. Next, a laser is scanned across the powder to sinter and fuse the powder. This process is repeated layer-by-layer to create a 3D-printed structure. Aluminum 6061 has recently been developed into a powder by Elementum3D (Erie, CO) and has generated high interest from Lockheed Martin for use in 3D-printed spaceflight hardware. Overall, this printing and material technology is extremely novel, and its capabilities have not yet been thoroughly explored and established. Therefore, in order to produce a successful bracket, the manufacturing team first needed to determine the abilities and restrictions of the machine with Elementum3D's Aluminum 6061 powder.

This project posed a unique set of challenges, as the powder itself is also so new that a material property set for it does not exist within the 3D-printer's software. A variety of test pieces were printed in order to dial in the print parameters of the machine. In order to judge the quality of the prints, they were inspected for surface finish quality, shift lines, short fed areas, or excess sintered powder.

Once a material profile was developed for the machine, two bracket designs created by the software team were to be printed. However, each design had to be pre-processed in order to prepare the design to be printed. This included checking for mesh errors, checking for overhangs, and looking for holes, overlaps, or any other problematic geometries, all of which could result in a failed print. A checklist was created to help guide the process from final design to 3D printing in an effort to optimize the process.

Ultimately, we successfully printed five aluminum bracket parts including side pieces for the conservative design and a bracket thruster mount for the generative design. Some parts were determined to be best suited for subtractive rather than additive manufacturing, which resulted in a combination of manufacturing methods for the final bracket assemblies. Due to the state of world events that limited access to the facilities, several components of the final bracket assemblies were not able to be printed using aluminum as planned, and instead were additively manufactured using polymers in order to provide a sufficient model for presentation.

## Overview

Initial efforts of the manufacturing team were focused on determining the capabilities of the M290 with aluminum 6061 powder. Working together with Lockheed Martin, several instructional sessions for proper use of the machine were conducted, contributing to the establishment of a functional set of operator guidelines. Similarly, the team underwent training for material handling and equipment safety.

The first training that the team was a part of was a one day, eight-hour training course purely focused on the aluminum powder. This training covered everything from the handling of the powder, how to properly store the powder, labeling both for the team and the safety of visitors, and how to safely dispose of the waste created by the powder known as condensate. The training showed the team how to use the equipment that would be provided with the M290 to transport, remove, and clean powder from the printing chamber. Personal safety was a big, if not the biggest factor of the training as the instructor also covered how to handle emergency procedures, as well as the urgency of the buddy system, in that an operator was never allowed to use the machine alone and was required to have another operator with them for assistance and help in case of an emergency.

## Methods and Prototyping Process

Throughout the iterative process of printing experimental builds, we were able to identify that there was an issue with the machine's hard re-coater, which lays out new layers of powder during the printing operation. Specifically, this original re-coater was rigid and inflexible, and was knocking into high aspect ratio parts as they were being printed if the blade received any dings or dents from the parts as they were made, the result of which is shown in Fig. 1.

***Figure 1:*** *Example of high aspect ratio parts being pushed over due to a rigid re-coater blade.*

In order to resolve this problem, a soft re-coater made with an Ultem holster and a silicone blade, displayed in Fig. 2, was implemented, which allowed for more pliability and resulted in printed parts staying in place, even if accidentally brushed by the re-coater, which greatly improved successful part production.

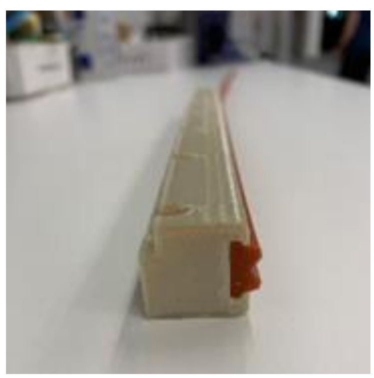

***Figure 2:*** *A silicone soft re-coater blade inserted into an Ultem holster.*

Each unsuccessful build was studied and utilized to further identify preferable design aspects, printer settings, and build setup parameters. For example, the team experimented with changing the dosing factor during some of the lengthier builds. The dosing factor is the amount of powder that gets added with every new layer by the re-coater blade to either increase or decrease the amount of powder. This was done with the larger builds in an effort to see if it would be possible to accomplish the build job with the initial bin of powder. This is important because the alternative would be to pause the build and add more powder to the machine which is a significantly more time consuming and tricky process that may leave an impression line where the build job was paused. However, controlling the dosing can produce some cons too, visible in the figure 3 and figure 4 below. Figure 3 shows one of the smaller byproducts of limiting the dosing during a build, where there will be small valleys forming in the corners and can expand toward the corners.

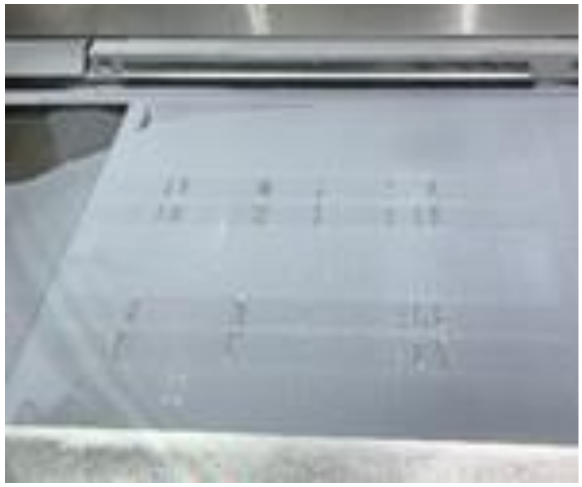

***Figure 3:*** *Under-dosing during a build can result in sections of the print bed not receiving new powder, as seen in the upper left corner.*

A more graphic representation is available on the Fig. 4, where a short feed, the term for when limiting the dosing affects the build, resulted in there being insufficient powder for the subsequent layers and the laser running its path on the already welded metal.

***Figure 4:*** *The results of the laser running over the parts when a new layer of powder has not been deposited*.

Each impediment in the printing process allowed us to further understand the capabilities and limitations of the machine, and permitted us to formulate a design checklist to be used both while using design software to create a part as well as while preparing the part for printing. This list includes suggestions such as reducing overhangs to less than 45degress to the build plate, designing holes perpendicular to the build plate with teardrop geometries, limiting mesh complexity to essential levels, properly inspecting STLs, ensuring the part volume fits within the machine's build volume, including sacrificial material for post processing and machined surfaces, and designing parts with limited shell counts. Examples of the benefits of ensuring proper design and print preparation are depicted in Fig. 5. The complete checklist can be found in the Design Innovation Appendix A, titled Learning Module (Fundamental Guide).

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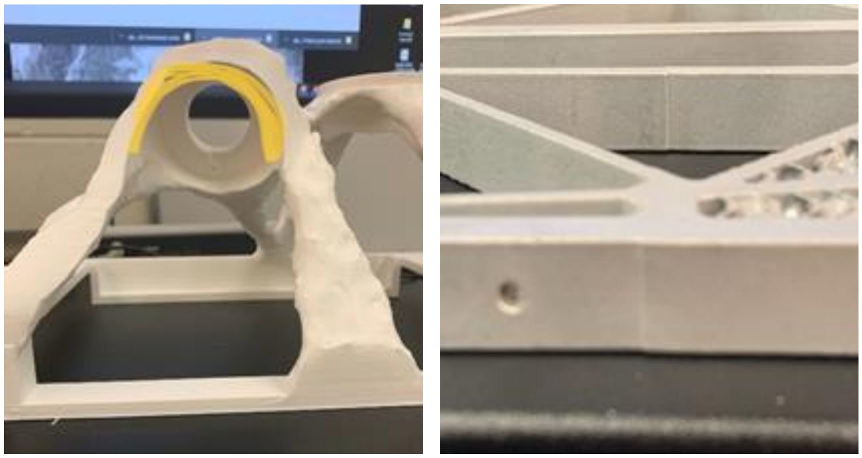

***Figure 5:*** *(Left) Large round holes that cannot be printed in the shape of a teardrop should incorporate additional material to allow for post-processing in the location of the yellow highlight so as to avoid an unsatisfactory surface finish due to the overhang angle. (Right) When several narrow geometries come together in one location, the heat of the process can pull the pieces slightly out of position and create shift lines.*

The process of bracket prototyping began with a physical representation of the design space. This was done using plastic sheets screwed together so as to allow the team to better visualize what we had to work with and what we were restricted by and can be seen in Fig. 6.

***Figure 6:*** *Physical representation of the given design space*.

Next, while the software team began creating various designs, the manufacturing team worked on using the M290 to print sample pieces, such as lattice tokens, depicted in Fig. 7, to further determine what design variations would print most successfully.

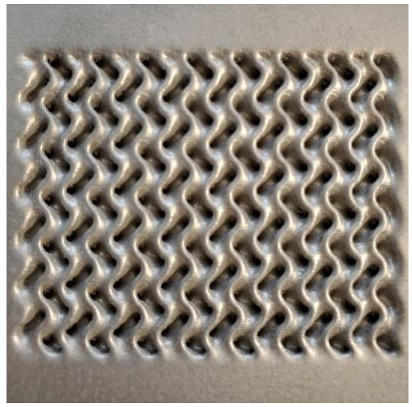

***Figure 7:*** *A sample token of a gyroid pattern lattice structure*.

From this print, we determined that even small overhangs would result in stalactites, which would require additional post processing to remove and smoothen out, something not desirable for the intended design. The next step was to begin printing bracket pieces. We started with the side pieces of the conservative design. Four of these parts were placed onto one build, which printed to completion. However, the print was short-fed for a number of layers in the middle of the build, which resulted in a particular area of each piece with voids and unattractive clumps of welded powder since there was no powder that reached that section of the build area. The parts are demonstrated in Fig. 8.

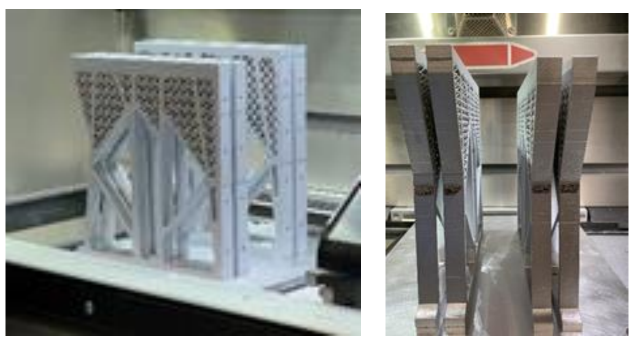

***Figure 8:*** *(Left) Completed build containing 4 conservative design side pieces. (Right) Side view of bracket pieces, where the middle shows voids due to short feeding.*

While we were unable to reprint these pieces due to restricted lab access, we found from other test prints that the short-feeding issues can be resolved by regularly checking up on the build and observing to see if the layers are approaching a layer of the build with more surface area. In these instances, the operator may raise the dosing factor and ensure the part will have enough powder covering each layer. In a few previous builds, we managed to complete high risk builds by adjusting the dosing when short feeding appeared eminent. Figure 8 shows the results of short feeding and demonstrates that, if caught early, these builds can complete successfully.

The final generatively designed bracket included a thruster mount bracket that had been optimized for additive manufacturing as much as possible. However, due to the limitations of the process, support material was still required, shown in Fig. 9. Support material is a part of the build process that is a caveat of many additive manufacturing processes. Parts that follow the "Design For Additive Manufacturing" (DFAM) principles during the design phase limit overhangs and build angles to less than 45 degrees to the build platform. This reduces the need for support as much as possible. Support material is required in the design anywhere there are  steep overhangs or unsupported areas where they would support the parts mass as it is being printed out. As previously mentioned, one of the goals of additive manufacturing is to reduce the need for support material as much as possible, as it has a number of detrimental factors associated with it. Namely, support material is material that will go to waste and in this case, the support was going to be made from the same powder making the part – this constitutes the cost factor associated with designing for additives. The other factor to consider here is that support material needs to be removed from the part which can be tedious or time consuming for the operators. Figure 9 shows the implementations done for the part to become additive friendly, albeit the need for support materials was still present. The orientation of the part was analyzed with it resting on the build plate from various surfaces of the part until this was chosen as the one with the least support needed. Furthermore, the top left corner seen in Fig. 9 was an infill added to the design with those angles and geometry purely to eliminate the need for support materials on that corner of the bracket.

***Figure 9:*** *Mount for generative design bracket, with support material before post-processing.*

Due to the fact that support material could not be removed from our designs altogether, it was necessary for our team to test various structures of support material in order to discover their ease of removal, effectiveness, and stability. We did so by printing 10 floating solid rectangular prisms, each supported by a different model of support material, seen in Fig. 10.

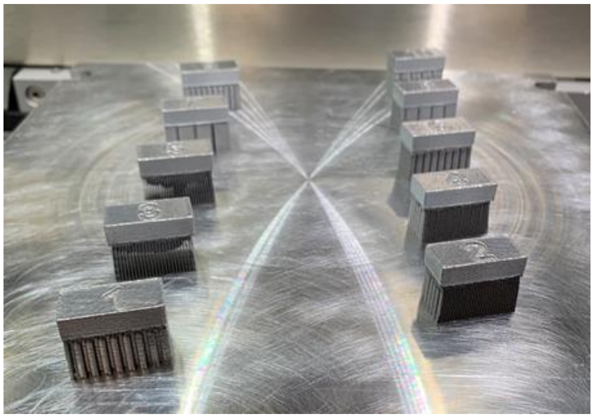

***Figure 10:*** *A build consisting of 10 labeled blocks, each held up by a different style of supports*.

All ten designs successfully held up the parts they were supporting, and the quality of each support pattern was then evaluated through the removal of the material. The best model was then used in following builds. Every single support design printing successfully came as a surprise too, as some were initially expected to fail but this also served to demonstrate the abilities of the machine. Ultimately, some of the designs had features that were too thin and wouldn't dissipate the heat as well from the build as it was being made, which was one of the things sought after when selecting support structures. Too much heat staying on the build as new layers were being added affected the builds, as the metal was too hot and it impacted the bonding of layers. On the contrary, other support designs were ruled out simply because of the amount of material they used up or their designs being prone to fail at complex angles where custom designs might be implemented.

Throughout the entire prototyping process, there were constant samples that would be printed in between jobs to provide for the testing team. These would benefit all of the groups as we would learn about both the printer and the material. It was important for the testing team to be able to test the samples and compare them to traditionally made metal primarily to understand the parameters of the printer with things like laser angle, layer heights, build orientation and sample orientation to produce the best parts possible. On top of these findings, it was important to have these results in order to work with the software team and keep them informed on the design limitations or strengths the M290 had to offer in order to facilitate part production.

**Results and Final Design Production**

The final bracket designs included pieces that were manufactured using both additive and subtractive methods. The face plate of the conservative design was milled using a HAAS CNC by programming tool paths using Fusion 360 and is shown in Fig. 11.

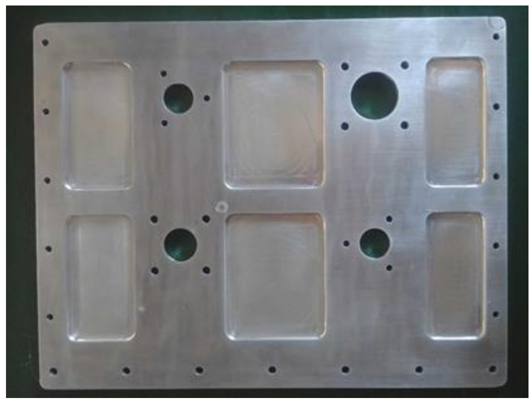

***Figure 11:*** *Subtractively manufactured face plate for the conservative bracket design*.

The rest of each bracket assembly would have been printed on the M290 if it had been possible to do so. However, all remaining pieces that had not yet been printed were instead created using a Prusa MK3s printer with PLA filament, at full scale when possible or 79% of full scale when the part was too big to be completed on the print bed of the Prusa. Several final design prints of the generative assembly are displayed in Fig. 12.

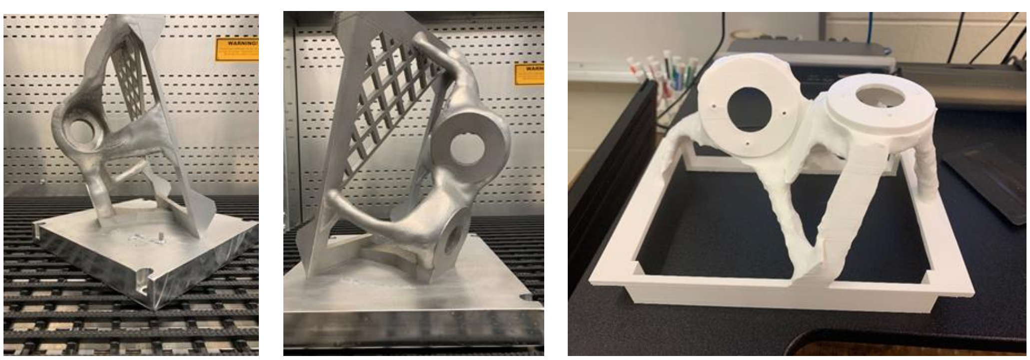

***Figure 12:*** *On the left and middle are final pieces printed on the M 290 with aluminum. On the right is a mount piece printed using PLA on a polymer printer.*

Despite the method in which they were manufactured, these parts were designed for the aluminum printer and embodied the principles we had found to lead to the most successful aluminum prints on the M290. Following successful builds, post processing would consist of support material removal, sanding, bead blasting, buffing, and polishing. Following these processes, a heat treatment would be applied. To achieve a T-6 treatment the parts would have undergone internal stress relief heat treatment of 300℃ (570°F) for 3 hours, then a solution heat treatment of 529℃ (985°F) for 2-3 hours, thickness dependent, with a glycol quench within 15-seconds. Finally, an aging process of 177℃ (350°F) be applied for 8-10 hours.

For comparison, Fig. 13 shows the other design approach that was being considered for production on the M290. This approach was less generative, meaning the designer had more influence on the design with a forethought of traditional manufacturing and a more straightforward design that had the rocket mounts split in two, brought together at the middle in the top after post processing. The image on the left shows a consideration given for additive manufacturing, where the hole through which the rocket mounts is instead a teardrop shape - thus eliminating the need for support material in that area of the part. This part unfortunately never went into production as the lab closed down, but its more traditional design was promising in terms of ease of print and in post processing as there wasn't any complex geometry to work around for support removal or resurfacing work on the part.

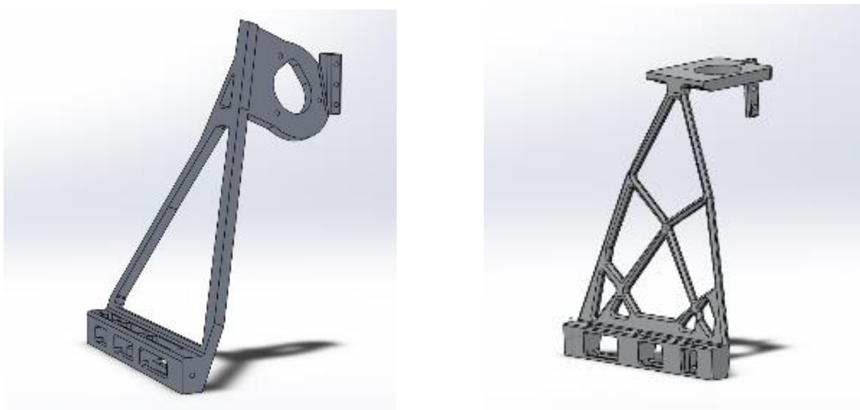

***Figure 13:*** *The more conservative, topology optimized design for the rocket mounts.*

Both bracket designs were brilliant in their design and would have met the goals of the project, and very well may have surpassed them. Both designs reduced part count tremendously, a very desirable feat to achieve to reduce the assembly time of the bracket and satellite. Also, both parts have noticeable reductions in the physical space they take up and pose significant weight reduction, while still meeting the criteria for strength and vibration needed to be part of the satellite.

**Conclusion**

Throughout the two semesters of this project, the manufacturing team successfully produced all pieces of both the conservative and generative design assemblies, either through additive manufacturing using aluminum and polymers or through subtractive manufacturing with aluminum. The aluminum parts met every design specification they were tested for, and although the polymer parts could not be properly tested, their computer-based analysis seems promising as well. During the process of establishing printer parameters and operational guidelines, the manufacturing team was also able to progress the establishment of safety regulations and printing procedures. We expect that the established methods will assist future teams working through the UCD and LM partnership to further progress the understanding of the EOS M290 and its capabilities and beneficial applications.

# APPENDIX

## Design Innovation Appendix A

Learning Module (Fundamental Guide)

Learning Module (Fundamental Guide ).