Design for Additive Manufacturing for Prototype Manufacturing

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Abstract

In today's industry rapid prototyping in the form of additive manufacturing is becoming very important to product development. These initial stages of product design are crucial to a product's lifecycle and ultimately to the manufacturability as well as profitability of a product. But sometimes the product developed does not allow for ease of additive manufacturing. This paper will explore design concepts for the manufacturability of prototypes formed by additive manufacturing as well as show examples of rapid prototypes versus traditional prototypes in terms of design.

Introduction

As part of the curriculum for the University of Dayton in Engineering Technology students are tasked with different steps in the design cycle. These take many forms throughout their years and in various classes. The goal is to get the students prepared for a start in industry and have the ability to design products and processes.

In this paper specifically two of these classes and the designs from these classes will be addressed. Students in their third semester take a course in an introduction to design. This class prepares them to design a mechanical product using industry accepted standards. They then have a capstone design experience in their final semester in which they partner with an industry sponsor to solve a problem or complete a project. This usually entails some form of design.

Students today come to the university with a wide variety of experience. But more recently they have come with at least a knowledge of what additive manufacturing is due to high school and elementary school work in 3d printing. What is being found is that the design itself is not being optimized for this type of work. And that this type of process has some very definite design practices that can be different than traditional manufacturing design.

In industry this has spilled over to final product development and has become the center of design in certain applications. Fused deposition modeling is used for anything from simple prototypes to tooling to fixturing. Being a relatively new manufacturing process has brought some inefficiencies in terms of the product design. It is critical to control costs. This starts with the design as with traditional manufacturing. Cycle times, material use, energy usage, and quality are similar concerns. But how these are embodied may be slightly different. To be competitive speed of manufacturing becomes a good measure as to how successful the part will be.

With advancements in software and also in various additive manufacturing techniques, it has become easier to consider manufacturability in the design stage. Design for manufacturability concepts have been around for a relatively long period of time, but with the advent of additive manufacturing some design principles have to be readdressed. This paper will address some design principles to be used specifically for products to be manufactured using additive manufacturing, specifically fused deposition modeling.

Background

Fused deposition modeling (FDM) has been used in industry since the early 1980s (http://www.livescience.com/39810-fused-deposition-modeling.html). So the manufacturing technology itself is a mature and stable process. But in today's environment FDM has become an option for production parts as well as prototyping.

To perform a FDM process a CAD file is converted to a .STL file. Software is then used to "slice" the part into layers. These layers are read by the FDM printer. Filament in the form of a spool is fed into the machine. Material can be either ABS or PLA. Although research is being performed on other material types. The filament feeds through a nozzle where it is melted. Then it is extruded onto a base or platform. This is done in layers per the sliced part. Layer by layer is added until the final part is completed. After the part is completed it can be handled immediately. Sometimes a "support" material is used to be able to finish the part. Post processing may include removing the support material by snapping it off or removing it chemically. Tolerances tend to be very good and the parts tend to be net shaped, but there are some limitations. These will be explored in this paper.

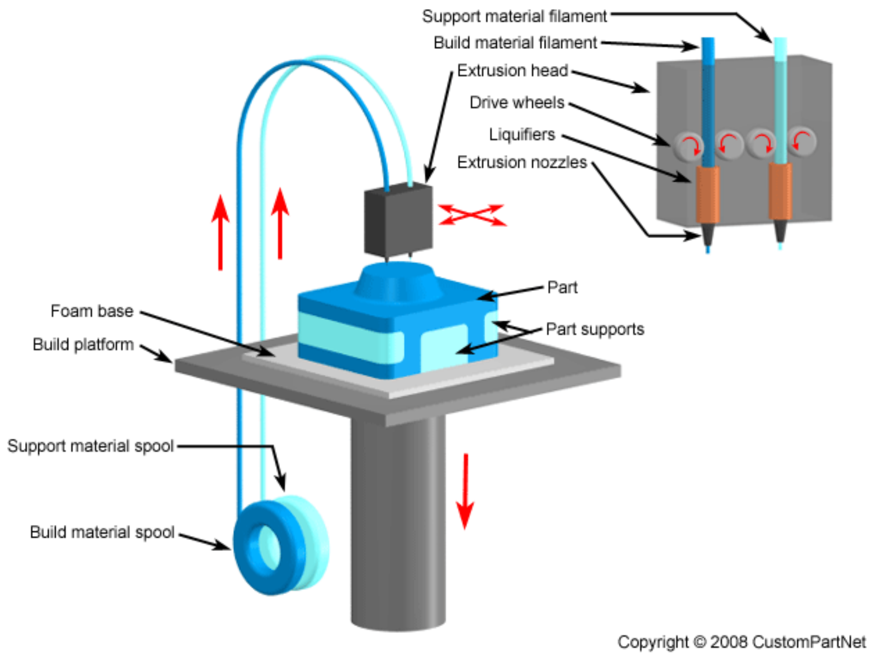


Figure 1 Fused deposition modeling Diagram (CustomPartNet)

At the University of Dayton 3 different machines are employed by the students for their prototypes. Based upon a grant students in the Introduction to Design class use a Stratasys uPrint SE Plus to build their parts. They use ABS as their material. The capstone design classes utilize (2) machines, a Fortus 360mc and a Dimension sst 1200es, both from Stratasys.

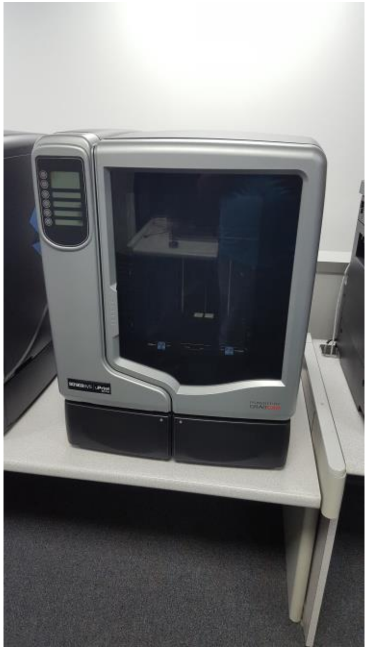


Figure 2 Stratasys uPrint SE Plus

Figure 3 Fortus 360mc

Figure 4 Dimension sst 1200es

Generally any CAD software can be used for design. An ability to convert files to a .STL file is needed. At the University of Dayton Solidworks is used for this design. Preparation software for the printers is available commercially. The University of Dayton utilizes Pronterface and Insight for its preparation.

Design Principles

The traditional design process is modified by adding a DFMA analysis after the system level design. Then through rapid prototyping the design can be optimized before finishing the detail design. (Wankhade Nitesh Prakash, V. G. Sridhar and K. Annamalai)

Part orientation is one of the most critical parameters to start with in additive manufacturing. Part file orientation controls many things such as material usage, part tolerance, part strength, and print time, all of which contributes to the total cost of the prototype. This all starts with the cad file. Orient the part in the cad file with some thought to how you would like to print the part.

Part orientation can also affect cycle time, affecting part cost. If making multiple parts place the parts as close together to reduce non value added travel time.

In looking at the orientation how the part will be sliced must be considered. At this point does it make sense to make in one piece or multiple pieces? Traditional DFM states to minimize the number of parts. So to divide into multiple parts is not intuitive. The following are reasons to look at dividing into multiple parts and joining post processing:

- Use of support material. If splitting the part reduces or eliminates support material look to this
- Part has an extensive bridge
- Part has an overhang greater than 45^{o}

- Part is larger than the build platform
- Protect fragile sections of the part

Walls must be sturdy enough to prevent warpage. Minimum wall thickness is dependent on layer thickness. The following chart is the recommended thicknesses from Stratasys. They suggest a wall thickness that is four times the layer thickness. For an extrusion width that is equal to the thickness, this allows for two perimeter paths of material on each side of the wall. These two perimeter layers will be continuous around entire part, thus increasing rigidity and decreasing issues with warpage.

General Recommended Minimum	
Slice Thickness IN. (MM)	Minimum Wall IN. (MM)
0.007 (0.18)	0.028 (0.71)
0.010 (0.25)	0.040 (1.01)
0.013 (0.33)	0.052 (1.32)
0.020 (0.50)	0.100 (2.54)

Table 1 Recommended Wall Thicknesses (https://www.stratasysdirect.com/resources/fused-deposition-modeling/)

Supports add cost and are removed from the part when complete. The cost model applied to supports considers the material itself, which generally is more expensive than the part material. But also to be considered is the labor and time to dissolve the support material. Reduce this where possible.

The longer the bridge the more the sag. Therefore where possible orient the part so that bridging is reduced or eliminated. Ask the question can the part be rotated on its side or even upside down. If a bridge is necessary, support material may be required.

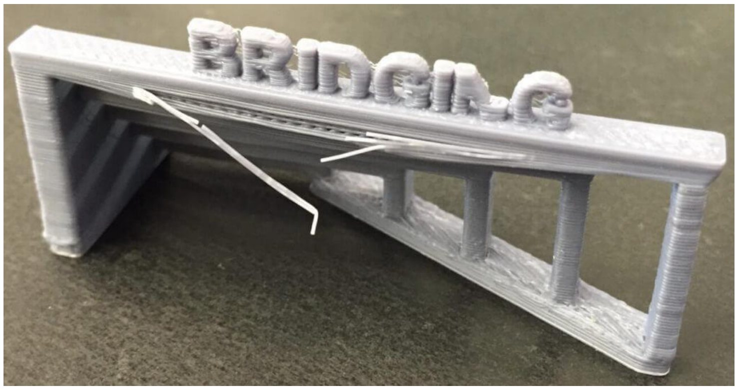


Figure 5 Bridging example (https://all3dp.com/3d-printing-concepts/)

Overhangs are very similar to bridging. This is where the part only has partial support from the layer below it. Without support if the overhang is greater than 45° the part may experience some warpage or may not adhere at all. This is due to the curling of material because from different cooling rates. Keep the overhang less than 45° or provide support.

Figure 6 Overhang example (https://www.3dhubs.com/knowledge-base)

Holes may be a bit undersized. If accuracy is needed then the CAD model must be modified or the hole must be drilled. Holes parallel to the Z axis are preferred. Holes that are in the sidewalls may have a slight out of roundness. If the sidewall hole is large, support material will be required.

The tendency is to think of the part produced as one piece. This is in line with traditional DFM principles. There are occasions in which an insert might be applicable. The following are situations that might demand an insert:

- Add threads for an attachment point that demands strength
- Add an electrically conductive contact

- Add weight to a part for “feel”
- Add a RFID tag for later identification

After these considerations there is time that will be needed to add these inserts. Builds are paused to place the insert adding cycle time. Also the final cost of the product then must include the insert itself.

For threads especially the thread made by the FDM process might be good enough for your application. If not a choice will have to be made between an insert and drilling and tapping. With drilling and tapping the part must be made with structural strength, sometimes with the expense of added material. Then the part must be fixture, drilled, and tapped, with a cost very similar to traditional machining. This has been proven to be a very high cost in manufacturing. These reasons are which inserts become very attractive.

Parts produced by FDM must adhere to the base plate for the entire cycle time. One of the issues in manufacturing is parts coming off the plate while printing. This can occur based on the cooling of the initial layer. Parts should be designed with a large enough base to adhere to the plate. Also a small radius can be placed on the part at the adhesion point. Parts will naturally have a small radius due to the nozzle construction. The radius will also allow ease of part removal when the part is complete. If the part itself does not facilitate this adding a raft may help. But adding this will add to post processing time due to the removal of the raft.

Posts have a special problem. Posts can warp due to the layers not being able to adhere to a previous layer. This mismatch will cause posts to move or to not be accurate in diameter or concentricity. Normally this occurs at less than 5 mm in diameter, because at less than this diameter there is no infill. Larger than this infill will help stabilize the part. For less than 5 mm include a fillet at the base to help with adhesion or consider using an insert. This adds cycle time, but will hold dimensional stability. If an insert is to be used, form a hole in the part to allow for the pin.

Parts created for production purposes or for prototype testing may have a strength requirement. FDM parts are anisotropic. So when orienting parts consideration must also be given to the loading. When doing a DFM analysis, part function must be looked at. Loading is then determined. Parts should be loaded in bending perpendicular to the layers or in tension parallel to the layers. Also parts can be printed with a smaller layer height. This encourages adhesion and makes the part structurally stronger. Infill percentage has an effect on the parts strength as well. The higher the infill, the stronger the part, to a point. But the more material that is needed and the longer cycle time due to this infill percentage will increase the cost of the part significantly. Numbers of shells (perimeters) can also be used to strengthen the part with a cycle time and material penalty, but not as much as an infill percentage adjustment.

Some other parameters that can affect the manufacturability of the part are the following

- First layer thickness – can affect the dimensional accuracy of the entire part
- Path / Bead width – can affect build time

Post processing adds cost to a part created by the FDM process. The following are some considerations:

- Support material – Takes time to remove. This also can affect the aesthetics of the part. This can be done mechanically or with the use of a dissolvable support material. Using the base material for support can reduce the initial cost of the material but still will need to be removed.
- Sanding – This can improve the surface finish of the part. It adds cost due to labor and can damage the part of not done properly
- Cold welding – This allows multiple parts to be joined with the use of an adhesive. It allows the part to be optimized for orientation. This requires extra labor and some degree of skill. Parts may not be as strong as a single unit.
- Sealing – Parts can be sealed with the use of an epoxy. This makes the part stronger and possibly waterproof. This requires extra cycle time and the cost of the epoxy. But may be a product requirement.

Figure 7 Support Cleaning Apparatus

Cost

In determining cost a simple model is calculating the volume of material and multiplying by the raw material cost. Some other considerations though in this model are the following:

- Part Size (oz) * Material cost/oz
- Support Material (oz) * Material cost/oz
- Time to remove Support Material * Labor rate
- Insert costs
- Time to insert inserts * Labor rate
- Cycle time of the part * Machine cost/time

Example Designs

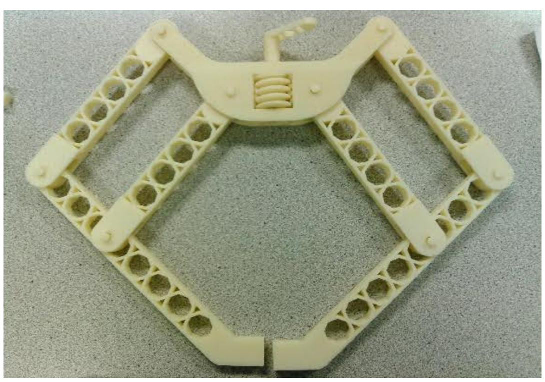
Drone Motorized Arm Attachment
Source: University of Dayton Intro to Design course

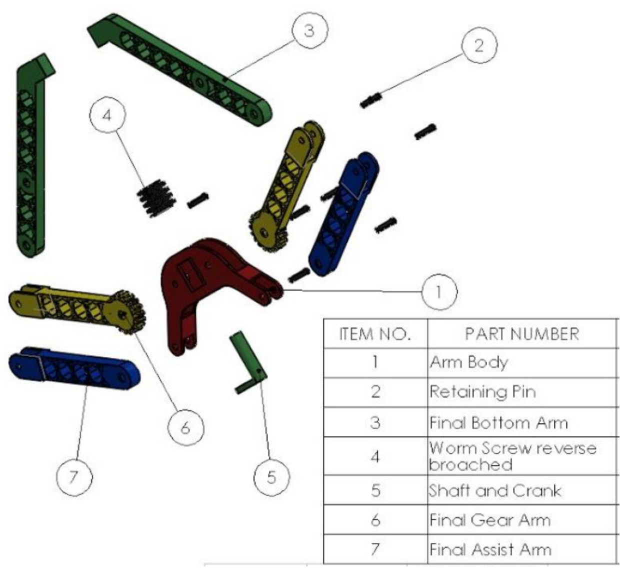
Application: A motorized arm that attaches to a drone. The arm would use a single motor to drive a worm screw, however, the prototype was created with a hand crank to simulate the motor.

Comments:

- 3D printing worked great for the spur gear teeth incorporated into the drone arms. The arms were printed flat so the working surfaces of the gear teeth did not have steps from the z-axis layering.
- The hexagon holes worked well for light-weighting and reducing print time while maintaining strength.
- The worm threads (Item 4) did not achieve a good surface finish. Post processing or using something other than FDM to create the part would have resulted in a more functional part. A coarser and shallower thread could have also improved the surface finish.

The pins were also printed for the prototype. These would have been much better served with a purchased component. A purchased pin would have been stronger, more accurate, and cheaper.





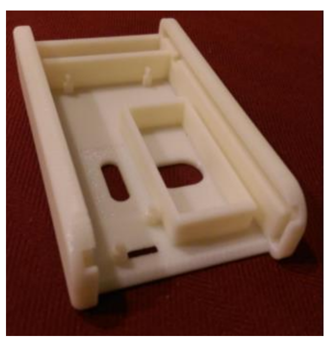
ITEM NO.	PART NUMBER
1	Arm Body
2	Retaining Pin
3	Final Bottom Arm
4	Worm Screw reverse broached
5	Shaft and Crank
6	Final Gear Arm
7	Final Assist Arm

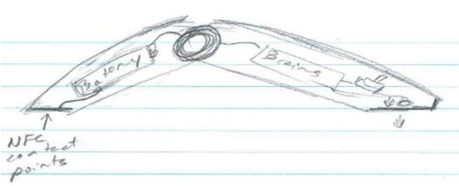
Flat Pack Bluetooth Mouse
Source: University of Dayton Intro to Design course

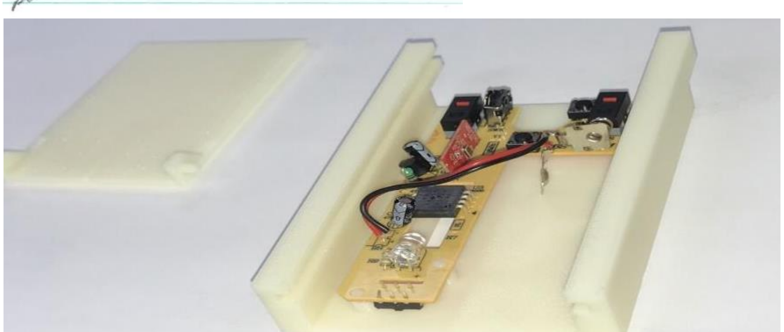
Application: A travel friendly wireless mouse that can collapse and pack flat. The electronic components used in the prototype were borrowed from a low cost existing blue tooth mouse.

Comments:

- The design of the mouse components minimized the amount of required support material.
- The narrow slots in the main housing were narrow and deep. These required support material and were difficult to clean out in the wash bath due to the aspect ratio (depth vs thickness). Shallower slots or other design changes could have improved this feature for printing.
- The small pin features for the hinge joints were very delicate when 3D printed. Robustness could have been improved by increasing these diameters or possibly making them spherical or conical in shape.
- The small pin features for locating the printed circuit board were tied into the wall. These features worked well.
- A snap fit was designed into the top of the mouse to assemble the hinge joint. This feature worked well because it avoided stress in the weaker z-axis.





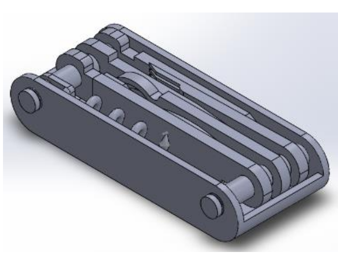
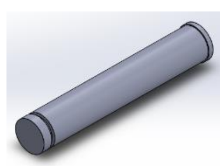


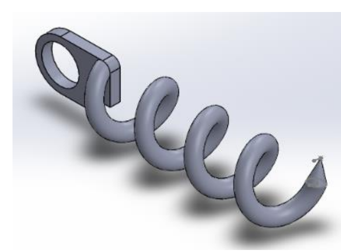
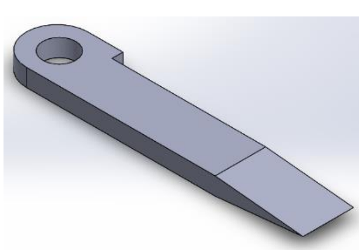
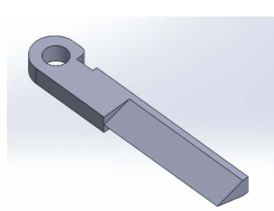
Multi-Function Camping Tools
Source: University of Dayton Intro to Design course

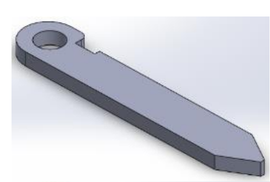
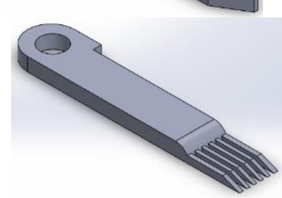
Application: A multipurpose tool that can fit into a normal pocket and pick-up basic foods. The tools could be printed on demand and easily changed out for any other camping needs.

Comments:

- 3D printing worked well for the case.
- The pins were printed for the prototype. These would have been much better served with a purchased component. A purchased pin would have been stronger, more accurate, and cheaper.
- The team did a good job of designing the tools to print flat; however, some tools lend themselves to 3D printing much better than others:
    - The corkscrew is the least conducive tool for 3D printing. It requires strength in X, Y, and Z. The three dimensional curved surfaces result in a stair step effect from the print layers no matter the build orientation. It requires a significant percentage of support material in any build orientation. Ultimately, 3D printing with FDM does not result in a functional component.
    - Knives cannot be printed with a sharp edge. These features were printed in the z-direction and ended up with a stair step effect. These features were also very fragile and not at all functional.
    - The fork and spoon both have potential to print functional components using FDM. The spoon design was very durable as-is, while the fork design needed larger tines for increased durability.

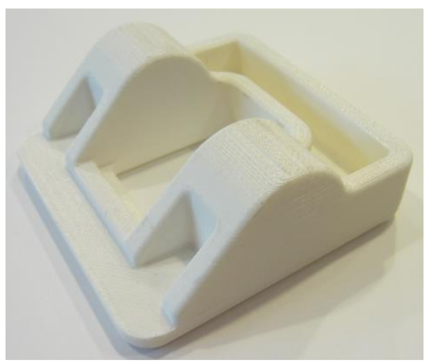



Clevis Block
Source: an global medical equipment manufacturer

Application: A vibration isolation mount for an actuator used in a medical procedure chair. The clevis block was initially prototyped as a machined component. A prototype was then printed out of ABS plastic and used as the master pattern for multiple Aluminum sand cast prototypes.

Comments:

- This process worked well. Machined components proved out the initial concept, but it was possible to quickly prove out the final part's fit, function, and material properties by creating a 3D printed master pattern. It also allowed the supplier to do a small amount of process testing before creating the final master patterns.
- The printed pattern had to be scaled up approximately 2% to account for part shrinkage during processing. The hole was drilled after casting for tighter precision.
- Ultimately, the prototype cast parts held in excess of 10 000 lbs, and a 20 000+ cycle life test could be completed while production tooling was completed. This alone saved about 3 weeks out of the design cycle.

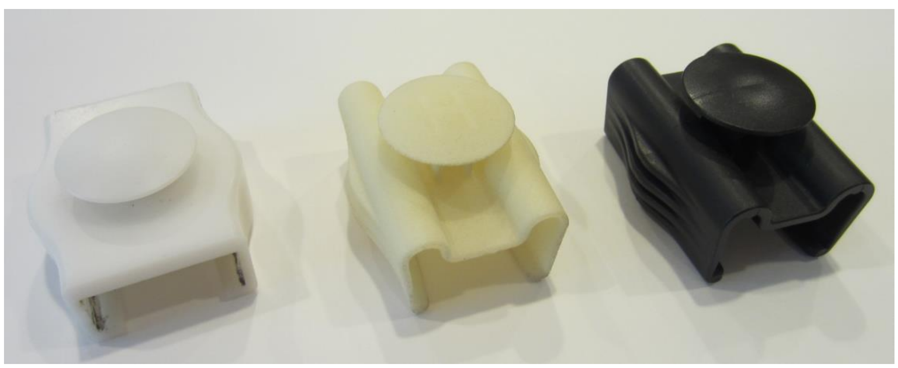




Control Hanging Button
Source: a global medical equipment manufacturer

Application: A mounting system for a corded hand control used for a procedure table. The button is designed to slide onto a standard surgery rail so that the control can be stowed in multiple positions and orientations. The end manufacturing process is injection molding.

Comments:

- A prototype was attempted by creating a multi-piece assembly out of acetal. This proved difficult to get the necessary springiness into the arms of the design so that it could easily grip the rail.
- SLS (Selective Laser Sintering) was used to print the next round of prototypes. This process was chosen to generate a more functional part out of nylon. There were also multiple thin features that were judged to be difficult to print using FEM. These parts effectively proved out fit and function of the part before cutting steel for injection mold tooling.
- While tooling was in process, several parts were successfully printed using FDM. By printing the spring arms in the x-y ases, the parts functioned effectively; however, the feature resolution was not as fine as the SLS process.



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