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Design and Manufacturing of a 3D Printer for Teaching and Research

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Abstract. The goal of this paper is to design and fabricate a 3D printer that will be the most accurate and cost-effective printer possible, while still being faster than the Rapid Prototyping (RP) Lab’s Stratasys FDM-1650 at Loyola Marymount University. This project is done to greatly increase the capability of the RP lab in addition to exposing students to the design and fabrication of a 3D printer. To complete the construction of the printer, the design is originally generated in Solidworks to ensure the components would work together effectively and to aid with design selection. The frame is then constructed using V-slot aluminum and RP parts that are made in house. Following which, the motors and extruders are assembled according to design plans and the circuitry is wired through an Arduino based programming system. Further steps needed to be taken were reconstructing the Y-axis motion and calibrating all aspects of the machine to finalize the assembly of the printer. The printer has been completed recently and is being used for teaching and research on design and manufacturing applications.

1. Introduction
3D printing refers to the fabrication of a physical, three-dimensional part from a numerical description (such as a CAD model) by means of an automated process without any need for tooling [1-2]. Also known as rapid prototyping, 3D printing can aid in prototyping parts very quickly in a “layer by layer” manufacturing technique that builds up (or down) a model in discrete slices. Fused Deposition Modeling (FDM), a popular subset of 3D printing, achieves this by controlling the position and movement of a heated nozzle that can selectively deposit molten thermoplastic onto a model. While FDM lacks the resolution that other 3D printer systems can achieve (SLA, SLS, DLP, etc.), its main advantages are that it is far less expensive (about $2000 -$500) to operate, needs no hazardous chemicals, and is relatively fast at completing prints. These benefits make FDM a popular tool for designers who want to be able to prototype new designs quickly and inexpensively.
This paper sets out to explore the important parameters that influence the fabrication and function of a FDM printer. Design considerations such as frame rigidity, printing accuracy, and electrical component selection are detailed in such a way as to show just how these constraints impact the operation of 3D printers.
2. Necessary Parts
There are a multitude of necessary parts needed to make a 3D printer [3]. First there are the extruders. Extruders are the parts through which the printing material is deposited. Within a FDM printer, an extruder consists of a nozzle, a hot end, and some form of mechanical drive to push the material through the nozzle. The hot end is a piece of metal that heats up to melt the thermoplastic into a molten form before it is placed. The extruders need to be able to move in the X, Y, and Z planes to be able to print a part properly. There are multiple different ways to do this, but typically a FDM printer will consist of a combination of belt and screw driven motors. Motors actuate both the screws and the belts to provide motion in each direction. Screws are typically used for the Z motion since they provide very fine control over the layer thickness. In the X and Y planes belts are used to reduce complexity and size at the cost of some accuracy. All these components are held within some sort of ridged frame.

3. Functional Description and Design Analysis
To fabricate this 3D printer, many materials and processes were utilized. Most of the parts used for this project were ordered, however, many of the complex and or custom parts were 3D printed using the MakerBot 2 RP machine of the department.

The fabricated printer can print nearly every RP material including ABS and PLA, giving it a huge advantage over the other printers in the LMU RP lab. This is largely due to the hot end of the extruders. The hot end can print different materials due to the range of temperatures they can achieve. Each hot end in its current state can reach 300°C, and with few modifications as high as 400°C, allowing them to print plastics with extremely high melting points. Additionally, the RP machine is designed for dual extruders, allowing it to print two different materials at once. This allows the printer to extrude either two different colors or both build and support material at the same time.

Three common frame archetypes were considered for the 3D printer: square, delta, and A-frame [4-5]. Ultimately the A-frame was chosen due to its enhanced rigidity and larger build envelope as compared to the square and delta frames [1]. Rigidity improves accuracy of machines by preventing the machine from shaking while it is printing. In terms of durability, the machine can be picked up and moved around without needing to be recalibrated due to the strength of the triangular designs on the sides of the printer. Fig. 1 depicts the A-Frame Design.

![Fig. 1: A-Frame Design](image)

Multiple extruder types were also considered for the design. A Bowden extruder takes the motor and extruder components and moves them from the X-Y carriage to the frame. There is better control of the filament through reducing weight of the X-Y carriage.

Direct drive extruders were also considered. Direct drive extruders keep the motor and other extruder components on the X-Y carriage, while driving the filament directly into the extruder. There is less fine control due to the extra weight on the carriage. This also typically requires a higher torque motor.
However, by adding gearing to a direct drive extruder, there is no need for a higher torque motor. Though direct drive extruders may have some drawbacks with respect to increased weight on the carriage, they are still very accurate in comparison to a Bowden extruder. Therefore, a geared direct driven extruder was picked for use within this design for accuracy. Using this type of extruder in combination with a .25mm nozzle, which is small for a 3-D printer, very accurate parts can be created at the cost of print speed. The gears used on the extruder also use herringbone teeth to prevent backlash from occurring, which would produce extra plastic when not necessary. A picture of a geared extruder can be seen in Fig. 2.

Heated build plates are critical parts when it comes to printing certain materials such as ABS. A heated build plate prevents thermal gradients from forming within the printed material. Thermal gradients can cause deformation and warping, which is not ideal for the parts that need to be produced. A figure of a heated build plate can be seen in Fig. 3.

This printer uses an Arduino mega 2650 combine with a ramps shield to control the printing process. The ramps shield contains 5 pololu stepper drivers to run the X, Y, and Z axes in addition to two extruder motors. The use of an open source firmware called Marlin is uploaded to the controller and will give future students the ability to expand and tune the new machine. Extra code can be added to either augment or increase the capability of the machine, such as automatic bed leveling, additional lights, and fan inputs. All features of the rapid prototyping machine are controlled via the Arduino.

4. Build Process
The 3D Printer was first designed in Solidworks, a Computer Aided Design program, in order to show compatibility of parts, size of the printer, logistics for construction, and to provide the builders with a
The Solidworks files operated as a blueprint for the construction of the printer and can be seen in Fig. 4. The first step to construction was to cut down the 1.5m V-slot stock on the horizontal band saw. There are 18 different V-slot extrusions in 6 different lengths needed for the whole assembly.

Using this model, the frame was constructed using V-slot aluminum, RP parts from the Makerbot Replicator 2, and varying fasteners. Extra fastening points were inserted into the frame for the various mounts for the Y and Z-axes. The base was constructed first to provide a sturdy platform for the rest of the construction of the printer. The top half of the frame was then assembled and mounted on top of the base. The bottom bracket holds the platform together and the top bracket holds the top half of the frame to the platform.

There are four rapid prototyped mounting brackets that mount the A-frame to the top supports. These mounting brackets hold the top of the assembly together. During construction, it was imperative to put T-slot nuts within the frame where more parts would be fastened, as T-slot nuts cannot be added or removed without disassembly. These T-slot nuts were used to fasten all the brackets to the V-Slot.

With the frame constructed, the Z-axis motor supports, and a Y-belt drive motor and Y-idler were mounted to the frame. The motor mounts and idler mounts are also designed and made with RP parts. The next step was to build the frame for the Z carriage. This was assembled and mounted within the frame on the 2mm pitch Z-axis screws. With the vertical supports somewhat loose in the frame the z carriage can be used to move up and down to align the vertical supports. Once the vertical supports are aligned they can be tightened down to prevent them from moving. The Z-axis screws can be fastened to the Z-axis motors and mounted in the RP ends of the Z-axis carriage. The mounts for the V-slot wheels are slid into the supports and tightened down stabilize the Z-axis carriage. The Y-axis carriage is comprised of a ¼ inch acrylic with holes for V-slot wheels and acentric spacers to tension them. The acrylic also has holes to mount the spring suspended heated build plate. The final part of the axis assembly is the X-axis plate that has 4 V-slot wheels mounted in slots to tension them on the Z-axis carriage aluminum extrusions. Belts can be run for the X-axis and the Y-axis and zip tied to prevent them from slipping.

The extruders and extruder mounting plate were assembled next. The extruders work by gearing down the drive from the NEMA 17 stepper motor via herringbone gears to increase both torque and filament control. The gears drive hobbed bolts to create give smallest diameter filament drivers. 688 bearings that are spring loaded against the bolt act as idlers to force the filament against the hobbing on the bolts. The filament is forced through the hot ends using the stepper motors. Each hot end mounts into its corresponding extruder and has building instructions that can be found on the manufacture website. The two extruders are mounted to the plate and the entire dual extruder assembly is mounted to the x carriage on 4 springs to allow for hot end leveling. The mounted dual extruder tips can be seen in Fig. 5.

The next step is to mount the Arduino board, as seen in Fig. 6, and start the process of wiring. Each of the stepper motors has a corresponding location to plug. The heaters for the hot end and the relay input for the bed must both be properly secured to prevent short circuits and bad connections. The
thermistors on each hot end and bed must also be plugged into their corresponding locations. The final part of the wiring was the 12v rail of the ATX power supply to provide power to the whole ramps board. Endstops need to be mounted adjustably to each frame axis. Endstops allow the printer to find the origin in 3D space. Special care must be used when wiring the end stops to make sure they function properly.

5. Result and Future Improvements

The final fabrication of the newly built 3D printer is shown in Fig. 7. It is producing parts to meet the design and research needs of the students and faculty. This project has encouraged other students to participate in 3D printing technology. All industries of the world are using rapid prototyping and 3D printing to expedite their product development process and reduce costs of manufacturing and reduce waste.

Fig. 7: LMU 3D Printer

There are a multitude of different modifications that can be made to this design to further improve its ability to print. The printer is printing parts, but they are not as accurate as we would like them to be. The next improvement would be the addition of an enclosed build chamber. By enclosing the print area, the parts printed within the heated volume of the printer will not warp easily, as they will be of uniform temperature throughout the printing process. Another improvement that could be made to the machine would be increasing the size of the extruder nozzle. By increasing the size of the nozzle, faster dispensation of plastic can occur and create an overall faster build process for the 3-D parts. All technical specifications are listed in Table 1.

Table 1: Technical Specifications

| Build volume (X, Y, Z) | 220*220*230[mm] |
|------------------------|-------------------|
| Nozzle diameter        | 0.25[mm]          |
| X/Y speed              | 150[mm/s]         |
| Maximum nozzle temperature | 300[°C]   |
| Maximum bed temperature | 110[°C]          |
| File type              | G-Code            |
| Layer thickness        | 0.05-0.2[mm]      |
| Power requirement      | 100-240[V] AC     |
Installing an automatic bed leveling system would also greatly reduce the maintenance time needed to ensure that the heated build plate is both level with the frame and offset from the Z origin. Finally, the wiring harness should be properly maintained in order to ensure that the electrical connections are secure and not likely to interfere with the printing process.

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