

3D PRINTER EXTRUDER DESIGN FOR PRINTING WITH DEFORMABLE MATERIALS

Aurelian Zapciu[1], Catalin Gheorghe Amza[2]and Diana Popescu[3]
[1]UniversityPolitehnica of Bucharest, aurelianzapciu@yahoo.com
[2]UniversityPolitehnica of Bucharest, acata1@camis.pub.ro
[3]UniversityPolitehnica of Bucharest, dian_popescu@yahoo.com

ABSTRACT: This paper presents the replacement of a conventional FDM 3D printer extruder which uses thermoplastic filament with a new extrusion device that can extrude deformable materials. The paper presents the development process, design choices made by the authors and discusses their advantages and disadvantages. The extruder's container which stores the build material is a syringe made out of chemically-resistant plastic material. This container can be loaded with deformable materials such as gel, paste or clay and inserted in the device. A plunger pushes the build material through a nozzle, carrying out the extrusion process. The plunger is actuated using a drive screw-nut mechanism driven by one of the 3D-printer's stepper motors. Other features of the new extrusion device are the capability to heat build material up to 85°C with the use of the 3D-printer's ceramic heaters and to cool the material once it's deposited on the build plate with the use of a side-mounted fan. A prototype device was built with parts manufactured using the 3D printer and thermoplastic extruder which it is meant to replace. The design choices make possible the installation of the device on the desktop 3D printer without any additional electronics.

KEY WORDS: Additive manufacturing, Fused Deposition Modeling, clay extrusion, recycling.

1. INTRODUCTION

Additive manufacturing (AM) is a manufacturing technology that allows the fabrication of objects layer by layer (i.e. in an additive manner). Starting 2009, when the patent on Fused Deposition Modeling (FDM) [1]technology expired, AM has experienced a continuous expansion [2] in terms of technological capabilities, materials and process technology due to an increased interest from both industry and private consumers[3]. New additive manufacturing technologies, as well as new materials for use with these novel technologies are constantly being developed, enabling the integration of additive manufacturing into new areas of activity. Initially limited to rapid prototyping, AM has found its way into multiple other applications, which include making mechanically functional parts, accurate visual models, creating organic structures, etc. Thanks to its relatively low cost and the simplicity of technological equipment, which led to the RepRap phenomenon, FDM has become the technology adopted by most private users, with the main build materials being thermoplastic polymers [4].

More recent developments have seen FDM being adopted in other areas of interest, by replacing the thermoplastic polymers with a new and growing range of materials, many of which come in the form of gels, clay or paste. In the medical field, researchers have 3D printed scaffolds which are used to grow live tissue [5], or even live tissue itself[6]. The low cost of AM relative to injection molding and the possibility of creating complex geometric shapes have opened the door to 3D-printing customized medical implants[7]. In the construction industry, large efforts are put into using 3D-printed concrete and cement to create buildings [8]. Paste-like materials have also found various artistic applications, such as designers creating ceramics art[9]or bakers making 3D printed food ornaments [10]. Along with these new ways to use AM technology, its initial use of creating rapid prototypes also shows interest for deformable materials. While 3D printing enables designers and developers to quickly manufacture prototypes, giving them the ability to have a better control over the design process, as well as faster turnovers, it also introduces a new problem: the amount of waste that is generated by manufacturing multiple iterations of the same object[11]. Therefore, there is significant interest in ways to reduce waste by recycling 3D printed parts[12] or by using biodegradable materials [13]. 3D printing with deformable materialswhich can be reused after the fabrication process is a promising solution to the waste problem. These new developments would not be possible without creating new extrusion devices, which is the reason why the authors have focused on improving such a devices, by designing a paste extruder which is easy to integrate into a desktop 3D-printer while being versatile compared to existing solutions, by having the ability to heat up the build material, cool down the deposited filament and to be used in a sterile environment.

Existent solutions have been analyzed in terms of mechanical design, features and electronics needed to function. The most prevalent design is one that uses a plunger inside a cylinder to push build material through a nozzle fixed at one end of the cylinder. The plunger can be electrically actuated, usually by a stepper motor. The movement can be transmitted to the plunger through a drive-screw and nut mechanism. Linear rails are needed to guide the plunger, meaning that the weight of the overall system is increased which makes the installation of the extruder onto the moving axis of a 3D printer more difficult. Other constructive variants are also available. The open-source Universal Paste Extruder by RichRap[14] uses a drive belt mechanism to drive the plunger and 3D printed parts for its structural components. This design reduces weight by not requiring guide rails, but eliminates an important feature for the FDM process, the ability to retract build material when passing over areas where material doesn't need to be deposited. The absence of this feature significantly reduces the quality of the fabricated object.

The plunger design can also be pneumatically actuated. This drastically reduces the weight of the extrusion device by eliminating the electrical motor but requires additional electronics in order to control an air compressor and a pressure valve.

Another constructive variant identified during our study is slightly more complex and uses an auger screw inside the cylinder instead of a plunger. Material is fed through an opening in the top part of the cylinder. This variant has both advantages and disadvantages over the plunger variant. In the plunger-type extruder the cylinder can hold a small amount of build material because the extruder is positioned on the moving axis of the 3D printing machine. Thus the fabrication process needs to be stopped in order to refill the printer. The auger screw type does not have this limitation, as build material can be stored in a larger enclosure and mounted to the fixed structure of the printer. However, this enclosure needs to be pressurized to ensure a constant flow of build material. This means that additional components are needed such as air compressor, pressure valves, control electronics, etc. Other design observations include the lack of additional features that increase the applicability of the extruder to materials that require heating or forced-air cooling/drying. At the moment this paper was written, the authors don't have knowledge of any device certified to be used in a sterile environment, but devices certified to be used in the food industry do exist. Following this analysis, we can conclude that for 3D printing small-volume parts the plunger-type extruder is preferable.

2. PASTE EXTRUDER

2.1 Design Requirements

The paste extruder designed for this project was developed to be installed on a typical FDM desktop 3D printer, namely the QidiTech Avatar IV [Figure 1].

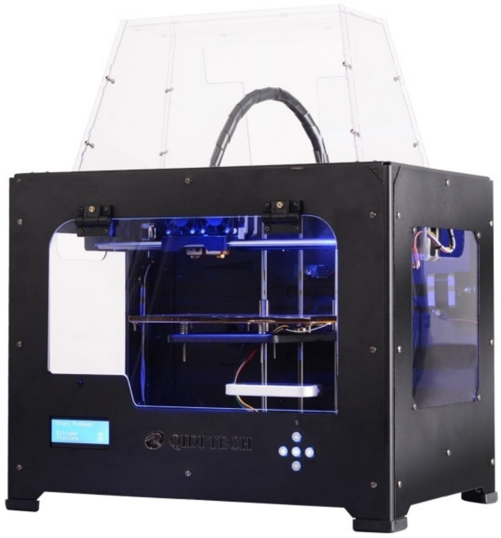

Figure 1. QidiTech Avatar IV Desktop 3D printer

This 3D printer is a belt-driven cartesian style FDM printer built based on one of the most popular printer designs, similar to the Makerbot Dual or the Flashforge Pro. The standard printer comes equipped with two thermoplastic filament extruders. These extruders function by grabbing thermoplastic filament 1.75 mm in diameter using a jagged wheel and pushing it through a heated nozzle. The wheel is driven by a stepper motor through direct drive. Heating the 0.4 mm brass nozzles and maintaining temperatures of up to 230°C is achieved using ceramic heaters and thermistors. The dual extrusion system includes a fan to keep each extruder at optimal temperatures and a third fan used to cool down built parts. In order to control all these elements, the printer uses an Arduino-based motherboard with 5 stepper motor on-board drivers (Allegro A4988), 3 ADCs used to convert signal from the thermistors and 3 relays used to switch the heating elements on and off.

The plate on which the extruder can be mounted measures 86 x 84 mm and has two mounting holes [Figure 2]. The axis which carries the dual extruder is rated by the producer to withstand printing speeds of up to 150 mm/s. This, along with the fact that this system which is mounted on the X axis of the machine weighs 750 g, was used to determine the weight limit goal of the new paste extruder, which was set at 800 g fully loaded with build material. The design of the 3D printer uses one of the stepper motors of the extruders to trigger the X axis stop limit, a fact which also needs to be considered when designing the paste extruder.

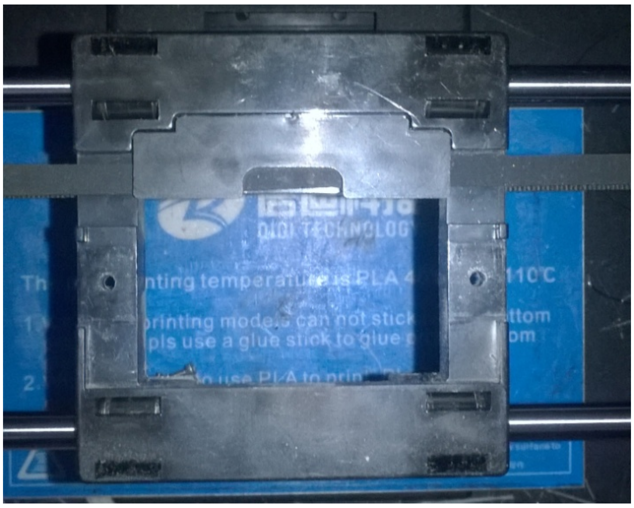

Figure 2. X-axis mounting plate for extruder

2.2 Extruder design

In order to fulfill the design goal of easy integration of the new device with the QidiTech printer, it was designed to use the stepper motor, heating cartridge and thermistor from one of the thermoplastic material extruders. This ensures that the 3D printer has all the electronics needed to run the replacement extruder. This also makes sense from a software integration point of view, since using the same electronics means the paste extruder can use the same open-sourced slicing software the producer of the 3D printer has provided. The QidiTech printer uses a binary Gcode file format, and Sailfish open-source firmware. This format is compatible with Makerbot'sMakerware software and requires minimal changes to printing process parameters to adapt to the replacement extruder.

Autodesk Fusion 360 was used to design the components of the device. The software allows the user to define materials and apply them to individual components, which is then used to determine the center of gravity of the entire assembly [Figure 3].

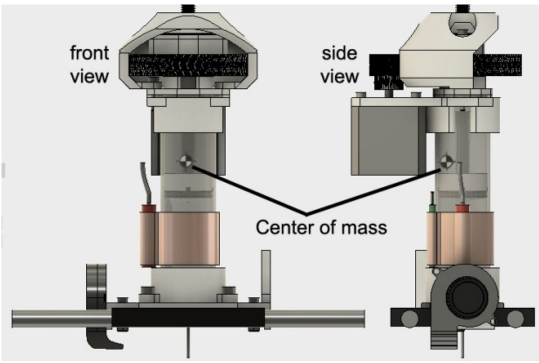

Figure 3. Virtual model with center of mass indication

This is useful when designing the system, as maintaining a low center of gravity is important for the dynamic performance of the printer. To achieve this, the stepper motor was not mounted on a linear guide system on top of the cylinder, but instead, it was mounted sideways. The rotating motion is transferred through a double helical gear mechanism (herringbone gears) [Figure 4] to a drive screw-nut mechanism which converts it into linear motion. The herringbone gear type was chosen for its ability to self-center. Unlike typical helical gears, herringbone gears do not produce additional axial load. The two mirrored sides of the gear eliminate the need for a thrust bearing. Also, with herringbone gears, more than two teeth are in mesh at any moment in time, which makes the power transfer smoother[15]. This minimizes the requirements for part accuracy, giving the possibility to obtain good results by fabricating the gears through FDM 3D printing. The large gear is fixed axially by using two ball bearings [**Figure 5**].

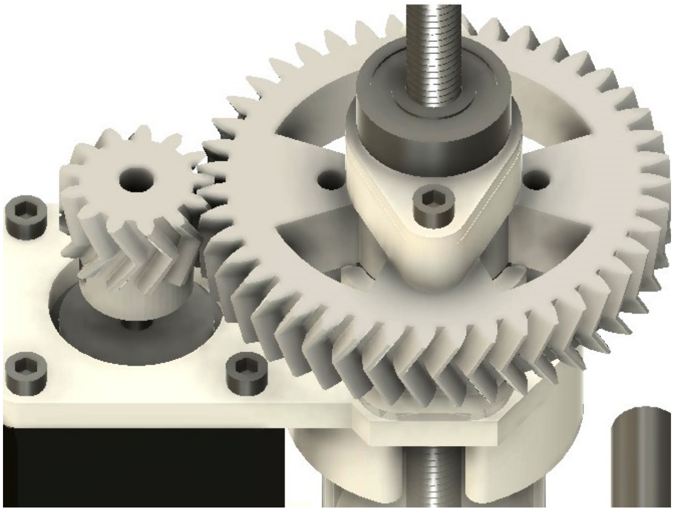

Figure 4. Herringbone gears

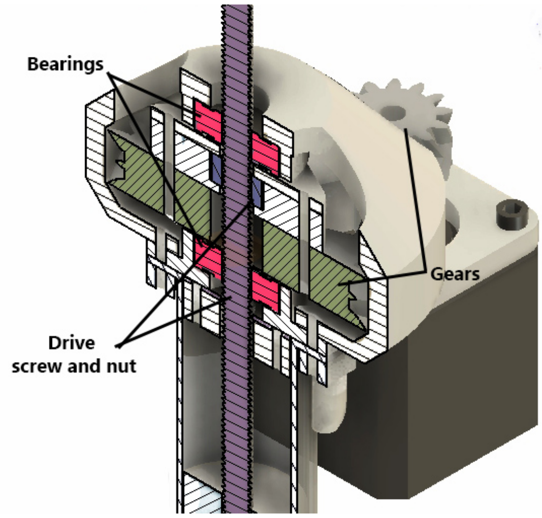

Figure 5. Drive mechanism

For the cylinder which stores the build material, a syringe tube made out of polypropylene (PP) was chosen. PP is a widely used thermoplastic which can withstand operating temperatures of up to 90°C and is resistant to fats and almost all organic solvents apart from strong oxidants[16]. The syringe comes equipped with a plunger made out of polyisoprene rubber which expands when pushing the build material and prevents the plunger from rotating inside the cylinder, making sure that its motion is linear. The tip of the syringe is a luer lock which allows the use of standardized luer needles [Figure 6]. Various diameter needles will be used to test the device. The use of a standard 60 ml syringe also enables easy loading/reloading with build material and allows the use of the extruder in applications where sterile equipment is needed, as other parts of the device do not come in contact with the build material.

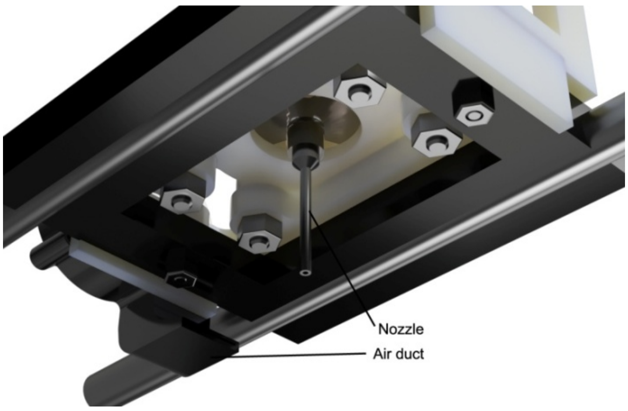

Figure 6. Paste extruder - underside view showing nozzle system and air duct for part cooling or drying

Additional features like the possibility to heat the build material have been integrated in the design. One of the ceramic heaters from the standard thermoplastic extruder of the 3D printer has been attached to a copper sleeve which wraps around the PP cylinder. The temperature is controlled and maintained using the thermistor taken from the same extruder [Figure 7].

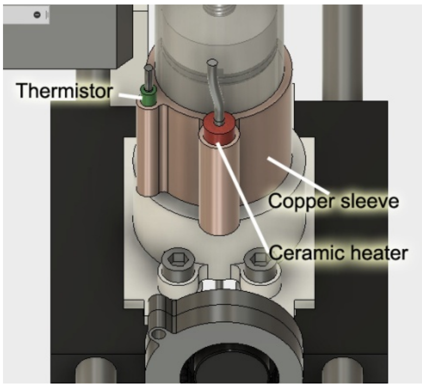

Figure 7. Temperature control system

As the temperatures during functioning will not exceed 85°C, no additional cooling is needed for the extruder components. However, a side-mounted fan has been designed to help with cooling the layers of material that have been fabricated when working with heated build materials or with drying the deposited material when working with air-drying build materials. To account for the removal of the stepper motor normally used to trigger the X-axis end-stop, the mounting bracket has been designed with a protrusion used to trigger the electromechanical switch.

2.3 Extruder prototype

Following the design process, a prototype was built using parts that are either standardized, 3D printed, or taken from the standard thermoplastic extruder of the QidiTech printer [Figure 8]. As mentioned previously, the device was built around using the existing electronics of the 3D printer.

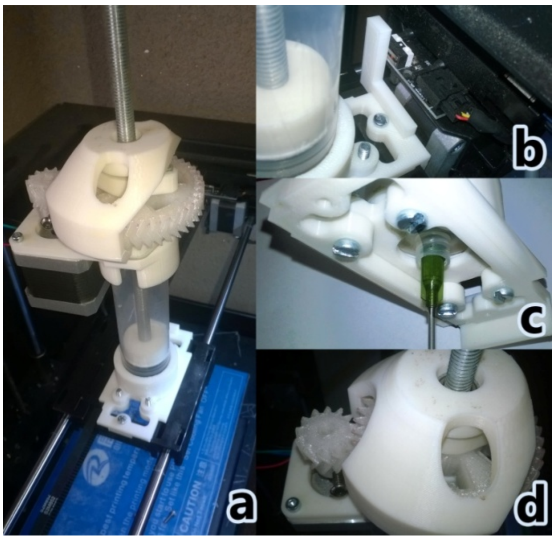

Figure 8. Paste extruder prototype: a) device installed on the 3D printer and loaded with build material; b) end-stop; c) extrusion nozzle; d) herringbone gears.

The electric motor is a stepper motor, set to work with a resolution of 200 steps per revolution and a microstepping setting of 1/16steps. The heating system was also taken from the thermoplastic extruder and consists of a DC ceramic resistive heater and an NTC thermistor [Figure 9].

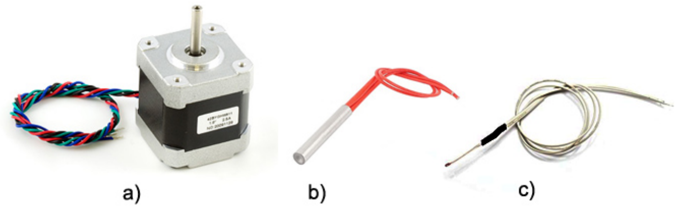

Figure 9. Electronics taken from standard thermoplastic extruder and integrated into new design; a) stepper motor; b) ceramic heater; c) thermistor

For the 3D-printed parts, first, STL files were created from the Fusion 360 3D models. The STL files where then imported into Makerware software, sliced and sent to the QidiTech printer to be fabricated.

The two herringbone gears were 3D printed from Polyethylene-terephtalate-glycol (PETG)[17], a thermoplastic polymer blend derived from PET. PETG has better mechanical properties than the more commonly-used Acrylonitrile-butadiene-styrene (ABS), consisting in a higher tensile strength, and better FDM process-related properties such as better layer adhesion and less warping. Also, due to its lower thermal expansion coefficient, PETG is more suitable for parts that require dimensional accuracy. After consulting other works regarding the influence of infill geometry and density on structural strength[18], the gears were printed using a 0.15 mm layer [Figure 10], at 60 mm/s, with two surface contours and a 65% orthogonal infill. The nozzle size was 0.4 mm and the nozzle temperature was set at 235^{o}C, while the bed was maintained at 70^{o}C.


Figure 10. 3D printing the large herringbone gear in PETG

The rest of the components were 3D printed from ABS[19]. Being one of the most used thermoplastic materials in the field of AM, ABS process settings and mechanical properties are well researched [20], [21]. The structural parts of the paste extruder were printed with a 0.12 mm layer, with two surface contours and 50% hexagonal infill. The infill type and density ensures that the parts are strong enough to fulfill their functional role, but light enough to meet the weight goal. During the printing process, the print bed was set at 110^{o}C.

The geometry of the top part of the extruder, which houses the two ball bearings, was designed to easily attach on the syringe tube using two screws. For this part support material was used when manufacturing [**Figure *11***].

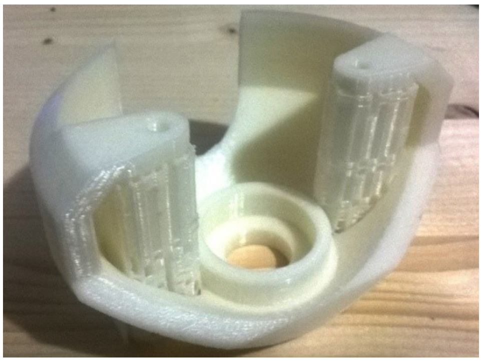
Figure 11. Top part of the extruder - 3D printed in ABS, with same material support

The finished prototype fulfills the design goals of low weight, low center of mass. The prototype was installed on the 3D printer and successfully fabricated several test parts.

3. CONCLUSIONS

The use of soft, paste-like materials as a way to produce new parts but also as a way to quickly recycle prototypes needs to be backed by appropriate hardware. The development of paste extruders for the use with FDM AM technology allows the integration of AM into new fields of activity.

This paper was focused on designing and manufacturing a paste extruder which can be integrated seamlessly in a typical cartesian desktop 3D printer. By analyzing the constructive options existent on the market, the authors have drawn conclusions regarding advantages and disadvantages of several constructive variants and used this analysis to develop into a new product. After a 3D modeling design stage, a prototype was manufactured using FDM 3D printing, with parts being manufactured from thermoplastic materials by the same extruder the prototype is meant to replace. The 3D printer's open-source software was set up to print several test parts.

Our research showed that a device that can extrude soft materials can be successfully made using only standard FDM desktop 3D printer electronic components, 3D printed parts and other easily obtainable hardware parts.

4. ACKNOWLEDGEMENTS

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