Designing a Universal Liquid 3-Dimensional Printer

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Abstract

Purpose: Liquid three-dimensional (3D) printing using non-traditional materials has a vast range of applications. However, current technology has failed to create a low-cost and efficient system. Researchers have demonstrated that liquid 3D printing is useful when working with living cells, soft materials, and even industrial-grade materials, however, research and applications are restricted by prohibitory costs and limited print material capacity deposition systems. The current project aimed to address both the problems of cost and print material capacity by creating a low-cost, universal liquid 3D printer apparatus. **Method**: A novel method of material transport, using a peristaltic pump, was created in this project. The apparatus is platform-independent, thus is able to be used with a variety of existing low-cost 3D printers. The apparatus is comprised of three main components: the extruder assembly, pump system, and reservoir. An open reservoir is used to store the print material, allowing for more material to be added mid-print without disrupting the ongoing print job. A peristaltic pump is used to transport the material from the reservoir to the extruder assembly. The extruder then deposits the material through a needle into the build area. A common test print was fabricated and data regarding the dimensional accuracy of the given print was collected. **Results**: This prototype has provided a proof of concept that liquid 3D printing can be accomplished with a peristaltic pump system with dimensional accuracy. **Conclusion**: This project can have profound impact on 3D printing technology/rapid prototyping as printers capable of using non-traditional build materials cheaply and efficiently become more prevalent.

1. Introduction

Traditional fused-deposition modeling (FDM), also known as fused filament fabrication (FFF) three-dimensional (3D) printers, have recently soared in popularity as prices drop and quality increases. These FDM/FFF 3D printers use a process called additive manufacturing where material is laid layer by layer to create a 3D object, with little to no waste material. This process is opposed to older subtractive manufacturing techniques, such as carving, where objects are created by taking material away from a pre-existing block of material (Conner et al., 2014). The explosion in accessibility of 3D printers has revolutionized the world of rapid prototyping and opened possibilities of creating new objects otherwise impractical or simply not possible with older manufacturing techniques. However, there is still much to be done in the advancement of non-traditional liquid 3D printing.

One name for traditional 3D printers is fused filament fabrication 3D printers because they print using spools of plastic filament. These spools of filament consist of a continuous thin plastic wire, most commonly 1.75mm in diameter (What Material, 2016). This process is practical for 3D printing for two main reasons. First, the continuous strand of plastic wire is easily fed to the extruder assembly by a motor. A motor can adequately grip onto the plastic filament and continuously feed the plastic until all the filament is used. Secondly, the materials used are thermoplastic, as they become pliable above a specific temperature and solidify upon cooling. In the extruder assembly, the filament becomes molten after being heated and is then pushed onto the build platform as more filament is fed into the extruder assembly. As the plastic is laid onto the build platform, it is instantly cooled and hardened, thus creating a 3D object (Bellini, Guceri, & Bertoldi, 2010). The most common plastic used is polylactic acid (PLA), a biodegradable thermoplastic derived from renewable resources. However, other plastics are used such as acrylonitrile butadiene styrene (ABS) and thermoplastic elastomers (TPE), all having their own advantages and disadvantages (Lederle, Meyer, Burnotte, Kaldun, & Hubner, 2016). Despite having different material composition, these plastics all come in spools.

A recent innovation in 3D printing technology is stereolithography (SLA) printing, also known as resin printing. This newer technology involves a pool of liquid resin and a laser. As a laser is projected into the liquid resin, the resin cures and solidifies at the point of contact. The solidified object is then slowly raised out of the pool, and the laser continues to project onto the object, solidifying more resin layer by layer, creating a 3D object. This process results in smooth finishes (Crivello & Reichmanis, 2014).

Both traditional and new resin methods of 3D printing work by using a build material that can easily be changed from a fluid state to a solid state, either through melting and cooling, curing, or other means. However, this severely limits the types of materials that can be used for 3D printing. One type of materials that cannot be used are liquids. Liquid 3D printing creates the problem of not having an easy way to lay the build material onto the build plate layer by layer. Liquids and pastes have a tendency to flow, so precisely controlling the position of the build material is difficult. However, liquid 3D printers are able to bypass this problem by utilizing different printing strategies. One common strategy is to print in a gelatin-like support bath. The support bath is made of a granular gel that allows the extrusion needle of the printer to glide through the bath when printing, but when the print material is deposited inside the bath, the print material stays in place (Hilton et al., 2015). The support bath acts as a scaffold would in a conventional 3D printer.

Liquid 3D printing has a variety of applications, ranging from food and art to material science and biology research. For instance, there has been a recent surge of research in 3D bioprinting. 3D bioprinters are similar to traditional 3D printers, but instead of using a plastic filament, they use viable cells. Researchers using liquid 3D printers are able to fabricate various functional tissues and organs, such as blood vessels and cardiac patches. 3D printing has opened a whole new world of medicine (Shafiee & Atala, 2016). Another example of liquid 3D printing in use is in MIT's Self-Assembly Lab, where researchers are investigating new 3D printing techniques with new materials. They have developed a process called ‘Rapid Liquid Printing,’ where a liquid 3D printer prints within a gel suspension, allowing for creation of large-scale products made of industrial materials (Self-Assembly Lab).

Many of the current liquid printers exist in the field of food, such as the PancakeBot, Choc Edge, and Sanna. These three inventions all utilize an xy plotter mechanism to move an extruder assembly as it lays down the print material. They are comprised of a round bottle as a part of the extruder assembly and each design is specified for a small selection of foods. The PancakeBot is used for creating pancakes, with a large squeeze bottle extruder assembly (PancakeBot). The Choc Edge is used for printing chocolate, with a syringe like extruder assembly (Choc Edge). The Sanna is used for printing blended food pastes, with a syringe like extruder assembly (Digital Food). However, these inventions have two main limitations. First, the printer is only able to print with the specific type of food. Second, the extruder assembly stores the printer material, which limits the amount of print material that can be used in one print cycle. In addition, storing the print material on the extruder assembly adds weight to the unit which may deteriorate the print quality.

Current higher quality liquid 3D printers are expensive, and use a syringe cartridge system, For example, the Discov3ry consists of a syringe and syringe pump as the means for extruding the build material, but has limitations on the size of the print, as the syringes have a relatively small capacity (Discov3ry).

The current project aimed to solve both the problems of price and print material capacity by building an apparatus that can be used in conjunction with a pre-existing traditional 3D printer. The liquid 3D printer built uses a revolutionary method of material transport, utilizing a peristaltic pump. Compared to the existing liquid 3D printer designs that primarily utilize a syringe pump, a peristaltic pump is superior as it is not limited by the capacity of the syringe, but rather the capacity of the reservoir from which it is drawing.

Three engineering goals were established in designing this system: low cost, high quality, and high volume. Low-cost was defined to be no more than than $650, half the cost of the $1,299 Discov3ry Paste extruder. High quality was defined by the degree of dimensional accuracy, as assessed using data collected from the resulting fabricated object. High volume refers to the print material capacity, defined as more than two liters in comparison to a standard 20 mL syringe. The project was able to create a novel form of material transport using a peristaltic pump system, successfully extruding liquids with acceptable dimensional accuracy. This project could have profound impact on 3D printing technology as we move into printers capable of using non-traditional build materials cheaply and efficiently.

2. Methods

The printer is comprised of three main parts: the extruder assembly **1**, pump system **2**, and reservoir **3**, as depicted in **Figure 1**. All three parts fit along one line of tubing, having the reservoir at one end and the extruder assembly at the other, with the pump system in the middle transporting the print material from the reservoir to the extruder assembly. The extruder assembly is attached to the gantry system of an existing 3D printer, while the pump system and reservoir remain separate.

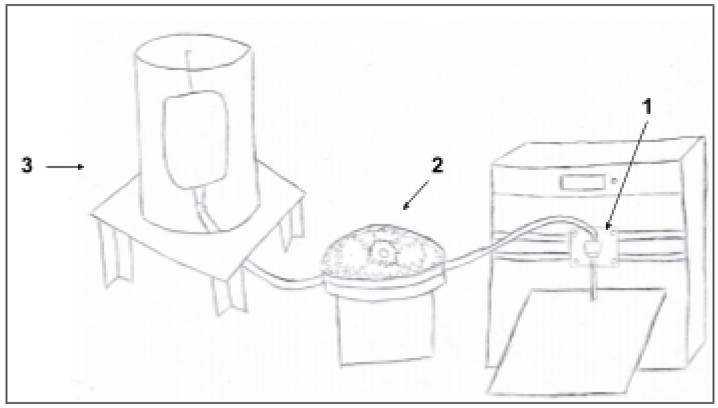

Figure 1: Overview of assembly

2.1 Reservoir

The reservoir **3**, as depicted in **Figure 2** serves to store the print material until it is used for fabrication of the desired object. The reservoir utilizes a gravity-fed bag setup, with a flexible plastic bag suspended inside a 22-quart cylindrical plastic container **4**. This setup is advantageous because print material can be added to the reservoir without interrupting an ongoing print, allowing for much larger prints using more material. Additionally, the gravity-fed setup pulls materials down towards the tubing as printed material is transported away ensuring a continuous stream of material, aiming to mimic the pressure print material would experience under a syringe or pneumatic deposition system. Tubing starts from the bottom of the plastic bag and runs

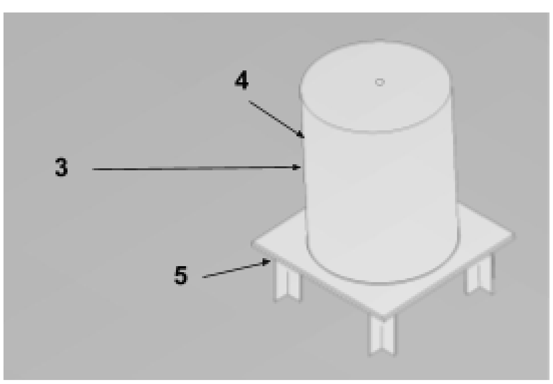

Figure 2: CAD model of reservior

through a hole drilled in the center base of the plastic container. The plastic container is slightly elevated by a laser cut cardboard stand **5**, allowing for the tubing to freely continue from the bottom of the plastic container to pump assembly. **Figure 3** depicts CAD drawings that were used in laser-cutting the cardboard stand.

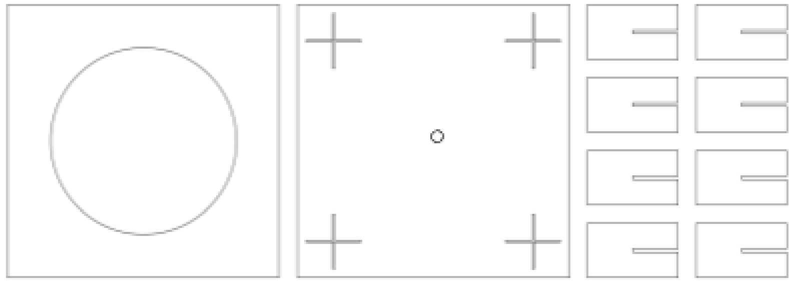

Figure 3: CAD drawing of reservoir stand

2.2 Pump Assembly

The pump assembly serves to move the print material from the reservoir to the extruder assembly through creating a positive displacement of liquid by congressing a flexible silicone tubing. A 3D printed peristaltic pump **8** is used, modified from an online Creative Commons design. The pump mechanism is mounted to a NEMA-17 stepper motor using a custom 3D printed motor mount **6** as depicted in Figure 4. Four holes **7** are used to attach the motor mount to the motor. The the peristaltic pump mechanism **8** is then printed glued along the outer ring **10** to the motor mount, and hole **9** is slid over the motor axis. Tubing was fed through the pump mechanism from the reservoir, and then connected to the extruder assembly.

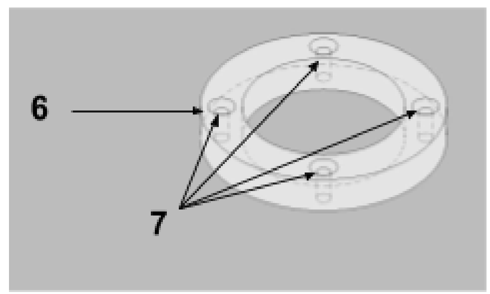

Figure 4: CAD model of motor mount

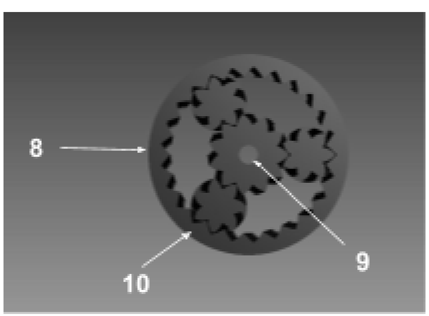

Figure 5: CAD model of peristalic pump mechanism

2.3 Extruder Assembly

The extruder assembly serves to deposit the print material onto the build platform, fabricating the desired object. **Figure 6** depicts an isometric view of the extruder assembly body **11** specified for the Anet A8, however, one can easily design a body specified for their own printers. Tubing from the pump assembly connects to a hose barb to male luer adapter, to which a 15 gauge needle was attached. The barb to male luer adapter was then inserted into a hole **12** on the extruder assembly body.

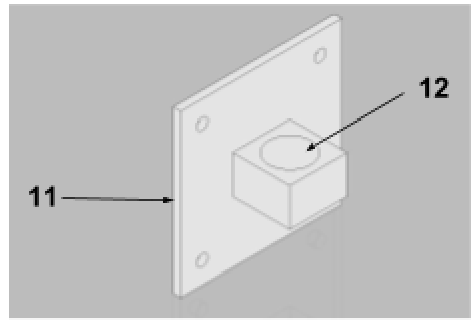

Figure 6: CAD model of extruder assembly body

2.4 Control System/Electronics

The 3D printer gantry system was controlled using custom-written G-Code to maximize control of the printer. The G-Code followed standard RepRap conventions. The pump motor was controlled using an Arduino UNO R3 microcontroller. A standard L298 H Bridge Module was used, connecting stepper motor wires A1, A2, B1, and B2 to the module pins OUT 1, OUT 2, OUT 3, and OUT 4 respectively, and module pins IN 1, IN 2, IN 3, and IN 4 to Arduino digital pins 8, 9, 10, and 11 respectively. A 12V, 2 amp power supply was connected to the module, which served to power both the stepper motor and Arduino microcontroller. The Arduino microcontroller was then programmed using the Arduino IDE, creating a standard program utilizing the stepper motor library, which allowed for the regulation of the rotations per minute of the motor.

2.5 Test Print and Data Collection

A standard, single-layer test print was used to access the dimensional accuracy of the printer. Tap water was used as the print material. The test print consisted of a 75 mm by 120 mm rectangle and a 35 mm circle inside of the rectangle, as programmed in the G-Code. A standard 55 mm/sec print speed was used. A total of four trials were run, and measurements of 18 set points on the print were taken: 9 inner dimensions and 9 outer dimensions. The data of the 18 points were then compared to the predicted measurements as determined in a CAD file, as well as data collected in the same fashion using a syringe based deposition system as a basis of comparison. The data were analyzed using an analysis of variance.

2.6 Suspension Printing

Following initial testing by printing directly on the print bed, a suspension printing strategy was tested using the peristaltic pump setup. A granular gel support bath was prepared by dissolving 1 gram of carbomer 940, a crosslinked polyacrylic acid polymer, into 1 liter of deionized water. Sodium hydroxide was then added to the mixture to neutralize the solution, creating a viscous gel. This gel acted as the suspension medium and was poured into a rectangular tank with an open top. The tank was placed on top of the print bed and secured with an adhesive. The previous test print was printed, except with the print five centimeters offset in the z axis. A total of four trials were run and measurements of 18 set points on the print were taken.

2.7 Cell Viability

To test the plausibility of using the peristaltic pump setup in a bioprinting application, the viability of cells that had been passed through the peristaltic pump system were tested. *E. coli* cells suspended in 4500 µL of Luria Broth were placed in the reservoir and a sterile beaker was placed under the extrusion needle. The peristaltic pump was activated until all liquids had been transferred from the reservoir to the beaker. 100 µl of the cell suspension were transferred to an agar dish to cultivate. After 72 hours, the number of colonies on the dish was counted and recorded. This process was done a total of four times and compared to cell suspensions that were not run through the peristaltic pump system.

3 Results and Discussion

The liquid 3D printer created functioned to successfully print four trials of the test print. All three engineering goals were accomplished.

3.1 Cost

First, the final cost of the liquid 3D printing apparatus was $325, including all parts of the reservoir, pump system, extruder assembly, and the 3D printer gantry system. This is a major reduction in price from previous existing liquid 3D printers where prices ranged from thousands to hundreds of thousands of dollars. In addition, many of the parts of the apparatus were 3D printed or utilized rapid prototyping materials, but can easily be made with more robust materials for a price increase.Nonetheless , the resulting price would still be under the cost of existing liquid 3D printers.

3.2 Dimensional Accuracy

Second, the dimensional accuracy of the prototype was determined to be acceptable as there were no significant difference from the CAD model. An ANOVA revealed that there is no significant difference between the predicted measurements, peristaltic pump experimental measurement, and the syringe experimental measurements, $F(2,189) = 0.01$, $p > .05$, $\eta_p^2 = .001$. These results show that in terms of dimensional accuracy, there are no significant differences between the two systems and the CAD model. On average, the peristaltic pump had a lower percentage difference when compared to the syringe, 5.17% compared to 6.41%, showing the possibility for a more accurate system, as depicted in Figure 7. Furthermore, the inner diameter dimensions tended to be smaller than the predicted CAD dimensions, and the outer diameter dimensions tended to be greater than the predicted CAD dimensions. This makes sense as when printing, the print material bleeds to the side, resulting in the outer diameter dimensions being slightly larger than what they should be, and the inner diameter dimensions slightly smaller than what they should be. Maintaining an acceptable degree of dimensional accuracy is important as it is vital for fabricating high quality prints.

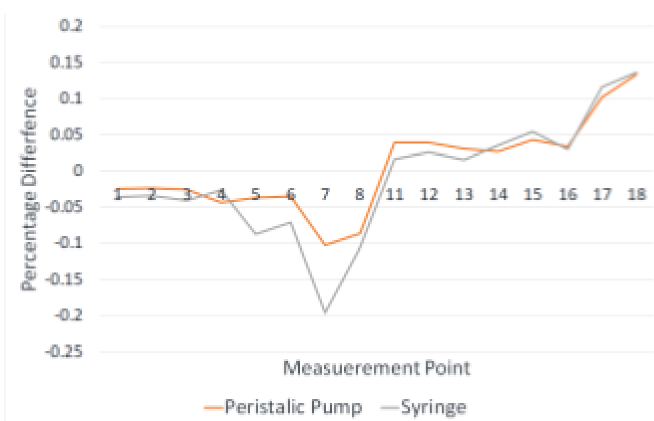

Figure 7. Percent Differences of Dimensions

3.3 Print Capacity

Third, a large print capacity was achieved as the reservoir had a maximum capacity of two liters. This is much greater than that of a syringe based deposition system used in existing liquid 3D printers, which usually has a maximum capacity of 20 mL. However, due to the nature of the reservoir, the gravity fed bag can be refilled during mid-print repeatedly, thus theoretically allowing for an infinite print capacity. The large print capacity permits for the fabrication or larger objects, only limited by the size of the build platform.

3.4 Suspension Printing

Utilizing a suspension printing strategy, the peristaltic pump successfully fabricated four of the test prints. An ANOVA revealed that there is no significant difference between the predicted measurements and the suspension print $F(2,231) = 0.01$, $p > .05$, $\eta_p^2 = .001$. However, the dimensional accuracy was lower than the test print fabricated directly on the print bed. This is not surprising, as the print bed is a solid, flat surface while the support bath consists of a granular gel with the consistency of hair gel. This does show that suspension printing can be accomplished with the given prototype, however, further tweaking may be needed to achieve a higher dimensional accuracy when printing with such strategies.

3.5 Cell Viability

Testing the viability of *E. coli* cells after being run through the peristaltic pump system, an ANOVA revealed that there was no significant difference in the number of colonies of the experimental pump group and the control, $F(2,616) = 0.00149$, $p > .97$, $\eta_p^2 = .001$. This indicates that the peristaltic pump does not affect *E. coli* cell viability and is an indicator of the liquid printer may work as a bioprinter.

3.6 Control System/Electronics

The proposed electronic control system proved to be successful in proper use in controlling both the xyz gantry system of the 3D printer and the stepper motor of the peristaltic pump. The native ANET V1.0 controller board of the 3D printer used was utilized for powering and controlling the gantry system while an independent Arduino microcontroller and H-Bridge controlled the peristaltic pump motor. This setup is advantageous when connecting the liquid printing apparatus to a pre-existing printer with a proprietary controller board, such as a Makerbot or Ultimaker. By using both the native board and Arduino, this allows for the peristaltic pump to work parallel, but independent from the proprietary printer. This was the system utilized when collecting all data. However, by using two boards, it requires that the Arduino to be programmed independently which can become tedious when a user wants to fabricate a piece quickly. Thus, another electronics control system was tested.

The second system created utilized an Arduino Mega equipped with a RepRap Arduino Mega Pololu Shield (RAMPS) 1.4. The RAMPS 1.4 controller board is a standard open source gantry control system often used for CNC and 3D printers. The board was flashed with the Marlin 1.0.2 firmware, another standard open source component often used with RAMPS. This setup allows for all gantry motors and the peristaltic pump motor to be connected and controlled by a single board, in addition to allowing for more customizability such as adding third party fans, auto-levelers, and extruders for various printing strategies. By using one board, it also allows for all the G-Code to be generated using a standard slicer, such as Slc3r, to control both the gantry system and peristaltic pump, resulting in a reduced pre-print work when preparing a print. This system proved to be successful in controlling both the gantry system and peristaltic pump in an efficient manner.

3.7 Further Studies

The current printer is still a prototype, with many aspects that can be refined and further developed. Further studies should investigate how different print materials and printing strategies work with the system. In this study, only water was used for the test prints, but other materials of different viscosities should be tested. Industrial materials such as pastes and resins should be tested, as well as other materials such as hydrogels. The viability of E. Coli cells was tested, but other more sensitive cell types should be tested such as mammalian tissues cell in relation to testing the applicability of this printer in tissue bioprinting. In addition, different printing strategies, in addition to the suspension strategy used here, should be tested for fabricating more complex objects in 3D space made of soft material. By utilizing the customizability of the RAMPS board, strategies that may utilize a laser for hardening resins or a second hot end extruder for printing plastic side by side with cell suspensions can be tested. By testing such materials and printing strategies, one can access how well these techniques used with liquid 3D printers utilizing a syringe deposition system carry over to a system using a peristaltic pump deposition system.

4. Conclusion

The prototype provides a proof of concept that liquid 3D printing can be accomplished with a peristaltic pump system, as well as at a much lower price and maintaining dimensional accuracy. Through extensive testing, the prototype has also proven to be able to fabricate objects utilizing suspension strategies, demonstrating the vast areas of application of such technology.

The project have also proved bioprinting can be accomplished with this printer without significant effects on cell viability. This is revolutionary as liquid 3D printing has never been studied using a peristaltic pump system and opens the door for a whole new type of deposition system. The project can have profound impacts on where and when liquid 3D printing can justifiably be used, not just in applications that warrant a high cost. Possible areas of expansion of use include medical applications in hospitals as well as manufacturing applications in material science. Additionally, by creating a platform for experimentation at such a low price, this can launch a wave of hobbyist experimentation with liquid printing, which has traditionally driven FDM printing development. The adaptability of the extruder assembly allows it to be mounted to any gantry system given a custom mount that can be easily 3D printed, facilitating easy creation and usage of the apparatus. As more studies are conducted utilizing a peristaltic pump system, 3D printing technologies using non-traditional materials will become more prevalent and efficient.

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