A Solid Free Form Fabrication Equipment to Manufacture Axisymmetric Parts with Improved Surface Quality

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Abstract

Competitive and Hobby grade Rocket makers quite often build custom nozzles. Solid freeform fabrication is most natural choice for Manufacturing of the Nozzles. Different geometries can be quickly manufactured and tested. However, staircase effect and limited accuracy of 2-1/2 based deposition prevents the design intent from fabrication. Additionally, using different blends of ceramic and sustaining the geometry during curing becomes challenging. This research presents a unique 3D printing system that dispenses ceramic to enable manufacturing of axi-symmetric parts as continuous bead. Relative motion of the material dispenser and rotational substrate as well as unique path planning enables a continually sculpted surface to reduce the staircase effects.

Introduction

Hobby grade Rocketry has recently become very popular with learners, educators and (Do It Yourself) DIYrs. These rockets may range in complexity and size. In addition to the design for aerodynamics the rocket builders' experiment with the controls, rocket fuel, rocket motor design, materials for rocket and motors etc. Different aspects of Robotics become natural vehicles for experimentation in science, technology, engineering, and mathematics (STEM) concepts. Additionally, many learners participate in various rocketry competitions. Mitchell et al. [1] implemented a 10-week project-based course in rocket building project that combines theoretical content from several subjects with a high-order learning approach (create, evaluate, analyze) to advance the engineering skills of students. Eugene [2] suggests a program on practical rocketry that introduces young students and their teachers to the aerospace environment-including the design, build, and fly process; teamwork; and competition. The American Rocketry Challenge (ARC) is an aerospace design and engineering event for teams of US secondary school students (6th through 12th grades) run by the NAR and the Aerospace Industries Association (AIA) [3]. TARC is one of the most popular high school rocketry competitions in the United States. Teams of student's design, build, and launch rockets to meet specific altitude and time duration goals. The competition often involves restrictions on rocket size and motor type, fostering creativity and problem-solving. NASA Student Launch [4] is another research-based, competitive, experiential exploration program that provides cost-effective research and development of rocket propulsion systems for middle and high schools, colleges, and universities across the nation. Teams design and launch rockets with scientific payloads. Teams must adhere to specific guidelines and safety regulations.

While primarily a college-level competition, some high school teams may participate in (Intercollegiate Rocket Engineering Competition) IREC. It challenges teams to design and launch high-powered rockets with specific objectives, such as reaching a particular altitude or deploying a payload.

In addition to these competitions, many regions have local rocketry competitions for high school students, organized by schools, community clubs, or educational institutions with varying rules and objectives. As a part of learning and experimentation, many teams design and manufacture their own rockets. With the focus on altitude gain and accuracy, many participants choose to design their own rocket motors.

The research presented in this paper is based on developing nozzles for hobby grade rockets. The authors intended to design, manufacture and then experiment with different geometries popular within the hobby grade of rocket motors. To manufacture motors for experiment, 3D printing was a natural choice. Availability of cost-effective 3D printer to manufacture heat resistant ceramic materials, cermits and other alloys was a limitation. Additionally, standard off the shelf as well as open-source 3D printing platforms use STL file, a 2-1/2 axis spatial manufacturing with zigzag path to deposit materials in sequential layers. Each being a challenge, authors pivoted to developing a novel 3D printing method amenable to axi-symmetric parts.

Over the course of development, availability of both propellants as well as ceramic material became a limiting factor to build actual propulsion units. However, authors realized that the unique manufacturing method developed by them had many novel and unique features. The research shifts from traditional cartesian system-based approach to a polar coordinate-based approach for representation and manufacturing. The paper presents the details of (1) 3D printer architecture (2) part and process representation (3) input file for the electrical actuator drives (4) extrusion and delivery of the ceramic materials. We present the preliminary results and some of the future developments based on findings.

Modeling Axisymmetric parts

Traditional additive and subtractive manufacturing processes are based on the geometric features of the parts being manufactured. For example, axi-symmetric parts may be manufactured using a lathe. By adjusting the rotational speed, pitch and tools, the process is optimized for rough machining and then fine machining. Similarly welding based repair of axisymmetric parts will benefit by adding the material while substrate is rotated about its axis. On the contrary, the 3D printers due to 2-1/2 axis architecture is limited to depositing the material that may not necessarily align with the geometry (Figure 1). The material is deposited such that the end effector follows some variant of zigzag path. Additionally, the part will be susceptible to staircase effect (Figure 1). If part features and surface smoothness is critical, the surface is smoothened by post-processing.

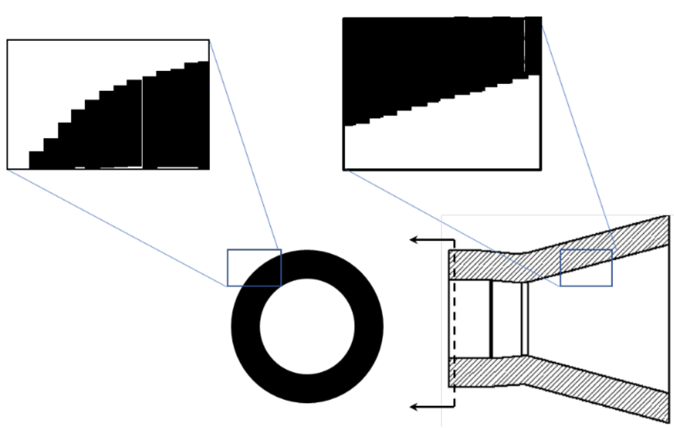

Figure 1 : Staircase effect and

The work reported in this research suggests an alternate architecture. The architecture is limited to axisymmetric parts.

6-axis robotic systems have been used to fabricate various axisymmetric and similar parts[5]. Yaou et. al [6] reported a robot controlled LBDMD system that couples a 6-axis robot arm with an additional 2-axis tilt and rotatory positioning system to manufacture complex revolved parts. Additionally, they coupled 2-axis tilt and rotatory system and a hybrid slicing method to map the overhanging structures of a revolved part. Ramos et. al [7] reported fabrication of metallic solid objects using an experimental spiral growth selective laser melting (SG-SLM) 3D printer. The system incorporates a cylindrical coordinate system, instead of the ubiquitous Cartesian coordinate system found in commercial powder bed fusion selective laser sintering/melting (SLS/SLM) equipment. The suggested systems above use expensive multi-DOF robotic manipulator.

The process to manufacture suggested in this work focuses on creating a continuous path for material deposition. Figure 2 describes an improved approach where material is deposited as circular contours [8]. However, when transitioning from one layer to another, dwelling is introduced. Surface is not smooth along the dwelling point. Excess material added during the transition may be controlled by limiting the material flow. However accurate estimation of material and other physical properties of the material such as surface tension will impact the surface quality. Deposition processes that are based on heat energy (lasers, welding, polymer melting) will see higher energy input during the dwell, hence cause geometric as well as microstructural variations.

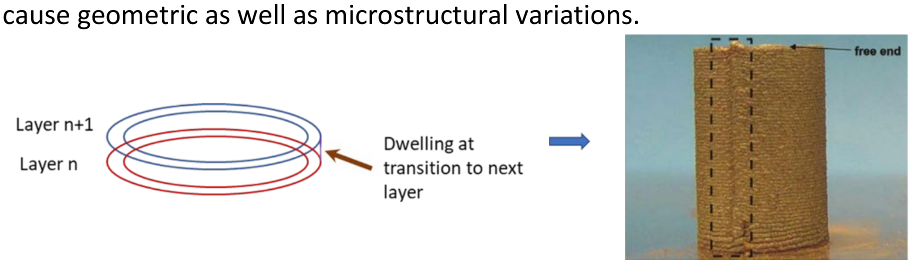

Figure 2 : axisymmetric part with contours and dwell at layer transition

As described in Figure 3, we are using a continuous path to overcome the dwell. The material flow is uniform across the path; however, the speed of the end-effector is adjusted to maintain uniformity.

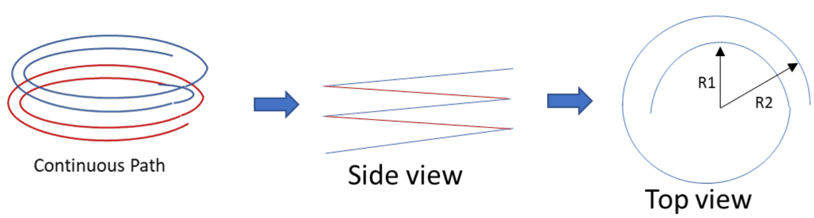

Figure 3 : Schematic of continuous path

System description

Figure 4 Describes the system used for 3D printing. The system comprises of 2 linear actuators, one rotary actuator and material dispenser. Vertical linear actuator (Y) traverses in vertical direction at a constant speed during the material deposition process. Second linear actuator (X) actuates the material deposition end-effector in horizontal direction to adjust the radial distance.

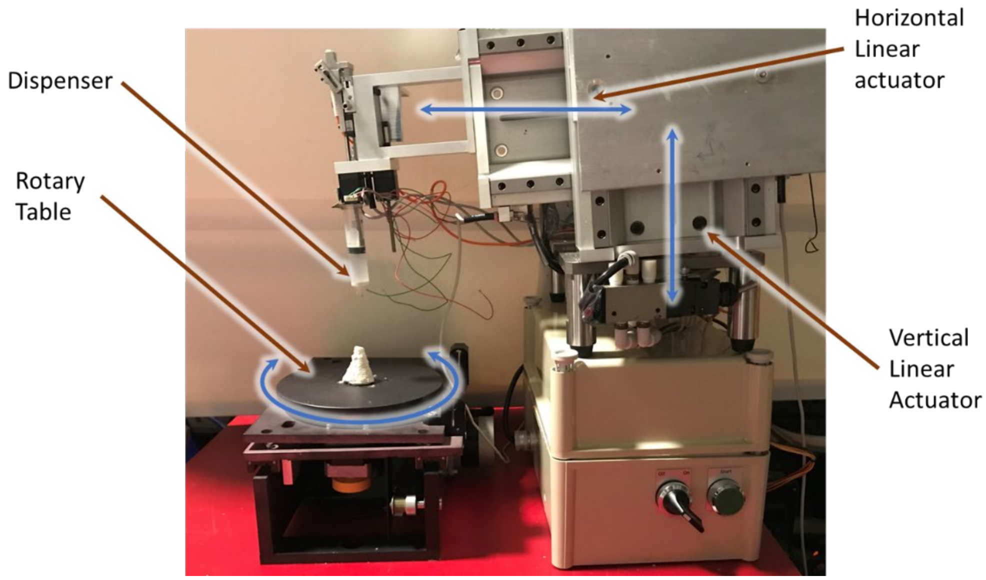

Figure 4 : 3D Printer Schematic

The rotary table (R) spins the substrate. The linear actuator uses a Misumui linear precision guide driven by haydon-kirk E46443-05-028ENG linear actuators. The rotary table is actuated using a general purpose NEMA23 stepper motor. The system is controlled with open-source Arduino stepper motor module.

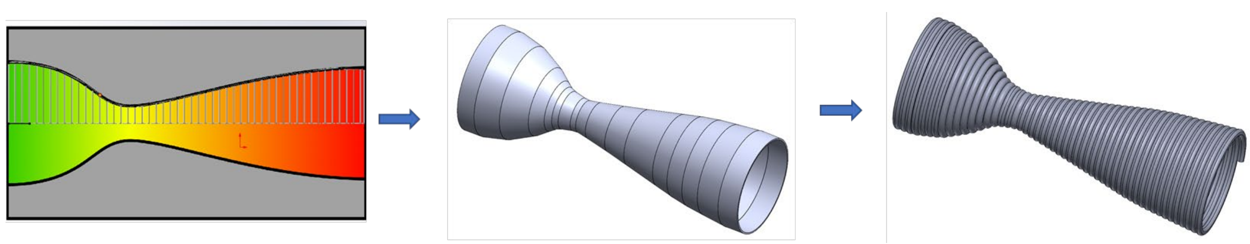

Figure 5 : Modeling the nozzle geometry based on geometric simplification and continuous path

Coding for the system was done per part basis. Figure 5 describes a sample axisymmetric geometry. Part is divided into multiple segments and then a continuous spiral is modeled. The geometric coordinates of the spiral are identified and converted to corresponding stepper motor speeds. Given the scope of this project and similarity of nozzle geometries we wrote a custom speed-based program. Authors intend to write a general-purpose software that enables usage of open-source libraries to create GCodes in future.

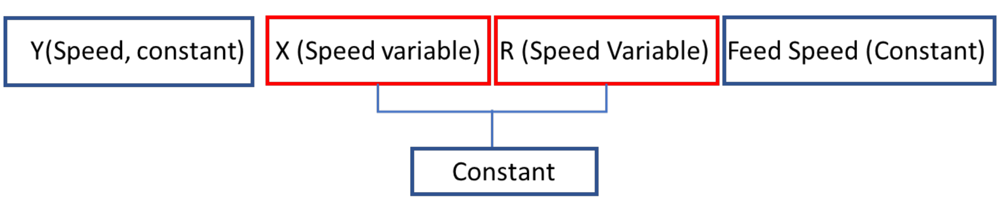

Figure 6 : Code implementation schematic

As described in Figure 6, to enable uniform flow of material, the vertical speed is constant. Material is fed at uniform rate. Adjustment between the Radial and rotational speed is done in such a way that the rate of material dispense is constant throughout the manufacturing.

Material and material dispensing System

High performance ceramics, such as Ceramic Matrix Composite (CMC) are used for liquid rocket engines [9,10]. The materials are expensive and have limited availability. Additionally, the manufacturing process for the materials is specialized. As described in the earlier sections, the research work started with assumption of ease of material; however, the material could not be available therefore we pivoted to using an easily available ceramic Calcium sulfate hemihydrate (10034-76-1). For testing purposes slurry was created with 1-part water and 2-part Ceramic by volume.

Figure 7 Universal Syringe adapter

Initial attempts for material dispensing using an off-the-shelf Universal syringe adapter (Figure 7) were not very successful. The plunger is actuated pneumatically. Pneumatics could not be controlled to sustain uniform flow and material flow is non-uniform. The pneumatic system was replaced with an electronic linear actuator. Controlling the rate of actuation as well as the load is significantly improved with electronic actuation system. The system comprises of a screw that is actuated using stepper motor.

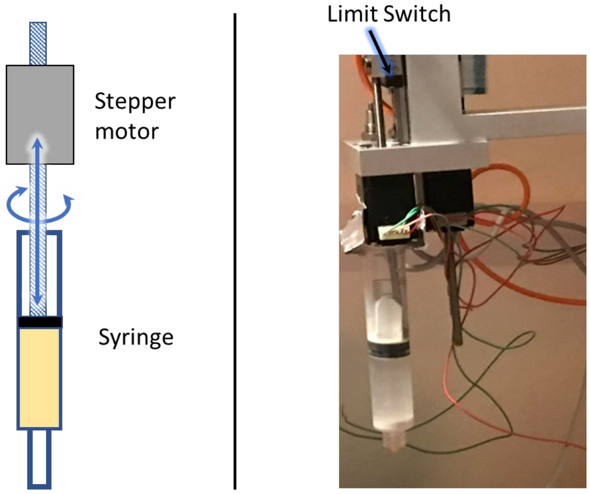

Figure 8 : Stepper Motor actuated material dispense unit

The material dispensing unit utilizes a 10mL Luer Lock Syringe as reservoir and dispenser. The piston for the syringe is actuated using a Haydonkerk Size 8 Series 21000 Non-Captive Linear Actuator (Figure 8). The actuator is 3.56mm screw with 0.04mm lead per step.

Initial Results

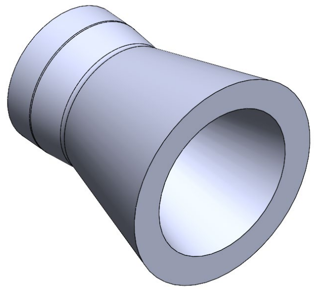

Figure 9 : CAD model of the tested part

Figure 9 describes the geometry that was tested for axisymmetric manufacturing. Part is 50mm tall. Two set of syringes were tested for material dispensing.

Pass 1 Pass 2 Pass 3

Figure 10 : manufactured parts

Pass 1 Implementation: First experiment for dispensing was performed with 16 Gauge needle (1.6mm). The slurry starts to run and therefore frequent interventions are needed for the material to retain the shape. With the build up of the semi-solid liquid, at approximately 5mm thickness, the material structure starts to sag and part is not able to retain its shape as intended.

Pass 2 Implementation: Second experiment is performed with 18 Gauge needle (1.2mm). We see a reduction in the slurry run. However, settling of the particles within the material reservoir causes intermittent obstructions to material flow; therefore, frequent interventions are required. We also adjusted the ratio of water in the slurry to 1-part water to 2.25-part ceramic. The uncured material is structurally stable; however, at approximately 7mm thickness material starts to deform.

Pass 3 Implementation: Third experiment is based on improvements observed in the phase 2. Material is dispensed using 18 Gauge needle (1.2mm). The slurry has 1-part water to 2.25-part ceramic. The settling of material in the reservoir is reduced by tapping at interval of approximately 2 seconds. The ceramic is partly cured on the top surface by blowing hot air using 1200W hair dryer. The Slurry run is minimized and the instances of material flow obstructions are reduced.

Conclusions and Future work

A 3D printer and process that can be used for printing axi-symmetric parts was demonstrated. Part specific code was implemented. The system was implemented using open source control hardware.

Process was improved by (1) adjusting the ceramic-water ratio (2) preventing the ceramic particles from settling (3) curing the ceramic along surface using hot air. The development was motivated with intent to developing nozzles for hobby grade rockets; however, timely material availability limits the developments. The researchers will improve the printer by adding modules that prevent ceramic material from settling. Additionally, researchers would create an code to convert any axi-symmetric geometry to a G-Code for implementation with open-source hardware.

References:

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1. R. Mitchell Spearrin, Fabio A. Bendana, "Design-build-launch: a hybrid project-based laboratory course for aerospace engineering education" , Acta Astronautica, Volume 157, 2019, Pages 29-39,ISSN 0094-5765
2. Fleeman, Eugene. "Small air rocket design, build, and fly program for aerospace engineering education and outreach." 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit. 2004.
3. https://www.nar.org/team-america/
4. https://www.nasa.gov/stem/studentlaunch/home/index.html
5. Dwivedi, Rajeev, Srdja Zekovic, and Radovan Kovacevic. "A novel approach to fabricate uni-directional and branching slender structures using laser-based direct metal deposition." *International Journal of Machine Tools and Manufacture* 47.7-8 (2007): 1246-1256.
6. Ding, Yaoyu, Rajeev Dwivedi, and Radovan Kovacevic. "Process planning for 8-axis robotized laser-based direct metal deposition system: A case on building revolved part." *Robotics and Computer-Integrated Manufacturing* 44 (2017): 67-76.
7. Ramos-Grez, Jorge Andrés, Javier Vera-Hoffmann, and Magdalena Walczak. "Spiral growth selective laser melting of axisymmetric objects from Cu-Ni–Sn alloy powder: a mass rate efficiency and physical properties study." *The International Journal of Advanced Manufacturing Technology* 126.3-4 (2023): 1055-1066.
8. Zekovic, Srdja, Rajeev Dwivedi, and Radovan Kovacevic. "Thermo-structural finite element analysis of direct laser metal deposited thin-walled structures." *2005 International Solid Freeform Fabrication Symposium*. 2005.
9. Herbell, Thomas P., and Andrew J. Eckel. "Ceramic composites for rocket engine turbines." SAE Transactions (1991): 254-260.
10. Bach, Christian, Frank Wehner, and Jan Sieder-Katzmann. 2022. "Investigations on an All-Oxide Ceramic Composites Based on Al2O3 Fibres and Alumina–Zirconia Matrix for Application in Liquid Rocket Engines" Aerospace 9, no. 11: 684. https://doi.org/10.3390/aerospace9110684