Student Benefits from Participation in a NASA-mentored 3D Printing Research Project

Andrew Jones
Dept. of Computer Science
North Dakota State University
Fargo, ND 58102
andrew.jones.4@ndsu.edu

Jeremy Straub
Dept. of Computer Science
North Dakota State University
Fargo, ND 58102
jeremy.straub@ndsu.edu

Abstract

The 3D Printing Material Use Optimization project allows engineering and computer science students to gain research experience. The project, which has been undertaken in conjunction with NASA's Jet Propulsion Laboratory (JPL), involves working to develop support structures that will reduce the amount of filament used for 3D printing objects. This is in contrast to many existing support structure algorithms that are primarily concerned with optimizing print quality. The idea behind this shift of focus is to accommodate situations where filament is far more expensive than typical – such as on the International Space Station (ISS), in deep space or on another Planet's surface. This paper provides an overview of this project and the work of the students participating in it. It also assesses the educational benefits provided by the project and the correlation between project activities and the educational benefit produced.

1 Introduction

The 3D Printing Material Use Optimization project allows engineering and computer science students to gain research experience. The project, which has been undertaken in conjunction with NASA's Jet Propulsion Laboratory (JPL), involves working to develop support structures that will reduce the amount of filament used for 3D printing objects. This paper provides an overview of this project and the work of the students participating in it. It also assesses the educational benefits provided by the project and the correlation between project activities and the educational benefit produced.

2 3D Printing

3D printing is a process of joining materials to make objects from 3D model data, usually layer upon layer [1]. It has been used for various commercial purposes, such as fabricating prototypes, replacement parts, automobile components, aircraft components, robotic components, hearing aid molds, dental crowns, eyeglass frames, and prosthetic limbs [2][3][4][5].

A common 3D printing method, widely used in modern commercial 3D printing, is Fused Filament Fabrication (FFF). This method involves extruding polymer through heated nozzles to create a part's cross sections [6]. Other common 3D printing methods include the use of an ultraviolet laser to harden a photosensitive polymer (Stereolithography), or using a laser to selectively melt metal or polymeric powder (Laser Sintering) [2][7].

2.1 Applications in Space

Experiments conducted by Made In Space, Inc. and NASA demonstrated that certain 3D printing techniques, such as Fused Filament Fabrication (FFF), can be effective in microgravity environments [8][9]. In fact, there is currently an Additive Manufacturing Facility setup on the ISS. The facility is capable of printing using a wide variety of thermoplastics and has the capability to craft parts, entire experiments, and tools [10].

In addition, there are 3D printing techniques and technologies being evaluated for use on the surface of another planet or moon. One of the techniques being considered is the use of a D-shape printer for building structures out of regolith on the Earth's moon. The D-Shape printer utilizes stereolithography to bind sand with an inorganic binder to create stone-like objects [11]. Another technique being evaluated is Contour Crafting (CC), which is a layered printing technology that extrudes concrete through a computer-controlled nozzle [12].

3 Project Overview

The goal of this project is to develop support structures that will reduce the amount of filament used for 3D printing objects. This is in contrast to many existing support structure algorithms, which are primarily concerned with optimizing print quality. The idea behind this shift of focus is to accommodate situations where filament is far more expensive than typical – such as on the International Space Station (ISS), in deep space or on another Planet's surface. To do this, the project explores the development of an infill structure that isn't a 2D design that is built up layer by layer, but instead a 3D support structure that is generated by an algorithm that designs a fill pattern based on the shape of the object being printed and tolerance constraints inputted by the user.

The structure of the project itself consisted of an initial analysis of algorithms to generate support for 2-dimensional grid points. The second phase was then to expand on this and generate algorithms to support points in 3-dimensions. In this section, the progress that has been made on the various stages of the project is discussed.

3.1 Initial 2D Grid Analysis

The starting phase of the project involved supporting every top grid point with a support member (column). There were two types of support members that could be used, a vertical line between points on the same column and one row apart, and a diagonal member that could connect points that were one row and one column apart. The objective was to use as little material as possible – with each member type having a defined cost.

An optimal solution based on these constraints was determined by the group and published in [13]. Figure 1 depicts a sample of the solution output for varying grid sizes.

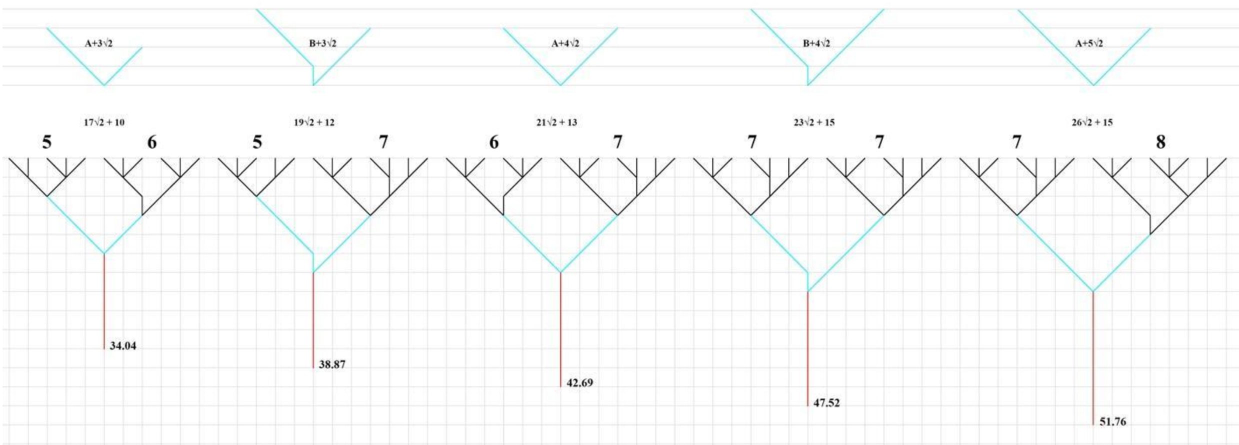

Figure 1: 2D Support Structure.

3.2 Towards 3D Infill

The next phase of the project involved developing a 3-dimensional version of the support generating algorithm. The two teams, mechanical and software, went through various stages in developing a potential solution. These stages are now discussed.

3.2.1 Software Team

In this phase, the software team's initial goal was to research filetypes that can store 3D model data. The notion here was to find a filetype that had a format that allowed easy model generation through code, as opposed to the need for proprietary file formats and graphical user interfaces. The generic '.obj' filetype was chosen for this purpose.

The next step for the software team was to develop a program that could generate 3D objects with a structure that was determined by the mechanical team. The program, in its current form, is being written in Java. This was chosen due to the programming language preferences of the software team. The end result/deliverable will be focused on the algorithm itself, thus making this program a useful tool for development rather than a deliverable.

During this development process, test shapes and patterns were tried and one in particular, given the working title of "pyramid infill," has been used as an initial prototype structure in the project. The pyramid infill structure is depicted in Figure 2.

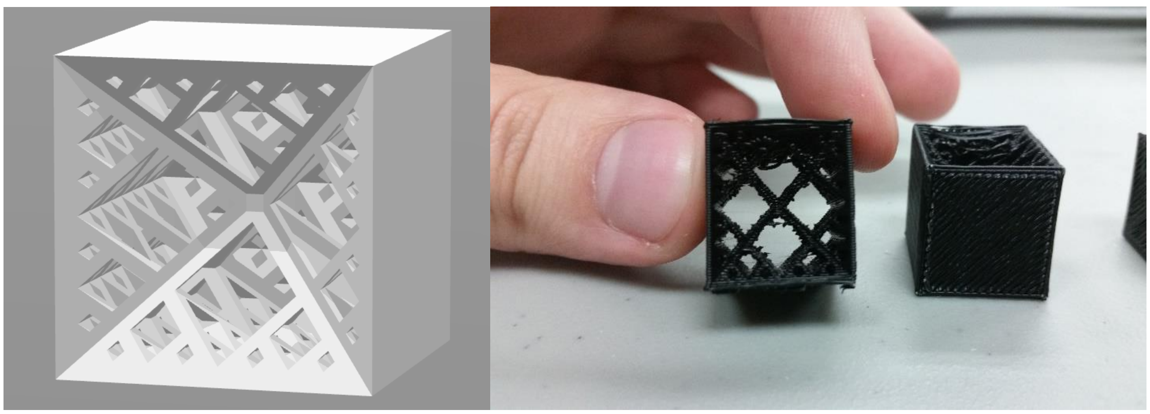

Figure 2: 3D Model of the pyramid infill (left). 3D Printed cube with pyramid infill (right).

3.2.2 Mechanical Team

With this phase of the project having a relatively high level of difficulty, the mechanical team has gone through many ideas and prospective solutions. The initial strategy was to arrange small 'building blocks' in a 3D grid, with the blocks forming into an infill pattern starting from the base and ending at the top. However, one of the constraints was that the structure couldn't have material protruding at angles greater than 45 degrees (3D printers can encounter problems printing such structures). In addition, there was a dilemma where keeping blocks only in their respective grid (one block per grid) made it so the diagonal grid connections had very little surface area to connect without intruding on adjacent grid locations. This eventually led to the notion of only considering grid points, and not focusing on using blocks that fit inside a grid.

The mechanical team also conducted analysis on some of the test patterns that were constructed by the software team. A compression test was performed on the pyramid infill, which uses an amount of filament equivalent to 23% rectilinear infill. It was found that the pyramid infill could withstand a higher compressive load than the 23% infill and going further it withstood more than 30% infill. The data from this experiment is given in Table 1 and Table 2.

Sample #	Max Compressive Stress (Psi)	Local Peak Maximum (Compressive load 10 % Change) (kgf)	Extension at Local Peak Maximum (Compressive load 10 % Change) (mm)	Load at Local Peak Maximum (Compressive load 10 % Change) (kgf)
1	13.470	455.281	-2.704	-455.28055
2	14.364	485.511	-1.836	-485.51134
3	15.374	519.652	-1.727	-519.65167
4	15.289	516.770	-1.766	-516.76984

Table 1: Cube with 30% rectilinear infill.

Sample #	Max Compressive Stress (Psi)	Local Peak Maximum (Compressive load 10 % Change) (kgf)	Extension at Local Peak Maximum (Compressive load 10 % Change) (mm)	Load at Local Peak Maximum (Compressive load 10 % Change) (kgf)
1	18.199	615.110	-5.483	-615.11007
2	18.273	617.633	-5.574	-617.63333
3	18.505	625.473	-5.461	-625.47301
4	15.321	517.836	-6.167	-517.83607

Table 2: Cube with Pyramid Infill.

4 Assessment of Educational Benefits

This section assesses the educational benefits provided by the project. First, the educational disciplines from which student participants are involved with are presented. Then, the educational benefits for students involved in the problem-based learning structure of this project is discussed.

4.1 Educational Disciplines

The project involves students from a diverse range of STEM fields, including mechanical engineering, industrial and manufacturing engineering, physics, computer science, and computer engineering. Students participating in the project receive course research credit for their work, and gain design, development, testing and project management skills. In addition, the project encourages students to work together, take the initiative with new ideas, and learn from the project mentors from NASA JPL. To this end, working with industry professionals at NASA JPL provides students with a meaningful opportunity - as well as participating in something that looks great on a resume.

4.2 Problem Based Learning

According to Savory [14], problem based learning (PBL) is an instructional (and curricular) learner-centered approach that empowers learners to conduct research, integrate theory and practice, and apply knowledge and skills to develop a viable solution to a defined problem. In this approach, students have the responsibility for their own learning. This can provide an incentive for students to become more intrinsically motivated to learn, and potentially develop or enhance self-directed, lifelong learning skills [15]. In addition, the problem often is an integration of a wide range of disciplines or subjects [14]. Thus, collaboration is essential, with many students becoming more effective collaborators as a result.

Conclusion

In this paper, an overview of the 3D Printing Material Use Optimization project was detailed. The educational fields involved, and the potential educational benefits of the project were discussed. The project is currently ongoing.

References

[1] C. K. Chua and K. F. Leong, *3D printing and additive manufacturing : principles and applications*. 2015.

[2] T. Campbell, C. Williams, B. Garrett, and O. Ivanova, "Could 3D Printing Change the World?," *atltantic Counc.*, 2011.

[3] B. Berman, "3-D printing: The new industrial revolution," *Bus. Horiz.*, vol. 55, no. 2, pp. 155–162, 2012.

[4] C. Schubert, M. C. van Langeveld, and L. A. Donoso, "Innovations in 3D printing: a 3D overview from optics to organs," *Br. J. Ophthalmol.*, vol. 98, no. 2, pp. 159–161, 2014.

[5] A. Jones and J. Straub, "Concepts for 3D Printing-Based Self-Replicating Robot Command and Coordination Techniques," *Machines*, vol. 5, no. 2, p. 12, Apr. 2017.

[6] T. Pfeifer, C. Koch, and L. Van Hulle, "OPTIMIZATION OF THE FDM™ ADDITIVE MANUFACTURING PROCESS," in *Proceedings of the Annual Technical Conference (ANTEC) of the Society of Plastics Engineers*, 2016.

[7] J. McMillan and M. Johnson, "Matrix Design and Algorithm for 3D Printing Material and Cost Reduction," in *AIAA SPACE and Astronautics Forum and Exposition*, 2017.

[8] M. P. Snyder, J. J. Dunn, and E. G. Gonzalez, "Effects of microgravity on extrusion based additive manufacturing," in *AIAA SPACE 2013 Conference and Exposition*, 2013, pp. 1–6.

[9] A. Jones and J. Straub, "Self-Replicating 3D Printed Satellites," 2017.

[10] M. Snyder and N. Werkheiser, "Additive Manufacturing Facility (AMF)," 2016.

[11] G. Cesaretti, E. Dini, X. De Kestelier, V. Colla, and L. Pambaguian, "Building components for an outpost on the Lunar soil by means of a novel 3D printing technology," *Acta Astronaut.*, vol. 93, pp. 430–450, 2014.

[12] N. Leach, "3D printing in space," *Met. Powder Rep.*, vol. 72, no. 1, p. 64, 2017.

[13] R. Nelson *et al.*, "Additive Manufacturing (3D Printing) Material and Cost Reduction Algorithm Proof," in *AIAA SPACE and Astronautics Forum and Exposition*, 2017.

[14] J. R. Savery, "Overview of Problem-based Learning : Definitions and

Distinctions," *Interdiscip. J. Probl. Learn.*, vol. 1, no. 1, pp. 9–20, 2006.
[15] C. E. Hmelo-Silver, "Problem-based learning: What and how do students learn?," *Educational Psychology Review*, vol. 16, no. 3. pp. 235–266, 2004.