# Preliminary Design of a 3D Printing System for Creating Infinitely Large Structures in Space

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## ABSTRACT

As interest in the space environment grows, the demand for larger and more capable space systems will follow. A possible solution to fill this demand is additive manufacturing in the form of 3D printing. This paper showcases a working preliminary system to 3D print large structures in space from a small satellite. This is achieved by replacing the normal Z axis control of a conventional CoreXY fused deposition modeling (FDM) 3D printer with a system to move along an infinitely extendable printed track. Having the ability to print and then move along this track creates a cycle of printing and movement that can extend the Z axis infinitely. The proposed track system utilizes three faces of the four-faced track allowing for one face to be used as a connection point for other structures. In demonstration, a cylindrical tube was printed adjacent to the track to simulate the creation of a space station capsule. While the CoreXY printer was useful for demonstrating the Z axis control of the track system, a robotic arm with an attached printer head would best utilize the unique Z mechanism. With future work this robotic arm system could start printing tracks in all directions that could then be switched to and from allowing for the print volume to be extended infinitely in all three dimensions. This would provide small satellites the ability to build structures infinitely beyond their size.

## INTRODUCTION

Additive manufacturing in space is not a new concept. The ISS has operated a 3D printer for over a decade in the micro gravity environment while multiple tests on earth have confirmed the ability to 3D print under vacuum.[2,11,14] All of these tests show a potential for additive manufacturing in space. The benefit of 3D printing objects in space comes down to three things: allowing for unique architectures, avoiding the launch environment, and overcoming volume limitations of the rocket fairing.[5] While 3D printing in space is feasible, to truly capture all benefits, a printer should not be limited by the rocket fairing volume. Most current 3D printers can only produce objects smaller than themselves. Unless assembly is an option, this translates to launching a 3D printer the size of a space station to print a space station. To transport a 3D printer of that size to space is cost prohibitive for both its mass and volume. Instead, a relatively small printer that is not restricted to its own build volume is ideal. Understanding this problem, many institutions such as NASA, AFIT, Redwire, Mitsubishi, and others have described promising solutions to create a relatively small printer with a build volume larger than itself.

NASA's concept utilizes robotic arms to grab onto printed structure and move the print head. The system was designed to create large apertures but theoretically could be used to print any large structure.[15]

AFIT's concept features a tube crawling 3D printer that extends the tube that it moves along. The concept is also designed to print the tube in branching directions.[5]

Redwire Space developed a working prototype printer as part of NASA's On-Orbit, Servicing, Assembly, and Manufacturing 2 (OSAM-2) project. Their design prints beams for extending solar arrays in space.[10]

Lastly, Mitsubishi Electric Research Lab developed a working prototype 3D printer satellite system for producing large communication dishes. The system moves the dish on an extendable boom relative to the print head.[9]

Currently, none of these concepts feature a prototype 3D printer that is both functioning and general use such that it can create a variety of structures larger than itself. Either there is no working prototype (NASA and AFIT) or the design is only capable of printing a single type of structure (AFIT, Redwire, Mitsubishi).[5,9,10,15] The goal of this research is to develop and demonstrate an improved general use system for creating any large structure in space.

## METHODS

### *Defining the Problem*

The first challenge for 3D printing any giant structures in space, evident in the above concepts, is making a printer that moves in space relative to the printed structure. This allows a printer to create something outside of its own volume. The second challenge is ensuring that the 3D printer can create any large structure such that it is general use. Together, the total challenge is creating a printer that can move in space relative to the printed structure without limiting what the printed structure can be.

### *Solution*

The solution chosen for this research is similar to that of the designs in relevant literature, such that it can attach onto a previously printed structure. This avoids using any thrusters that would require a constant supply of fuel. What's unique about the 3D printer outlined in this paper is that it attaches to a consistent printed track physically connected to the complex structure that is also being printed. Having a track to hold onto prevents the complexity of grabbing onto the varying shapes of the structure and allows a simple movement mechanism. Second, replacing the Z mechanism with a printable track allows the Z axis to be extended infinitely. Lastly, since the track connects to any complex structure the printer is not limited in the shapes it can print. This feature allows the printer to be general use.

To ensure precise Z movement along the track, a central threaded worm interfaces with a corresponding threaded surface on a rectangular track or rack creating a worm-rack system. Two sets of guide wheels follow on each side of this rectangular track along slots visible in Figure 5.

The worm-rack allows for more precise movement because it requires more turns compared to a similarly sized traditional gear-rack mechanism to move the rack the same distance. This means the same stepper motor using a worm-rack can make finer adjustments which translates to finer Z adjustments. Precise Z movement is important for 3D printing since layers usually range between 0.12 to 0.2 mm thick. Any variation in layer height creates inaccuracies in the part that could translate to failed prints. Additionally, the Z mechanism was placed in the corner of the build area. This allows for improved stiffness in the mechanism and again allows for more accurate adjustments. An important note for the design is that it lacks a traditional build plate. This allows the printer to extend parts infinitely without obstruction in the Z axis. This also means that an initial segment of this track is required to start the system printing.

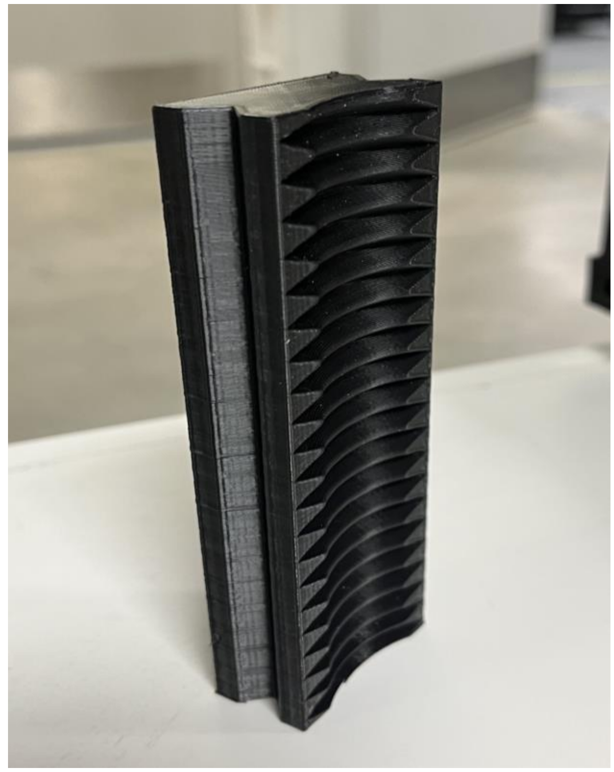

**Figure 1: 3D Printed Rectangular Track/Rack with Threaded Surface and Slots**

### *Initial Concept Test*

After determining the mechanism of the concept, a small mockup visible in Figure 2 was created to confirm that a 3D printed worm-rack would work with the extra friction as a replacement for the normal Z mechanism. A common hobby stepper motor was used in addition to a gear system with a 2:1 gear ratio. A set of guide wheels was also added to interface with the slots in the track and maintain linear movement. After verifying the function of the mechanism, work could then begin on making the final structure, hardware, software, calculations, and adjustments.

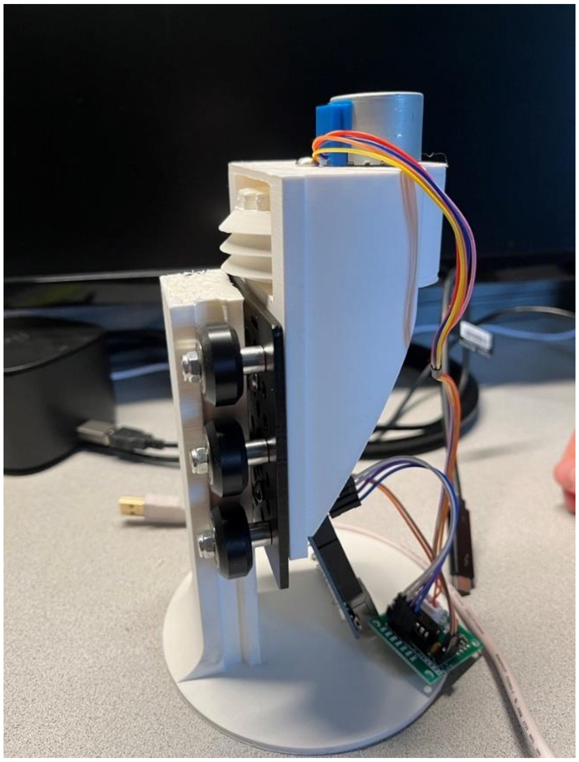

**Figure 2: Z Mechanism with Worm-Rack System for Concept Test**

***Printer Structure***

For the Z mechanism design, the Z movement of the track (the build plate) is provided with an independent motor. As a result, a printer that moves the build plate in the Z direction with an independent motor is necessary for the mechanism's integration. The two printer types possible to integrate with such a Z mechanism are a robot arm with a printer head attachment or a CoreXY printer. Ideally, a robotic arm would be used to allow for the most freedom moving along the track but for this research such a system was cost prohibitive. That left a CoreXY printer as the only option to demonstrate the proof of concept.

The chosen printer for the system was the Tronxy X5SA Pro. This choice mainly came down to cost. With a printer chosen, design sketches for the final design were created. These are visible in Figure 3 and showcase the proposed Z mechanism track with a mock space station attached.

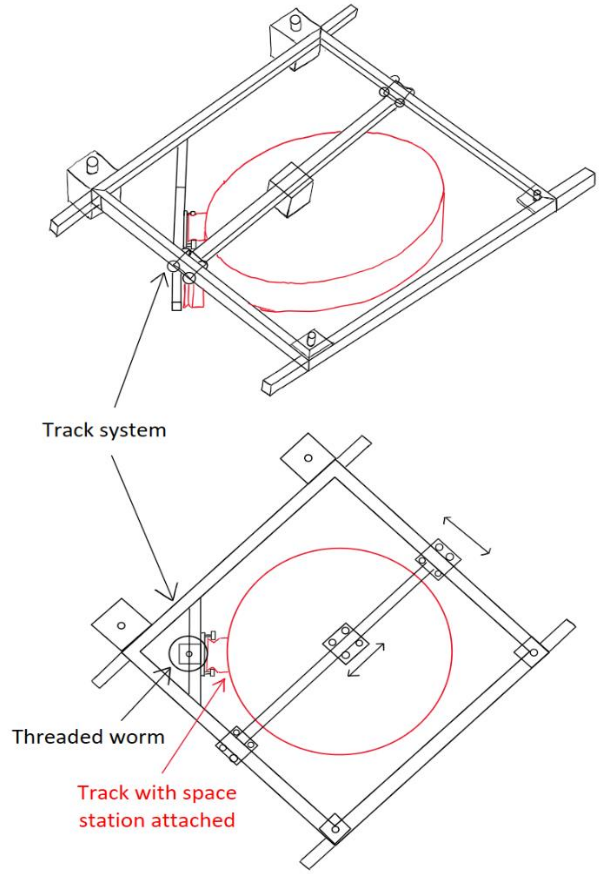


**Figure 3: Concept CoreXY 3D Printer with Z-Mechanism**

With sketches and the printer in hand, work began designing the system in Fusion 360 with the measurements of the Tronxy. The design reused most of what the Tronxy already included but removed the Z mechanism lead screws and build plate. In their place, the new track mechanism was integrated mirroring largely what was created in the initial concept test but with slight changes for integrating with the Tronxy.

Instead of a hobby stepper motor, the worm was changed to be powered directly by the Tronxy's NEMA (National Electrical Manufactures Association) 17 stepper motor, to improve precision and power.[7] To ensure the accuracy of the printed threads, the worm utilized large threads with a maximum 45° overhang that could easily be 3D printed. This meant that the corresponding geared surface of the track could also be easily 3D printed, visible in Figure 1. The thread angle was kept as small as possible while maintaining the thread thickness to decrease the travel of the rack with every revolution and to increase the accuracy with every movement of the stepper motor. The diameter of the worm was also carefully managed to allow it to extend beyond the stepper motor and into the track but not so deep that it would interfere with the grooved tracks for the guide wheels.

As seen in Figure 1, the track mirrored the design of a piece of T-channel aluminum with the addition of a geared surface that corresponded with the worm. The track was cut into sections at points that allow for sections of track to be stacked without any change in the thread pattern. This is important to allow the system to print infinitely. Since all track sections end at a set point in the pattern of the thread, additional sections are easily added. On the backside of these tracks is a flat face that easily allows for structures to be printed from it. Since the track operates in the corner of the printer, the area of the print bed is maximized.

The guide wheels were reused from the initial concept. However, instead of six wheels, the design was changed to four. Reducing the number of wheels provided improved tolerance for the system. This allowed the system to function even with slight inconsistencies in the 3D printed track.

Next, parts were designed to mount the Z motor mechanism, including both the worm and guide wheels, to the rest of the printer. Careful measurement of the Tronxy's hot end path ensured that the Z mechanism remained out of the way when printing and that the track was within the normal build plate area so it could be extended. T-channel screws were re-used from the Tronxy to attach the entire mechanism to the frame of the printer. The worm was placed above the stepper motor knowing that over time gravity might otherwise try to pull it off. With this configuration, the force of gravity always kept the worm attached to the stepper motor. This assembly is visible in Figure 4.

All structural parts not reused from the Tronxy or the guide wheels were printed on the Creality Ender 3 V2.

**Figure 4: Z Mechanism with Guide Wheels and Worm Mounted to Printer**

### *Printer Electronic Hardware*

After noticing one of the integrated stepper drivers for the procured printer no longer worked, an Arduino system was chosen as a replacement since team members had previous experience creating a DIY 3D printer with it.

The chosen microcontroller was an Arduino Mega with an ATMEGA2560-16AU chip. This chip offers 54 Digital I/O (Input/Output) pins and 16 analog pins allowing for easy feature integration.[6] On top of the Arduin Mega a stepper driver RAMPS (RepRap Arduino Mega Pololu Shield) board was added.[12] The RAMPS board is a modular board that can attach on top of the Arduino Mega, hence the "shield" in the name. [12] This modular board includes multiple attachments for hot ends, stepper drivers, heated beds, end stops, etc. There are redundant aspects across the board allowing for ease of customization. The board chosen was version 1.4, a version commonly modified and used in printers developed by Prusa Research and UltiMaker.[12] This board was also used as the main hardware to base Marlin software from (an open-source software developed by RepRap in 2011, commonly used in Prusas).[4] This background information assured that these parts would be capable of accomplishing the abnormal nature of this printer.

The stepper motors were SL42STH40-1684As re-purposed from the Tronxy X5SA Pro. This stepper motor is a variant of the NEMA 17 stepper motor, a commonly used stepper motor in the RepRap 3d printing community.[7] These stepper motors allow for high precision with 200 steps per revolution and high torque with each phase rated to draw 1.68 amps (3.36 amps total) while providing a holding torque of 40 N*cm.[7]

Due to the high power and complex control nature of stepper motors, a stepper motor driver is used to bridge the link communication between the Arduino's digital I/O pins and the stepper motor's phases. Certain stepper drivers can even provide increased accuracy with a concept called micro-stepping that allows for refined movement to 1/16, 1/32, and even 1/64 of a step on the motor. The A4988 stepper driver is one of the most popular stepper drivers known as a "bullet-proof workhorse" by the RepRap community.[1] It has the capability to micro step to 1/16. The RAMPS board is designed to hold up to five stepper drivers. Only four were necessary: one for each CoreXY motor, one for the extruder, and one for the Z axis.

Initially the A4988 driver was chosen based on its popularity and reviews, however after printing initial designs it was evident the motors were causing a lot of excess vibrations. These vibrations were created by the stepper driver switching on and off at a high frequency to ensure the motor did not go over the current limit set on the driver. The design of the frame allowed for these vibrations to shake the entire printer, which is not ideal when trying to print fast with high quality. Initially this was not taken into consideration, but it was evident a change needed to be made. These extraneous vibrations were reduced with newer stepper drivers that have a mode in Marlin known as StealthChop. This mode controls the motors by PWM (Pulse Width Modulated) signals instead of current.[16] These drivers are known as trinamic drivers. One of the most popular is the TMC2209. Fortunately, the TMC2209 was designed to easily replace the A4988. This allowed all systems and firmware to be easily re-configured. A connection to the drivers over UART (Universal Asynchronous Receiver Transmitter) was unsuccessful due to limitations of the RAMPS board. However, this was not necessary as the UART connection only provides the ability to adjust the current limit of the drivers and change the mode of the driver.[17] The current limit can be adjusted from a physical phillips screw potentiometer on the driver as seen in Figure 5.[17] Since we could not connect to UART, the mode of the driver could not be changed. This was not a problem however as the default mode is StealthChop, which was the desired mode.[17]

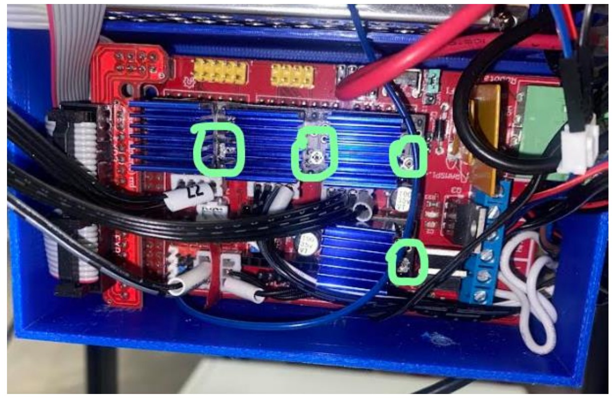

**Figure 5. Stepper Drivers Potentiometer Circled in Green**

A 12-volt power supply rated for 15 amps of current was chosen to power all components of the printer. This provided more than enough power for all systems as there was no heated bed necessary for this setup, which often draws high current. A 3D printed case was designed and printed to house all these electronics to protect the system and make it easy to use, as seen in Figure 6. The overall schematic for the design of electronics is visible in Figure 7. There is some variation from this design as the hardware purchased for the LCD screen came in a bundled PCB including an attached potentiometer, SD card reader, reset button, and backlight adjustment. This was connected to the RAMPS board in the same location indicated in the schematic in Figure 7, however there was an adapter for the LCD screen setup, using two ribbon cables to connect the two, as seen in Figure 6.

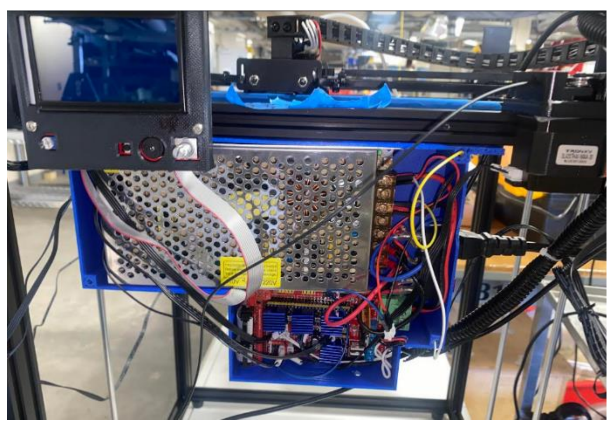

**Figure 6. Electronics Setup**

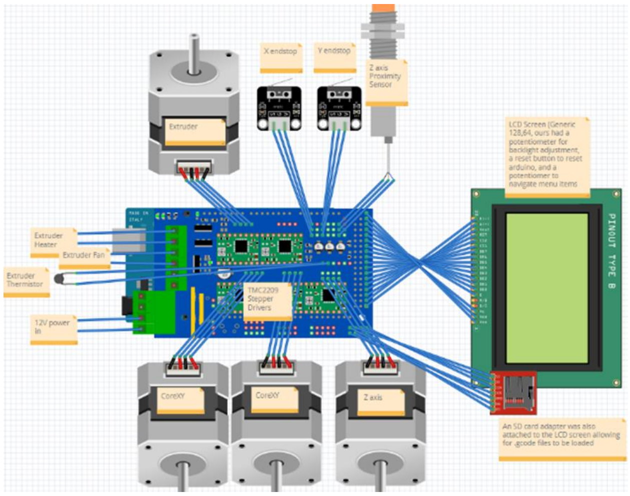


**Figure 7. Visual Schematic**

### *Printer Firmware*

As mentioned previously, Marlin Firmware was developed by the RepRap community in 2011.[4] As an open-source firmware, it has continued to be updated with constant feature upgrades. The latest stable version (2.1.2.2) was downloaded from the Marlin webpage (https://marlinfw.org/). Arduino IDE version 2.3.2 was used to open the Marlin firmware files, edit them, and then upload to the Arduino Mega.

Within the Marlin firmware, there are two files: Configuration.h and Configuration_Adv.h, both were edited to conform with our printer's hardware and provide easier calibration. In the Configuration.h the hardware was defined, and other necessary parameters adjusted. The use of the RAMPS 1.4, A4988 then TMC2209 drivers, CoreXY configuration, 128x64 LCD, SD card support, Z bed proximity leveling sensor were all declared in the scope of the firmware. Other aspects of the printer, however, required further modification after initial tests. The X and Y end stops needed to be inverted in the firmware as they were closed when not pressed (output = 1) and open when pressed (output = 0). This was changed by setting E_MIN_ENDSTOP_INVERTING to True. The heated bed was disabled as there is no heated bed in the system. This was set by setting TEMP_SENSOR_BED to 0. The position of the Z proximity sensor from the nozzle needed to be defined. An image of the hot end assembly can be seen in Figure 8, displaying the sensor and nozzle position. The offset distance was found initially by estimating with a caliper the offset in the X, Y, and Z direction. The Z calibration wizard was enabled to refine the Z offset from the LCD menu eliminating the need to adjust then re-upload the firmware. Baby stepping in the X, Y, and Z axis was also enabled so the offsets could be adjusted in real time. To accomplish this, in Configuration_adv.h we defined PROBE_OFFSET_WIZARD and BABYSTEPPING. The values adjusted in the LCD screen would not be saved when the system was restarted so it was important to re-upload the firmware with the fine-tuned values once they were found. The most crucial setting within the Configuration.h file is the steps per mm for the different stepper motors. This allows the firmware to translate the .gcode to precise movement in the stepper motor and create dimensionally accurate parts. This was crucial in our setup as any slight variation would compound error in long prints possibly leading to a binding of the worm-rack mechanism and a multitude of other problems. The derivation for finding the correct value for each stepper motor is described in the Calculations section.

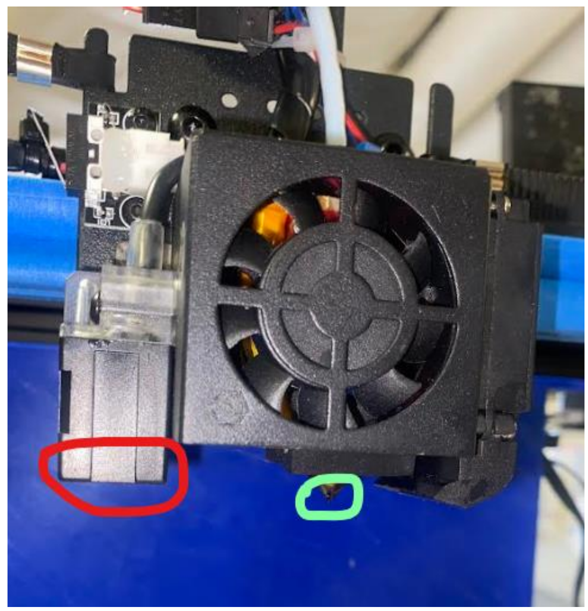

**Figure 8. Z-axis Proximity Sensor Circled in Red, Nozzle Circled in Green.**

### *Printer Slicer*

With firmware chosen, the last system needed was a 3D printer slicer. A slicer turns a stereolithography model (.stl) into a movement path for the 3D printer (.gcode). There are many options available on the market that all do mostly the same thing except for a few differences. For this project Cura was chosen for its advanced feature set and its many available presets for different 3D printers.[18] Importantly, one of these presets was for the Tronxy X5SA Pro. This reduced the overall fiddling with test parameters. The slicer was also used to adjust the X and Y offset of the printed track on the virtual print bed.

*Calculations*

After building the system, it now had to function. Using the known steps per revolution of the stepper motor and pitch of the worm, the correct steps per millimeter were calculated using Equations 1 and 2 for the Z mechanism.

$$\frac{ms}{rev} x \frac{mms}{ms} = \frac{mms}{rev} \quad (1)$$

$$\frac{mms}{rev} x \frac{1}{p} = \frac{mms}{mm} \quad (2)$$

where ms = stepper motor steps; mms = stepper motor micro steps; rev = revolutions of the stepper motor; and p = pitch (mm of translational movement / revolution of the stepper motor).

A similar method was used to calculate the correct steps per mm for the X, Y, and extruder stepper motors. The circumference of the gear that contacted the belt or filament was used instead of pitch to translate from steps per revolution to steps per mm. The circumference provided us with a measurement of translation movement in relation to revolution (mm/ revolution of the stepper motor). Once these values were calculated they were input into the firmware.

*Adjustments*

One of the most crucial aspects for this printer to function is the precise placement of the print so that the track joins with the existing track. To find the correct placement spot, the approximate location of the printed track was measured using calipers. This estimated location was then input into Cura's virtual print bed, and its output location was tested. When placement was off, the distance offset was measured with calipers and reinput into the location in Cura. Eventually this reiterative process allowed the printed track to join seamlessly with the existing track. The Z offset was found in a similar way to above but instead with input into the firmware.

The next big challenge was the quality of the printer. For this system to work it requires the printed track to be dimensionally accurate without extreme variations. To improve printer quality, additional adjustments were made to ensure the structure and resulting printed parts were square. Additional rigidity was added by re-assembling the printer onto its original frame to reduce large vibrations. With fine iteration and tweaking the system eventually functioned as intended.

**RESULTS AND DISCUSSION**

This system successfully demonstrated the track-based Z axis mechanism by extending the initial track segment over 125 mm while printing a cylinder (space station) beside the track at the same time. The triangular cutout of the cylinder, viewable in Figure 9, is a necessary initial feature when printing in a non-micro-gravity environment to limit the overhang of the print. In space this may not be necessary. While the system completed the print, it did so with some clear inconsistencies in the XY plane that caused the print to slightly layer shift over time. This phenomenon is commonly known as Z wobble.[8] This is presumed to be caused by slight misalignments of the initial print with the worm or the stepper motors skipping steps. The consistent pattern on the print in Figure 9 is due to the Z axis moving more or less than the desired layer height of 0.12mm. This phenomenon is commonly known as Z-banding.[8] The Z-banding is presumed to be caused by inconsistencies in the 3D printed worm's pitch. Another cause may be the rubber guide wheels not having a constant circumference when moving across the track and suddenly increasing their rolling resistance. Some possible solutions are to precisely machine the worm out of metal, improve tolerances between rack and worm, or manually adjust the gcode to account for the consistent pattern of change in Z axis movement.

A valid criticism of the work conducted in this section is that while the demonstration does prove the Z axis mechanism working on earth, it does not necessarily prove its function in its intended microgravity environment. While that statement is true, there is nothing about the function of the system that would inherently change in a microgravity environment. The system has even been tested to function upside down. So, while the criticism is true, with limited resources this is entirely sufficient as a demonstration of the concept.

**Figure 9: System Printing 125mm Extended Track with Attached Cylindrical Space Station**

## CONCLUSION

There are many possibilities for such a system in space. A cylinder was chosen to print beside the track to simulate creating a space station, but the system is not limited in the types of structures that it can print. While the current system can potentially extend the Z axis infinitely, simply adding the ability to switch tracks in all three directions could extend that capability to the X and Y axes. For this to happen, the system should be changed from a CoreXY setup to a robotic arm with an extruder attachment and a similar worm-rack mechanism on the base of the arm. This would allow the 3D printer the most freedom to rotate into other planes without getting in the way of itself and it would keep the printer system as small as possible. The robotic arm could have an additional attachment to grip onto a track in a different plane and then a mechanism to detach the rubber guide wheels from the current track. Another improvement is to implement a system to allow for gradual turns. Using gradual turns to make a corkscrew could simplify the process for making the biggest volumes (think of an ant walking in a circle up a water bottle). This track-based 3D printer also allows for the easy repair of structures by simply moving back and forth along the track. This opens the possibility for the system to be used as an orbital repair robot. Future work could also attempt to 3D print conductive materials to integrate power system directly into the structure. Other possible applications also include robot replication. If printing electronic components becomes a possibility, a similar system with multi-material capability could potentially even print a copy of itself.


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*The views expressed in this article, book, or presentation are those of the author and do not necessarily reflect the official policy or position of the United States Air Force Academy, the Air Force, the Department of Defense, or the U.S. Government.*

## REFERENCES


1. “A4988.” *RepRap*, reprap.org/wiki/A4988. Accessed 6 May 2024.
2. “Ceramics Manufacturing Module (CMM).” *Redwirespace*, Feb. 2021, redwirespace.com/wp-content/uploads/2023/06/redwire-space-mfg-flysheet.pdf.
3. Jacobson, Robert C. *Space Is Open for Business: The Industry That Can Transform Humanity*. HarperCollins Publishers, 2020.
4. MarlinFirmware. “Home.” *Marlin Firmware*, marlinfw.org/. Accessed 6 May 2024.
5. McCrea, John, et al. “Design of a zero-gravity, vacuum-based 3D printer robot for use of in-space satellite assembly.” *2018 AIAA Aerospace Sciences Meeting*, 7 Jan. 2018, https://doi.org/10.2514/6.2018-2201.
6. “Mega 2560 REV3.” *Docs.Arduino.Cc*, docs.arduino.cc/hardware/mega-2560/. Accessed 6 May 2024.
7. “Nema 17 Stepper Motor.” *RepRap*, reprap.org/wiki/NEMA_17_Stepper_motor. Accessed 6 May 2024.
8. O’Connell, J. (2022, August 24). Z Banding/ Z Wobble: How to prevent it. All3DP. https://all3dp.com/2/3d-printer-z-banding/
9. “On-Orbit 3D Printing Technology for Fabrication of Satellite Antennas.” *YouTube*, YouTube, 17 May 2022, www.youtube.com

/watch?v=ebZqaOBZApE&t=136s.+Accessed +28+Nov.+2023.

10. "On-Orbit Servicing, Assembly, and Manufacturing 2 (OSAM-2)." *NASA*, NASA, 30 Oct. 2023, www.nasa.gov/mission/on-orbit-servicing-assembly-and-manufacturing-2-osam-2/.
11. Quinn, Marshall, et al. "Effect of low vacuum environment on the fused filament fabrication process." *CEAS Space Journal*, vol. 13, no. 3, 16 Apr. 2021, pp. 369–376, https://doi.org/10.1007/s12567-021-00363-7.
12. "Ramps 1.4." *RepRap*, reprap.org/wiki/RAMPS_1.4. Accessed 6 May 2024.
13. *Redwirespace*, redwirespace.com/wp-content/uploads/2023/06/redwire-adsep-flysheet.pdf. Accessed 7 May 2024.
14. Spicer, Randy L., et al. "Development of a 3D printer capable of operation in a vacuum." *AIAA Scitech 2020 Forum*, 5 Jan. 2020, https://doi.org/10.2514/6.2020-1120.
15. "Spiderfab: Process for on-Orbit Construction of Kilometer-Scale Apertures." *NASA*, NASA, 5 Feb. 2024, www.nasa.gov/general/spiderfab-process-for-on-orbit-construction-of-kilometer-scale-apertures/.
16. Teemuatlut. "Trinamic Drivers." *Marlin Firmware*, teemuatlut, 20 Apr. 2024, marlinfw.org/docs/hardware/tmc_drivers.html.
17. TRINAMIC Motion Control GmbH & Co. KG. "POWER DRIVER FOR STEPPER MOTORS INTEGRATED CIRCUITS." TMC2209 DATASHEET, vol. Rev. 1.09–2023-FEB-16, 16 Feb. 2023, www.analog.com/media/en/technical-documentation/data-sheets/TMC2209_datasheet_rev1.09.pdf.
18. "Ultimaker Cura." *UltiMaker*, 24 Apr. 2024, ultimaker.com/software/ultimaker-cura/