Design and Manufacturing of Educational Fiber Extrusion Device and Smart Factory

by

Russel Bradley

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Abstract

Fiber Extrusion Device (FrED) is a desktop fiber extrusion system that mimics continuous fiber draw process for hands-on learning and/or laboratory experience on data acquisition, control system, and smart manufacturing. It allows learners to perform experiments, vary manufacturing parameters and control system, collect data, and perform analysis. Sucessful classroom activities have been conducted with FrED, however, the prior model is too costly to distribute to individual learners, given the rise of distant learning and MOOCs. A partnership with a university in Mexico, Tec de Monterrey, was formed to develop a low-cost FrED. This thesis covers the design, development and production of the low-cost variant in detail. Specifically discussing in depth the electronics system of FrED and the design for manufacturing and assembly (DfMA) process. An on-campus production and assembly facility, the FrED Factory, was made to mass produce FrEDs. The facility duals as a space for MIT students to learn about design and manufacturing. The FrED factory is undergoing digital transformation, aimed to streamline operations and to teach Industry 4.0 concepts. Three use cases are being developed: Machine Monitoring & Analytics, Smart Assembly Station and Digital Inventory Management. This thesis also covers the educational initiatives that has formed around the FrED ecosystem, both on-campus and with our partner university, Tecnologico de Monterrey, that has been conducted during the past academic year.

Thesis supervisor: Brian W. Anthony, PhD

Title: Principal Research Scientist

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1. Introduction

The Fourth Industrial Revolution (Industry 4.0) has brought about significant technological advancements and has the potential to transform industries and economies globally. Industry 4.0 involves the integration of cyber-physical systems, the Internet of Things (IoT), big data, and artificial intelligence (AI) into various aspects of manufacturing.

An international standard for Industry 4.0 adoption, Smart Industry Readiness Index (SIRI) [1], was initially developed by the Singapore Economic Development Board (EDB) and later adopted globally through the formation of International Center for Industrial Transformation (INCIT) through partnership with organizations such as the World Economic Forum (WEF). Various countries have adopted the SIRI standard. Some countries have developed their own version of the standard such as the Indonesia Indonesia Industry 4.0 Readiness Index (INDI 4.0) from Indonesia [2] and Reference Architecture Model Industry 4.0 (RAMI 4.0) from Germany [3].

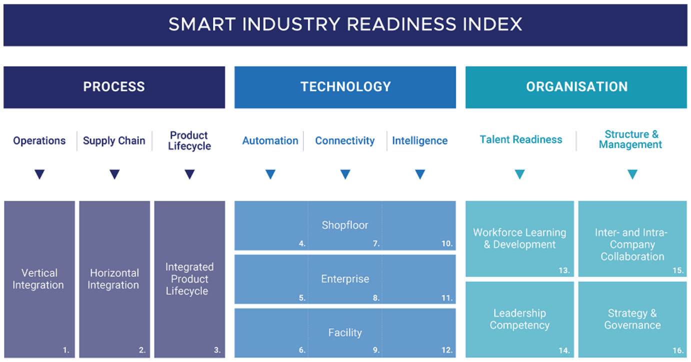


Figure 1. Smart Industry Readiness Index (SIRI) [1]

Figure 2. Indonesia Industry 4.0 Readiness Index (INDI 4.0) [2]

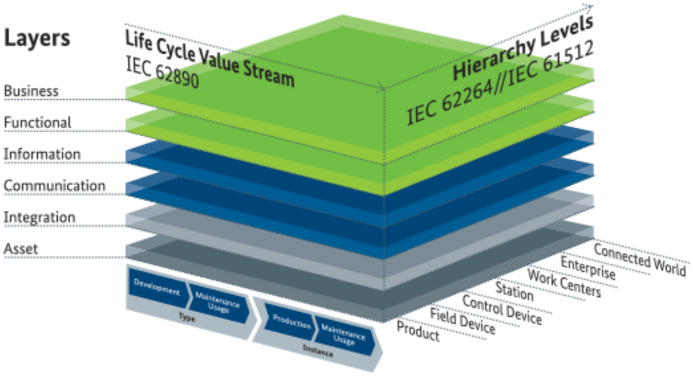


Figure 3. Reference Architecture Model Industry 4.0 (RAMI 4.0) [3]

Both SIRI and INDI 4.0 identify continuing education as one of the components to a successful industrial transformation. One of the pillars of SIRI is talent readiness in terms of “Workforce Learning & Development” and “Leadership Competency”. One of the focuses of INDI 4.0 is “Orang dan Budaya - Pengembangan Kompetensi” which translates to “People and

Culture - Competency Development”. This is not as easy for organizations to adopt. One of the major challenges with adopting Industry 4.0 is the education gap across the organization. Ensuring that all employees have the necessary skills and knowledge to work with the new technologies is critical for organizations to effectively leverage Industry 4.0 and achieve their business goals.

The education gap in Industry 4.0 affects all levels of the organization, from top management to field technicians. Employees need to be trained on new software, hardware, and processes to work effectively in a connected, digitized environment. Top-level management needs to understand the implications of Industry 4.0 on the organization's strategy, business models, and processes, while middle management needs to be able to manage the transition to the new technologies. Field technicians, on the other hand, need to be trained to operate and maintain the new technologies.

Addressing the education gap in Industry 4.0 is a complex and multifaceted challenge. The rapid pace of technological change makes it difficult for educational institutions to keep up with the latest developments, and there is a shortage of qualified instructors with practical Industry 4.0 experience. Additionally, traditional training methods may not be sufficient to address the unique needs and challenges of Industry 4.0. Organizations need to adopt innovative training approaches such as simulation-based training, virtual and augmented reality, and gamification to provide an immersive and engaging learning experience for employees. Organizations must invest in education and training programs that cater to the unique needs and challenges at all levels of the organization, including top management, middle management, and field technicians. By doing so, organizations can create a culture of continuous learning and development that will enable them to stay ahead in the rapidly evolving Industry 4.0 landscape.

The work done in this thesis aims to contribute in solving the overarching problem of the education gap in the manufacturing industry. This is done through two ways, the development of a desktop Fiber Extrusion Device (FrED) and an on-campus factory within MIT, the FrED Factory.

1.1 Background

Optical fiber is the foundation of network communication technology. Optical fibers are made using a continuous manufacturing process called fiber extrusion. There are several parameters that play a role in getting the diameter of the fiber in control, which is one of the critical quality parameters of optical fiber manufacturing. Early research on advanced process control in the Device Realization Laboratory at MIT Mechanical Engineering focuses on optical fiber manufacturing, due to funding and partnership reasons. A scaled down model of the fiber manufacturing process has to be developed to conduct experiments on the system physics and dynamics of the fiber extrusion technology. Inspiration was taken from the advent of desktop 3D printers and D.D.Kim et al. [4][5] began the development of a desktop fiber extrusion device (FrED) for research purposes.

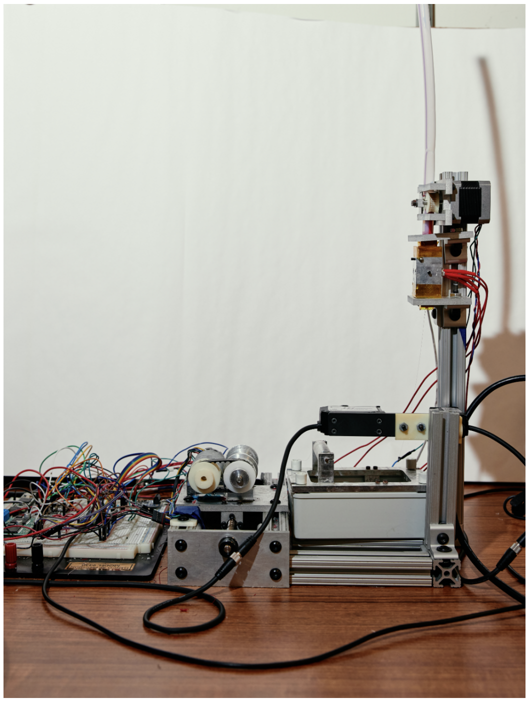


Figure 4. Initial version of FrED developed by D. D. Kim, et al.

Later, FrED was adapted to provide means to teach manufacturing and feedback control systems in a heuristic manner [4][5]. The students could change various process parameters to vary the diameter of the extruded fiber. Learners could experiment with implementing different control strategies on FrED. Learners could acquire manufacturing data from FrED and apply advanced analytics techniques, furthering learning on Smart Manufacturing. A successful early pilot was done in collaboration with manufacturing giant, Arconic [6]. Factory managers and directors gathered for a short course on Smart Manufacturing led by MIT faculty, Brian Anthony, which uses FrED as part of the hands-on learning experience. Below are several quotes that describes the successful demonstration of FrED in teaching manufacturing at Arconic:

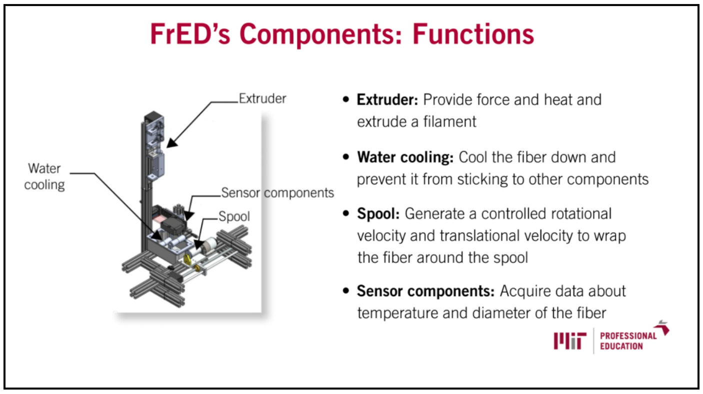
- "You control the temperature, material feed rate and uptake rate, and measure parameters like the diameter and mechanical properties of the product and temperature distribution of the fiber coming out and the actual speed of the uptake reel. Then you can start analyzing this rich multi-dimensional data to extract actionable information for feedback control or machine improvements." - Brian Anthony, Principal Research Scientist, MIT Mechanical Engineering
- "a great data set for identifying irregularities, and exploring whether they're coming from hardware issues or random errors. It's a good starting point to see how data analytics can be applied." - David Donghyun Kim, Lead Graduate Teaching Assistant, MIT
- "The real value of smart manufacturing is in gaining both a clear understanding of the technology and the ability to leverage that knowledge as part of what our people do every day. Partnering with MIT, one of the most widely renowned learning institutions, offers our operational and technical leaders this essential combination of learning and development experience, and it strengthens our position as a world class manufacturing organization." -Tim Myers, president of Arconic Global Rolled Products and Transportation and Construction Solutions.
- "This was truly a collaborative program development experience between our faculty and a leading manufacturer, Arconic, with MIT's 'mens-et-manus' ('mind-and-hand') approach firmly embedded in the curriculum design," - Bhaskar Pant, executive director of MIT Professional Education

Figure 5. Brian Anthony, PhD giving a lecture on Smart Manufacturing at Arconic [6]

The success of the collaboration with Arconic led to the development of an online course "Smart Manufacturing: Moving from Static to Dynamic Manufacturing Processes" with MIT Professional Education [7]. The course is targeted towards plant managers, engineers and data scientists who want to learn more about the fourth industrial revolution. The course is centered around FrED and has about 100 participants every session and four sessions offered annually. Offered in an online format, limitations of not being able to conduct hands-on activities on FrED arises. The online course instead uses datasets collected through FrED to teach concepts of smart manufacturing. The concepts taught in the course includes:

1. Data visualization
2. Time series analysis
3. Building models to examine and improve manufacturing processes
4. Explore role of sensors in smart manufacturing
5. Assess data types produced by sensors

6. Roles of feedback, process modeling and monitoring
7. Differences between actual and predicted dynamics
8. How to optimize machines
9. Machine vision
10. Statistical process control
11. Advanced data analytics



FrED's Components: Functions

- **Extruder:** Provide force and heat and extrude a filament
- **Water cooling:** Cool the fiber down and prevent it from sticking to other components
- **Spool:** Generate a controlled rotational velocity and translational velocity to wrap the fiber around the spool
- **Sensor components:** Acquire data about temperature and diameter of the fiber

Figure 6. Slide from MIT Professional Education course on FrED [7]

The need for a low-cost variant of FrED arose. The learning experience would be improved by giving online learners access to FrED for hands-on learning. It was decided that there is a need for the development of low-cost FrED and to manufacture it at scale by setting up an assembly facility at MIT. The assembly facility should also dual as a facility to teach manufacturing at MIT, specifically targeted towards the Master of Engineering in Advanced Manufacturing and Design [8] students. This was done in collaboration with Tec de Monterrey, a leading technical university in Mexico, with the goal of being able to replicate a similar course around FrED in their curriculum.

1.2 FrED (Fiber Extrusion Device) Overview

Fiber Extrusion Device (FrED) is a smart desktop fiber extrusion system developed for educational purposes [4][5]. First developed in 2017 by David Kim and Brian Anthony, FrED initially targeted professional education at MIT; then, later in 2021, Cuiffi *et al.* [9] further used FrED to train manufacturing workforce members. As opposed to actual manufacturing setups which are often large and expensive, FrED was purposely built to be compact, safe and low-cost, while also being able to generate feature-rich data allowing students to explore knowledge in smart manufacturing and feedback control systems [5]. Glue stick, used as the preform material, is safe to be heated and pulled to fabricate fiber with desired diameter. Various sensors are installed to provide a sufficient amount of data for data analytics and process control [4]. In addition to educational purposes, FrED can be used for new fiber design research and fiber prototyping in small batches as the system allows application of various materials and extrusion diameter control [5].

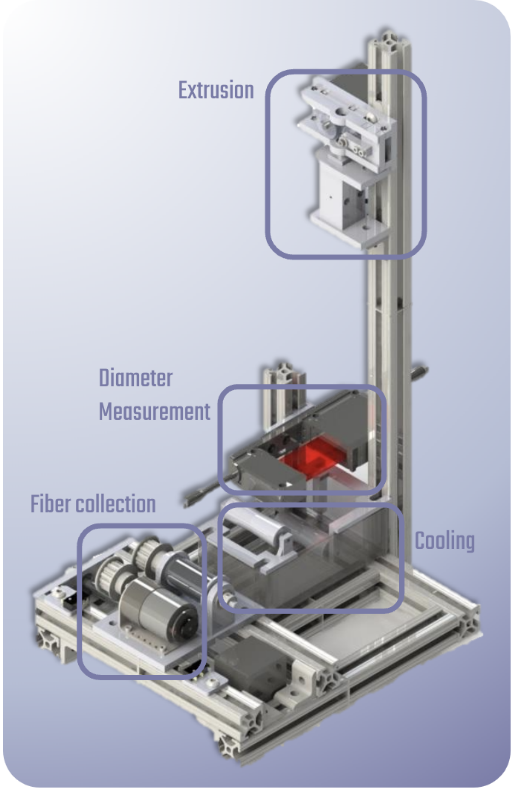


Figure 7. Four Existing FrED Systems

FrED is composed of 4 main elements, including extruder, cooling system, spool, and sensors, shown in Figure 7. The extruder heats the preform material and extrudes fiber using stepper motors as the actuators drive heated glue sticks through a smaller exit [5]. The extrusion rate is controlled by the stepper motor velocity [4]. Once extruded, the fiber moves downward to the cooling system consisting of a cooling tank and water as the cooling agent. The cooling system cools down the fiber to avoid them from sticking to other FrED components [5]. Then, the fiber exits the cooling tank as it is pulled and collected by the spool. A DC motor is used to rotate the spool, while a stepper motor and a lead screw works together to generate translational motion to evenly collect fiber along the spool length. The rotational velocity of the spool controls the fiber diameter. [4][5].

Three sensors are embedded in this system. First, the resistance temperature detector (RTD) is placed at the heating chamber of the extruder to measure the heating temperature for extrusion control [4][5]. Second, the laser micrometer is used to measure the diameter of the fiber before entering the cooling system. Data from these sensors goes to the closed-loop feedback control, which is critical to fiber diameter control [4][5]. FrED also includes a pair of limit switches as one of the sensors. It does not generate data for the diameter control system but provides the on-off signal based on switch contact that limits translational motion of the spool so that the fiber does not go off the spool.

Initially, a simple mass conservation model is used to control the fiber diameter based on the extrusion speed and spool's diameter and angular velocity [5]. However, this empirical model alone is not sufficient because the measured diameter was not in statistical control due to temperature inconsistency and stage motion time-mismatching. Accordingly, the closed-loop feedback control is introduced: the proportional controller (P-controller) and the proportional integral controller (PI-controller) take spool's rotational velocity and the error between measured and target diameter, respectively, as control feedback [4]. This control system can make the final fiber diameter be in control. Later, deep reinforcement learning (DRL) was proposed as the control system that does not require a numerical model [10]. DRL shows to improve the performance of tracking diameter error. However, it is noted that this method can still be improved by introducing data pre-training to reduce online training time.

1.3 Project Objectives

The initial prototypes of FrED were successful in meeting the requirements from a research standpoint but were expensive to make and deploy at a larger scale. The aim of this project was to reduce the cost of FrED from $5428 to less than $200 per piece and manufacture it at scale. A pilot production of 25 devices was aimed to be completed by the end of Summer 2022.

The motivation was further broken down to various objectives that needed to be achieved by the end of Summer 2022. These are listed below:

1. Re-design FrED to reduce its cost by using the principles of design for manufacturing and assembly
2. Build prototypes and test the functionality
3. Define a process plan to manufacture FrED at scale
4. Set-up a supply chain for materials and outsourced parts
5. Set-up an assembly facility within MIT to carry out the pilot production of 25 parts

The first run of FrED redesigned ended Summer 2022, but activities continue to run within the FrED ecosystem. A smart manufacturing infrastructure is built around FrED factory to facilitate the learning of Industry 4.0. In addition to that, FrED emerged in various manufacturing classes across MIT and Tec de Monterrey.

1.4 Methodology Overview

A systematic product development life cycle, as listed below, was defined for the development of a low-cost variant of FrED.

1. Defining functional requirements
2. Conceptual design of the low-cost variant of FrED
3. Iterative cycles of prototyping and testing
4. Process plan and sourcing plan
5. Assembly line setup and pilot production

Keeping in mind the principles of DFMA, the following four points were kept in mind while design the low-cost variant of FrED:

1. Usage of standard parts wherever possible
2. Reducing the total number of parts while still meeting the functional requirements
3. Taking a modular approach for easy deployment, repair and if required replacement of modules
4. Integrating parts as much as possible

1.5 Stakeholders

For the development of FrED, major parties of stakeholders were identified.

1. The founding team of FrED Factory, four Master in Engineering in Advanced Manufacturing and Design students who were primarily in charge of the design, development, and manufacturing of the low-cost FrED
2. Brian Anthony, PhD, MIT faculty who specialized in data science and smart manufacturing who provided guidance, advice to the first party. Brian is the Principal Investigator for the FrED and FrED factory initiative.
3. The Master of Engineering in Advanced Manufacturing and Design Office, consisting of Professor David Hardt, Jose Pacheco, MBA, and Brian Anthony, PhD. The FrED ecosystem is visioned to be a transformation for on campus manufacturing education.
4. Faculties from Tec de Monterrey, Erick Guadalupe Ramirez-Cedillo and Adriana Vargas-Martinez, who will be involved in a parallel development of Low-Cost FrED and teaching activities using FrED.
5. MIT Professional Education (PE) which provides online and in campus professional courses in Smart Manufacturing. FrED is visioned to be an education kit that will be shipped to learners enrolled in MIT PE classes.
6. MIT Mechanical Engineering Department. FrED factory provides a platform for students to learn manufacturing through programs such as undergraduate research opportunities program (UROP).

1.6 Team Contributions

While the team worked collaboratively throughout the duration of the project, each team member led different elements of the project.

Aviva J. Levi was primarily responsible for the redesign of the extrusion system, as documented in her thesis, “Design and Manufacturing of the Extrusion Assembly for an Advanced Process Control Educational Device” [11].

Rui Li was primarily responsible for the redesign of the fiber collection and diameter measurement system, as documented in his thesis, “Design and Manufacturing of the Filament Collection and Diameter Measurement Systems of Fiber Extrusion Device for Educational Purposes” [12].

Tanach Rojrungsasithorn was primarily responsible for the factory layout and process planning as documented in his thesis, “Factory and Material Flow Design for Mass Production of an Advanced Process Control Educational Device” [13].

Russel Bradley (author) was primarily responsible for the redesign of the electronics subsystem of FrED, manufacturing & assembly process development and sourcing of parts. Bradley continued to work on the project for another semester developing educational initiatives and spearheading the digital transformation initiative at the FrED Factory to create a smart factory.

Figure 8. FrED Factory Founding Team Picture

1.7 Thesis Outline

The following sections will cover in detail a summary of the design of low cost Fiber Extrusion Device (FrED), the redesign of the electronics subsystem of FrED and design for manufacturing for FrED. This is followed by the digital transformation of the FrED Factory, the on-campus facility to manufacture FrEDs at scale. A section will also highlight the educational initiatives that have been implemented in the FrED ecosystem.

2. Low Cost FrED Design

This section will cover the systems design of low cost FrED. This section will give an overview of each of the FrED subsystem redesigns.

2.1 Systems Overview of Low Cost FrED

The low cost FrED design consists of the following subsystems, shown in Figure 9:

1. Fiber Extrusion
2. Cooling
3. Diameter Measurement
4. Fiber Collection
5. Electronics
6. Frame

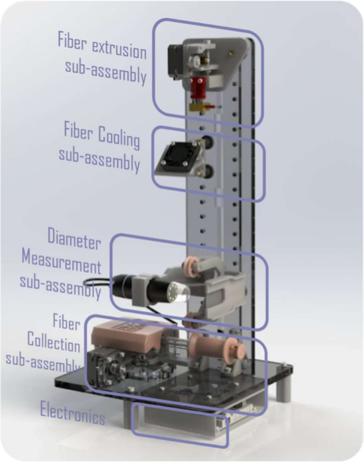


Figure 9. Labeled Render of Low-Cost FrED

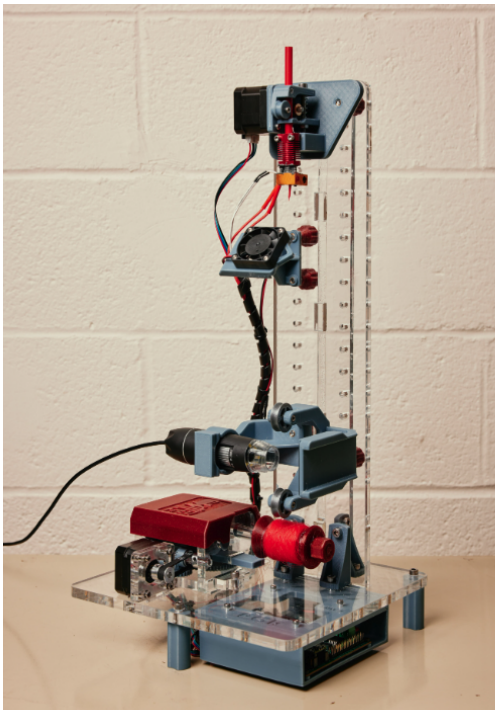


Figure 10. Low-Cost FrED Production Model

2.2 Fiber Extrusion System

The fiber extrusion system is responsible for melting the preform material and controlled feeding of the preform through a nozzle. It can be broken down into 2 components, the extruder and the heat block as shown in Figure 11. More detailed information on the design process of the extrusion system can be found in A. Levi's thesis [11].

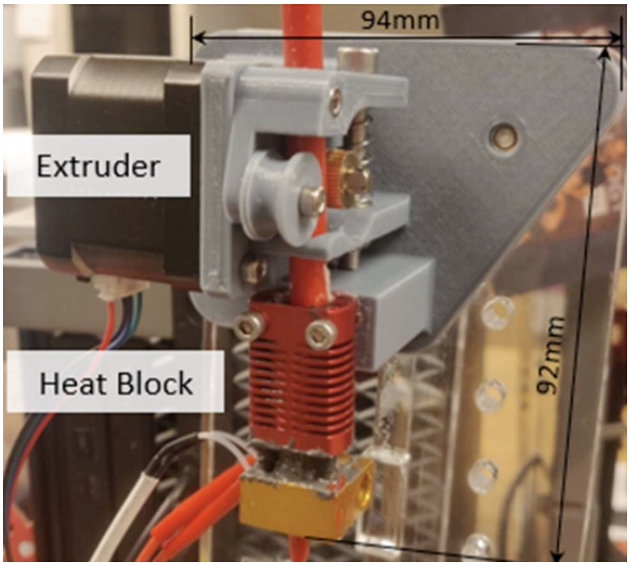


Figure 11. Fiber Extrusion System

The Low Cost FrED extrusion system is designed based on the extrusion system of a Creality Ender 3 3D Printer. This is due to the multiple similarities of the functional requirements of both systems and that the Creality Ender 3 3D Printers are manufactured and sold at very low prices [14].

Heat Block Design

The design of a heat block requires a cold zone, a hot zone, an inlet for 7mm diameter hot-glue preform, and an outlet of a smaller diameter than the preform. The Creality heat block satisfies the requirements except for the preform diameter size. It is designed to take in 3D printer filament (pre-form equivalent) of diameter 1.75mm and outputs through a 0.4mm diameter nozzle. Modifications to the design are required to adapt the Creality heat block to take in a preform of diameter 7mm. It was calculated that it is possible to achieve this by simple drilling operations on the off-the-shelf heat block, along with replacement of a few components. The design of the heat block is intended to be a modification of an off the shelf Creality Ender 3 heat block, shown in Figure 13, because it will significantly cost more to manufacture a new design at small scale than modifying an existing mass product that can be readily purchased off the shelf.

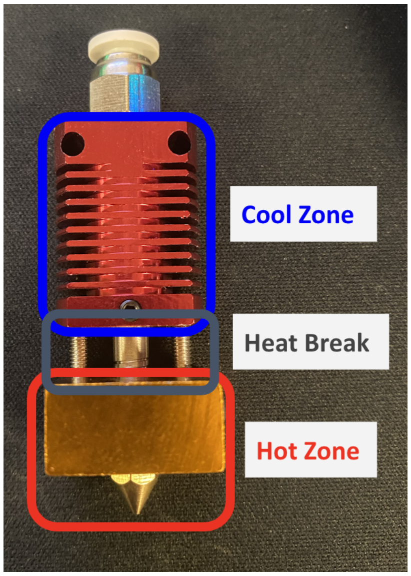


Figure 12. Creality Ender 3 heat block

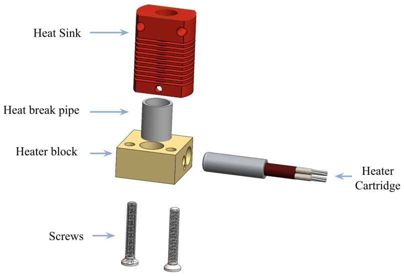


Figure 13 Modified heat block exploded assembly

A dimensioned drawing of the internal heat block is shown in Figure 14. The modification done on the Creality heat block are as follows:

1. Drilling to enlarge the hole of the heat sink and heater block to 7.75mm diameter
2. Substitution of the threaded heat break to a steel pipe of internal diameter 7.75mm and outside diameter of 9.50mm.
3. Addition of high temperature resistant epoxy adhesive as a sealant between the hot end and the heater block.
4. Removal of redundant fasteners, PTFE tube and pneumatic fitting.

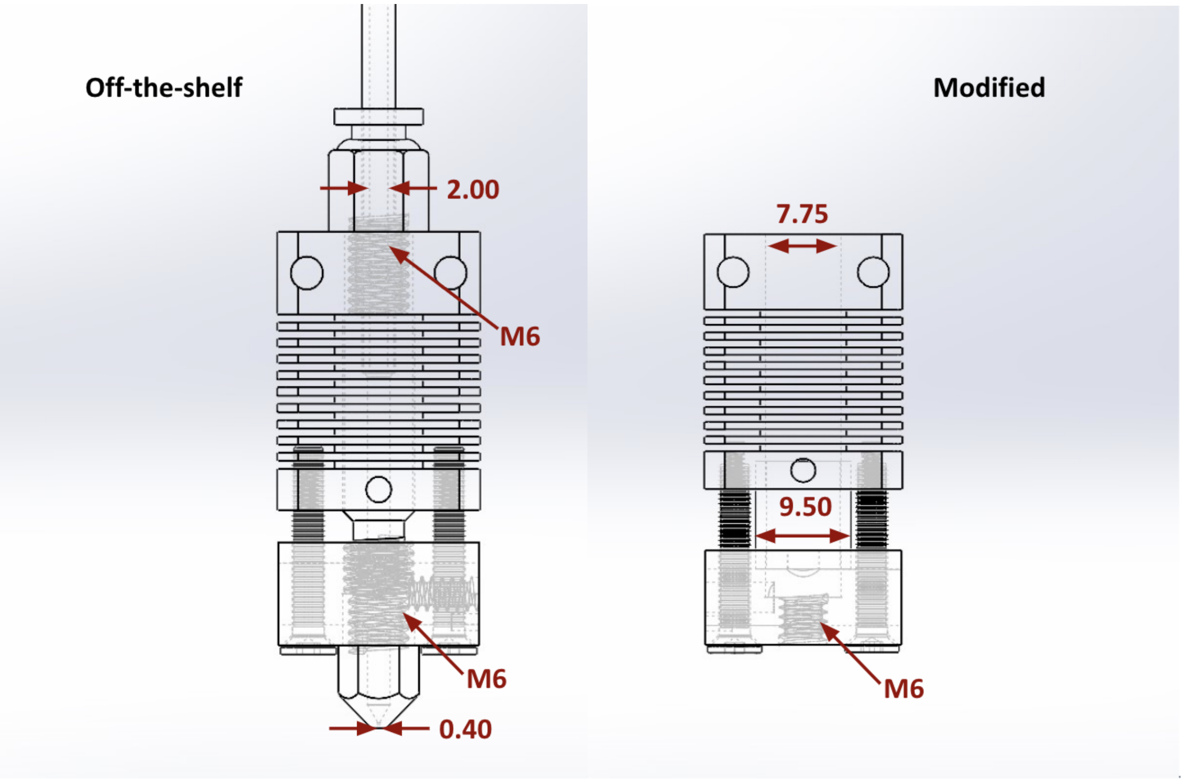


Figure 14. Internal geometry of modified heat block.

Extruder Design

The design of the extruder requires a precise control of feeding a preform into the heat block shown in Figure 15. This is achieved by a drive gear attached on a stepper motor feeding in preform from the top of the heat block. An idler pulley is attached on a spring loaded lever to handle preform diameter variability and to exert a clamping force needed for the drive gear to feed the preform.

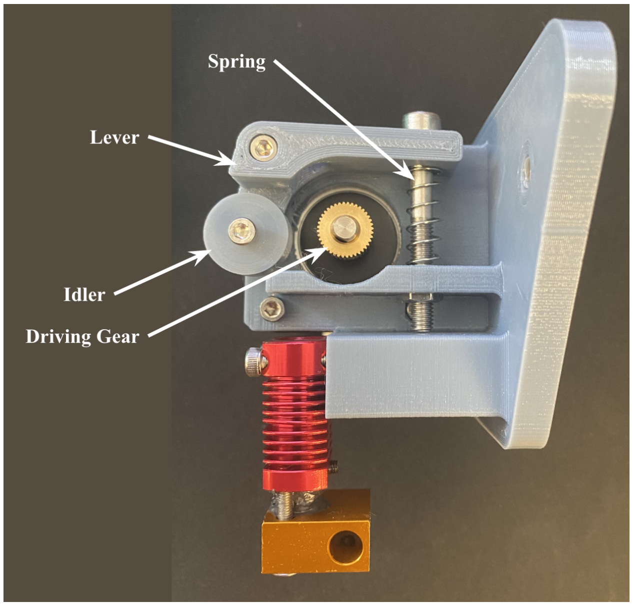


Figure 15. Labeled extruder mechanism

The design of the extruder is adapted from the Creality Ender 3 3D printer extruder. Minor modifications to the design were made to accommodate a preform diameter of 7.00mm instead of 1.75mm.

Figure 16. Creality Ender 3 extruder mechanism [14]

It was decided that modifications to an off the shelf extruder is not possible due to excessive material removal needed. Most of the components are manufactured with filament 3D printed plastic instead of die casted aluminum because of lower cost at a small production scale. The drive gear used comes from the Creality extruder as it is suitable for the modified extruder design. A spring with a different specification has to be sourced to provide a suitable compression force for the 7mm hot glue preform.

2.3 Fiber Collection System

The fiber collection subsystem requires precise control of spooling of the fiber. Variable of control of interest is the spooling speed, i.e. how many meters of fiber spooled per unit time. The spool is required to continuously rotate to wind up the fiber and also move side to side to distribute the fiber in the spool. A new fiber spooling system was designed that runs on a stepper motor and utilizes a scotch-yoke mechanism, as shown in Figure 17. More detailed information on the design process of the extrusion system can be found in Rui Li's thesis.

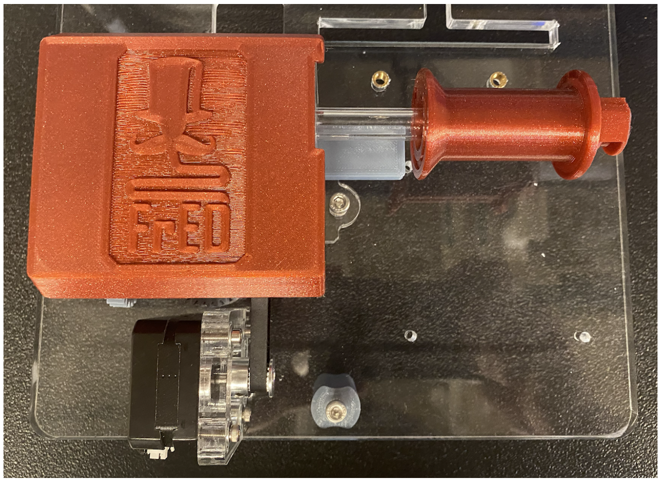


Figure 17. Fiber Collection System

A simple cost analysis on the research version of FrED shows that most of the cost of the fiber collection system comes from the complexity of requiring 2 motors to drive motion and the use of precision machine components. This translates to two design action items. First, designing a spooling system that utilizes one motor instead of two. Second, designing a system that does not require precise tight-tolerance components to function.

A scotch-yoke mechanism is adapted to convert rotational motion from the stepper motor into both rotational and linear motion in the spooling system, shown in Figure 18. This allows the reduction from using two motors to using one stepper motor to control spooling. However, this system comes with disadvantages: the ratio of rotational to translational motion is fixed to the design of the gear system, and the design requires a relatively complex gear system, shown in Figure 19.

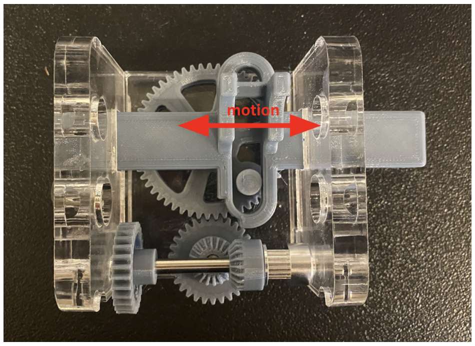


Figure 18. Scotch Yoke Mechanism

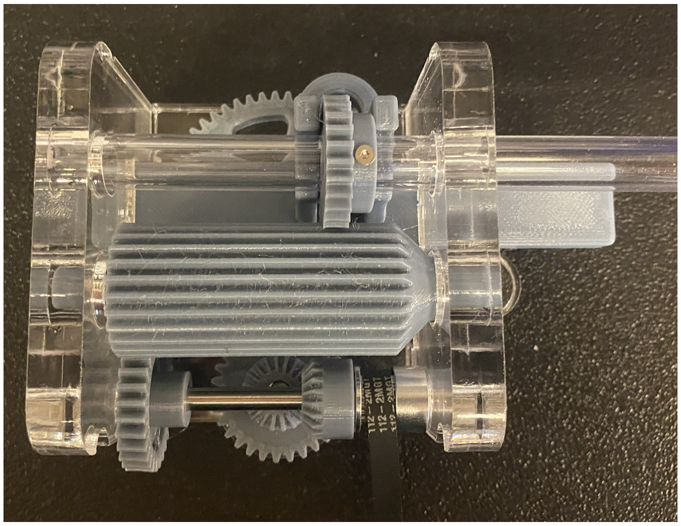


Figure 19. Gear System

The gear system functions as follows. The stepper motor is attached to a timing pulley which drives another timing pulley attached to a shaft with a bevel gear and spur gear. The bevel gear drives a scotch-yoke wheel that drives a slider resulting in the translational motion of the spool. The spur gear drives a series of spur gears that generate the rotational motion of the spool.

The complexity of the design would require custom made gears. Using conventional manufacturing methods would result in a very expensive design. On top of that, some of the gears would not be manufacturable with conventional manufacturing methods such as machining due to part complexity. Filament additive manufacturing was selected to be the manufacturing process for the gears. Filament additive manufacturing is not a precision manufacturing method but can be modified to provide the level of precision needed for this application. One such modification is changing the nozzle diameter to a smaller one (from 0.4mm to 0.25mm), so that finer features can be produced. This allows the gear teeth to be fabricated at better precision and usable to drive the fiber collection system of FrED.

An easy remove spool was also designed to improve the user-friendliness of the design. In the research version of FrED, the spool is attached to a shaft in between two end supports. This made it impossible to remove the spool without disassembling the entire spooling system. The user would need to cut the spooled fiber using a pen knife to remove the fiber from the spool. Low Cost FrED has overcome this problem by leaving an overhang on one side of the shaft supports, then attaching the spool to the open end of a shaft. A quick locking mechanism is designed to allow the spool to be easily locked and unlocked from the shaft. This is done using two protrusion on the lock and two slots on the shaft and spool that locks the spool relative to the shaft, and a round protrusion on the lock and the spool that creates a clamping force between the lock and the spool, shown in Figure 20 and 21.

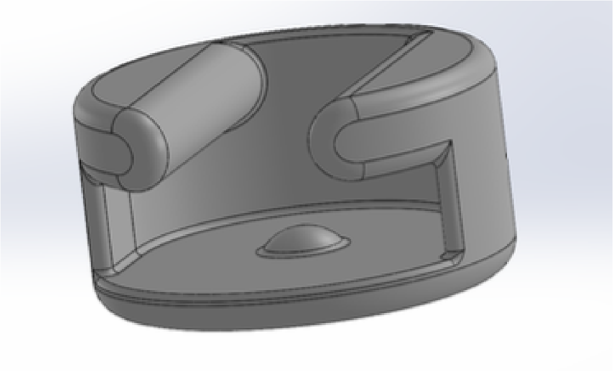


Figure 20. Spool Lock

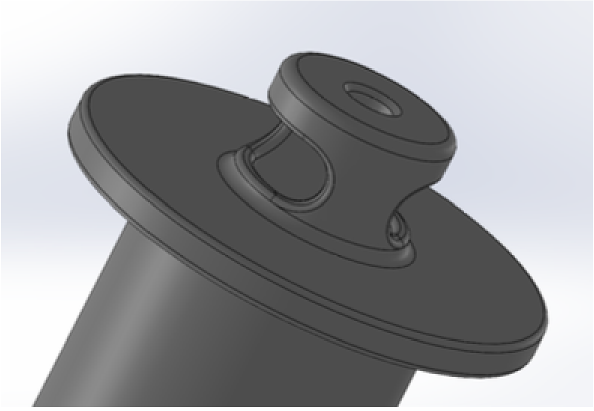


Figure 21. Spool Locking End

Research version of FrED uses a DC motor to control the spooling speed. This configuration requires an additional encoder, that senses the rotational speed of the motor, in order to form a closed loop control for spooling speed. This is because DC motors are controlled using pulse width modulation and it is not possible to get the exact speed of the motor just by referring from the parameters of the signal sent to the motor. A single stepper motor would simplify the architecture as there is no need for an encoder. It is possible to send signals to the stepper motor that directly correspond to the speed of the motor.

A cover with the FrED logo is added to the gearbox, shown in Figure 22. This is done to enclose the gearbox to avoid users fingers being pinched and stray fiber or hair being tangled in the mechanism. At the same time, this provides a good space for branding. Including the FrED logo enforces the FrED branding of these machines.

Figure 22. Gearbox Cover with FrED Logo

2.4 Diameter Measurement System

The diameter measurement system is required to measure fiber at a diameter of 0.4 mm and capture a resolution of at least 0.01 mm, with measurements done at a frequency of 100Hz. Research version of FrED uses a laser micrometer from Keyence that costs $3000. This is not viable for the LowCost FrED. Low Cost FrED requires a cheaper diameter measurement sensor.

This is a hard problem to develop a low cost sensor with the required specification. A proof of concept is developed using a camera based sensor that uses image processing algorithms to obtain the diameter of the fiber.

A contact based sensor was initially ideated based on a 3D printing filament diameter measuring sensor, InFiDEL [15]. Fiber is passed between a pair of bearings, one fixed and another attached to a lever. The lever displacement amplifies the variation of the filament diameter. The extreme end of the lever is equipped with a magnet. A fixed hall effect probe senses the variation of the magnetic field due to the relative distance between the probe and the magnet. The variation in the magnetic field can be directly converted to diameter values when interfaced with a microcontroller. However, the sensor fails to capture any variation of diameter from the fiber. The fiber is about 5 times smaller than a 3D printer filament, and requires a very high sensing resolution. Hence making this particular configuration of the sensor unusable for fiber measurement. In addition to that, there are concerns on using contact based sensors for fiber diameter measurement.

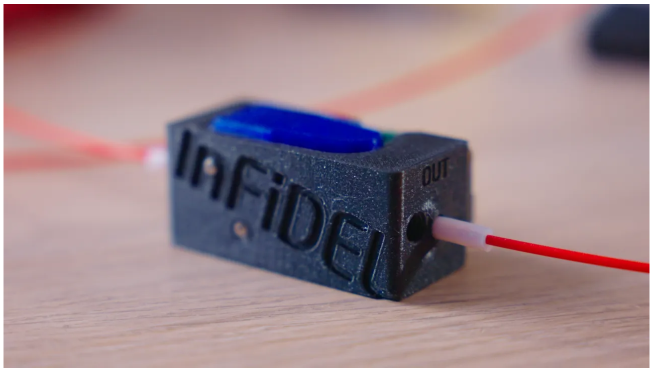


Figure 23. InFiDEL [15]

The unsuitability of the contact based 3D printer filament sensor resulted in the development of a camera based measurement system. The idea is that a camera with a magnifying lens captures a video of the fiber. A video is a series of images of the fiber. Image processing algorithms then can be applied to the series of images to infer the diameter of the fiber. A camera based system might not be able to accurately capture the exact fiber diameter, but can capture the variation of fiber diameter as a larger fiber will occupy more pixels in the frame.

A holder is designed and fabricated to hold a USB microscope, a pair of pulleys to position the fiber and a black sheet for a dark background, shown in Figure 24. This holder allows a stable positioning of the fiber relative to the camera, preventing the fiber from getting out of frame. The USB microscope is connected to a Raspberry Pi single board computer. Command line scripts are run to capture images from the USB microscope, shown in Figure 25.

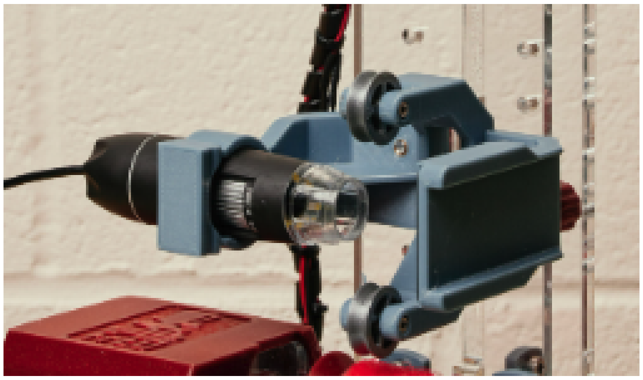


Figure 24. Camera based diameter measurement system

Figure 25. Fiber image from USB microscope

Image processing algorithms, edge detection, is applied to the images captured from the USB microscope. The result is shown in Figure 26. Followed by an algorithm to count the distance between two detected edges. The system is calibrated using a fiber with known diameter, a 0.37 mm fishing line. The system gives a resolution of 0.014 mm which is close to the requirement but still does not meet the requirement of 0.01 mm resolution. The measurement resolution is limited by the magnification of the lenses and the pixel resolution of the images captured. In addition to that, the camera is only capable of capturing 25 frames per second. This fails to meet the requirement of 100 Hertz or frames per second.

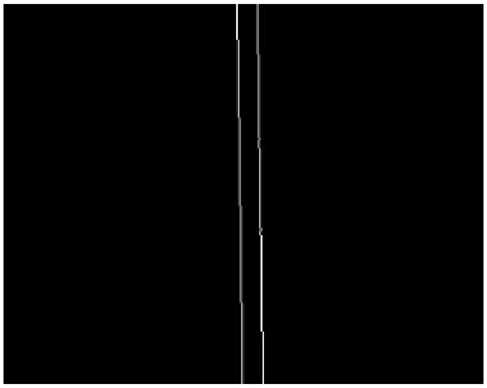


Figure 26. Fiber image output from edge detection algorithm

This successful proof of concept gives room for future work to develop a functional vision based measurement system for fiber. There are still a few problems to overcome, such as the frame rate of the video, minimizing the vibration of the fiber to get focused images, and building an operational data pipeline from capturing the images to sending numerical diameter values to the microcontroller.

Trials from using camera based diameter measurement have given images that shows defects such as air bubbles in the fiber. An example of the image is given in Figure 27. Figure 28 shows the image after it is processed by the edge detection algorithm. This example shows that even the current camera based system could not be a perfect sensor to FrED's feedback control loop, it could be used for other applications such as teaching defect detection using machine vision.

Figure 27. Image of fiber with air bubbles

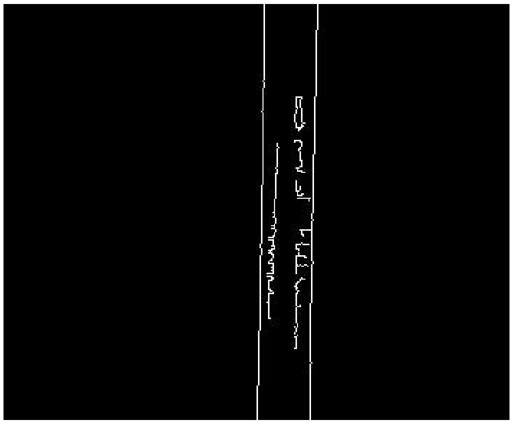


Figure 28. Fiber with air bubble image output from edge detection algorithm

2.5 Cooling System

Research version of FrED uses water cooling to cool the fiber in between extrusion and spooling. This poses a few concerns on the difficulty of spooling the initial extruded fiber through the water tank and the liquid spilling hazard near electronics. In the low cost FrED, the liquid cooling is replaced with air cooling. This utilizes a fan blowing down to the fiber. This has proven to be effective enough to cool the fiber down.

A 4010 12V DC fan is sourced to provide air flow towards the fiber. The intensity of the fan can be controlled through pulse width modulation by the microcontroller. A fan support is designed to hold the fan at an angle to the fiber, shown in Figure 29 and 30.

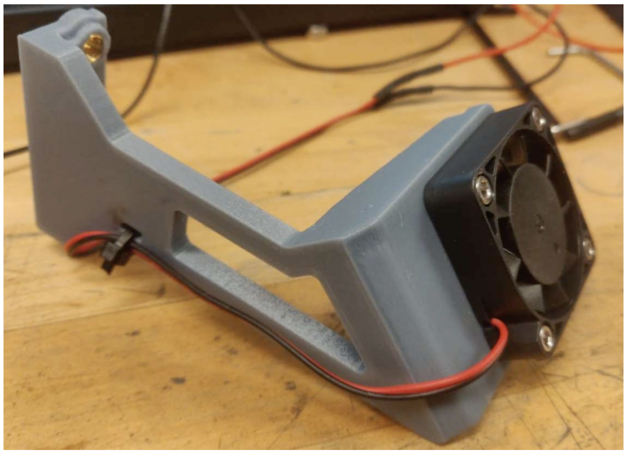


Figure 29. Cooling System

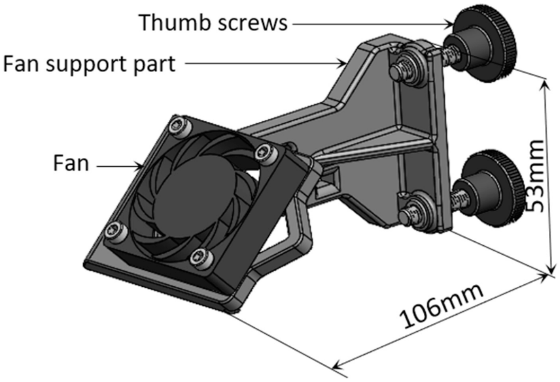


Figure 30. Cooling System CAD

2.6 Electronics System

The electronics system is required to provide power and controls to the electronic devices in FrED. It is a system of microcontroller(s) and drivers. A PCB is fabricated to house the microcontroller and off-the-shelf drivers. A few custom built circuits, such as PWM drivers, potential divider, etc., were also built to accommodate the functionality of FrED. A later section in this thesis is dedicated to an in depth discussion of the electronics system.

2.7 Frame and Modularity

Research version FrED uses aluminium profiles, which allows for modularity. It is possible to modify the positions of each individual subsystem easily, just by loosening and tightening a few bolts and nuts. Adding components to FrED can also be done by simply mounting them on the aluminium profile frame. But these frames come at a high cost. It is expensive to procure aluminium profile bars in the United States.

A similar modularity experience is needed in the low-cost FrED. The design utilized an array of holes with horizontal distance between the pair of holes 50 mm and the vertical distance between holes 20 mm, shown in Figure 31. The frame is made using Polymethyl methacrylate (PMMA) sheets, also known as acrylic sheets, using laser cutting process. This design, shown in Figure 32, significantly reduce the cost of the frame while not sacrificing the modularity experience. Thumb screws, shown in Figure 33, are fabricated for easy removal and attachment of the different modules.

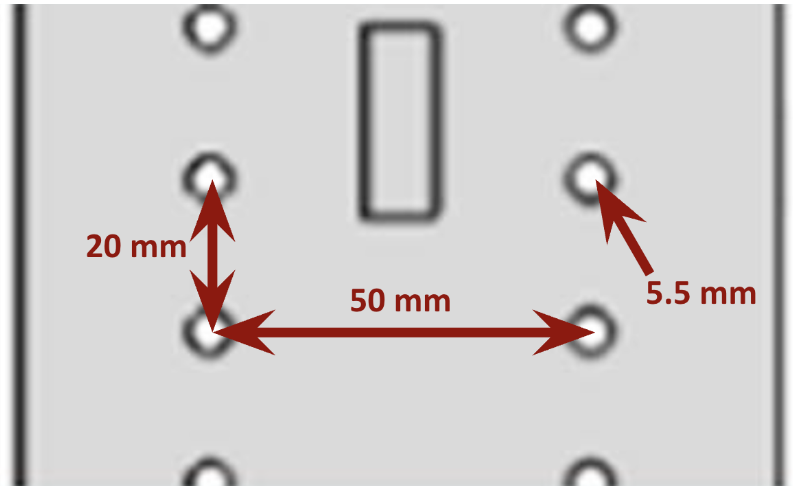


Figure 31. Hole array of frame dimensions

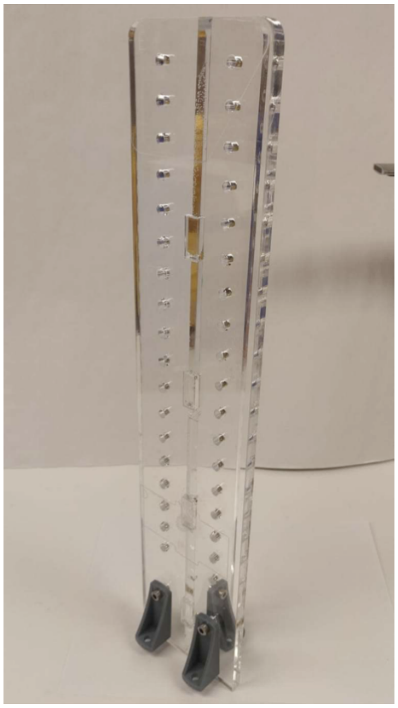


Figure 32. Modular frame design

Figure 33. Thumb Screws

2.8 Design Improvements

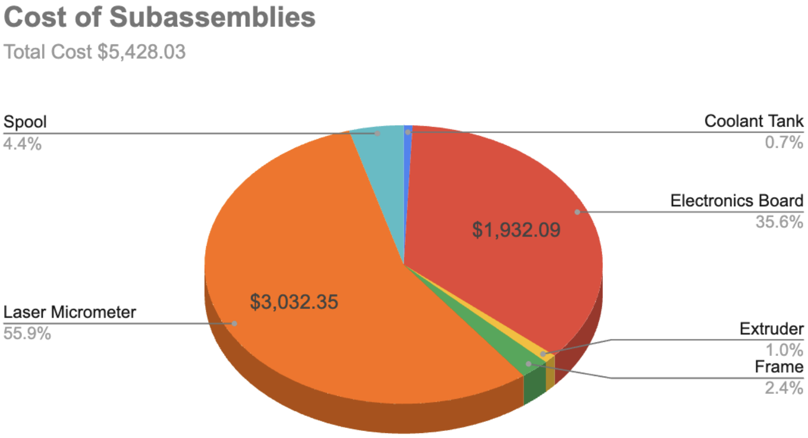


Figure 34. Research version FrED COGS

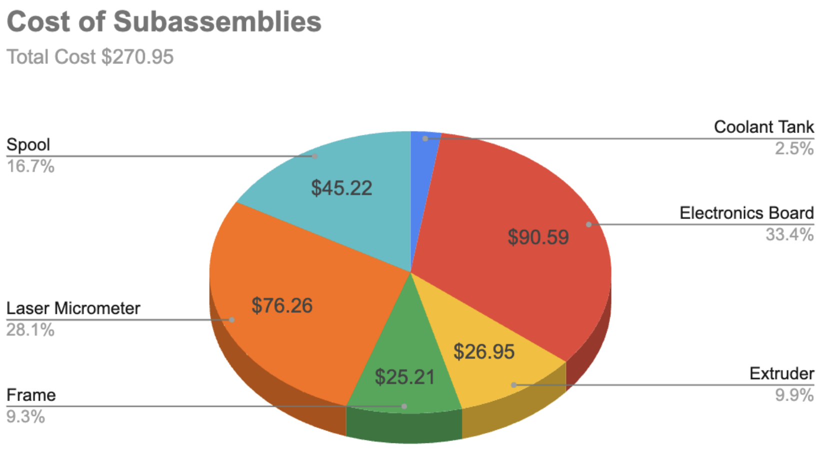


Figure 35. Low-cost version FrED COGS

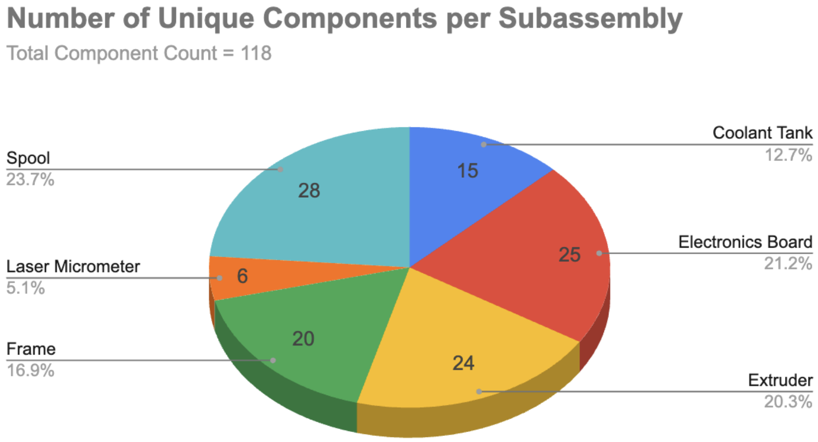


Figure 36. Research version FrED part count

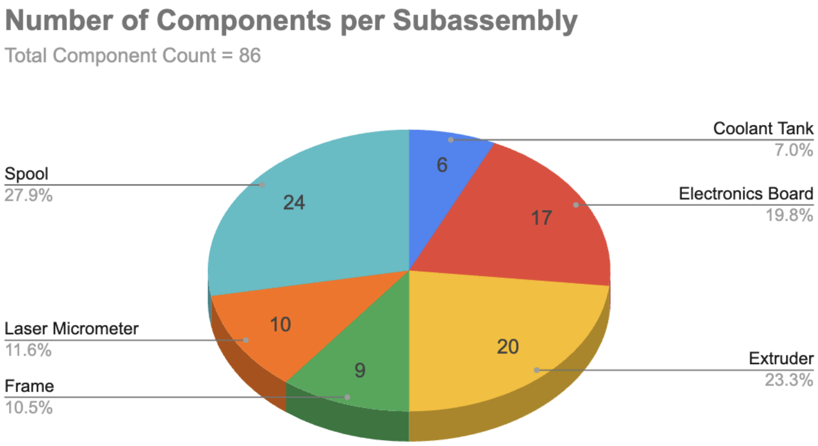
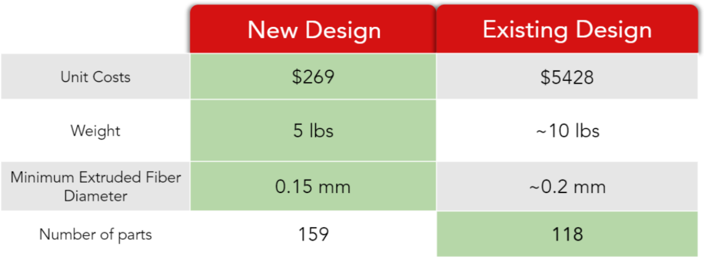


Figure 37. Low-cost version FrED part count

Table 1. Comparison of Low Cost (New) vs Research (Old) FrED



	New Design	Existing Design
Unit Costs	$269	$5428
Weight	5 lbs	~10 lbs
Minimum Extruded Fiber Diameter	0.15 mm	~0.2 mm
Number of parts	159	118

3. FrED Electronics Redesign Deep Dive

The electronics system is required to implement controls and data collection on the device. It consist of microcontroller(s) and drivers. Microcontrollers are used to control the FrED device. It provides functionality such as reading inputs from sensors, controlling outputs to actuators, and processing data. Drivers are required to interface with external devices such as heater cartridge and stepper motors.

A printed circuit board (PCB) that holds microcontroller and drivers is designed and manufactured for FrED as seen in Figure 38. The decision of using a PCB is made as this is an industry standard for electronic devices . A PCB provides reliable performance, no loose connections, saves time (automated process), compact, and cost reduction [16]. Although most education kits will come with electronics on a prototyping breadboard for their flexibility, we do not see the benefit of assembling a circuit from scratch towards the education experience. Instead, the PCB was designed so that it captures all basic functionality of FrED and options to extend to a breadboard for additional components, providing flexibility to the learning experience.

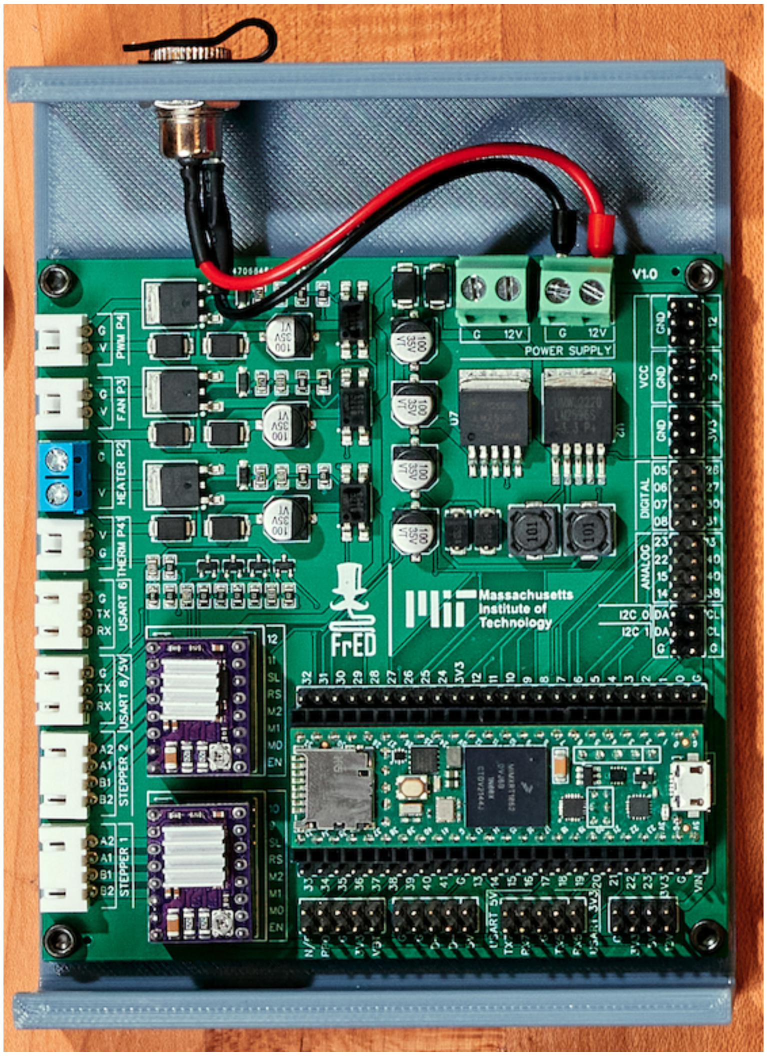
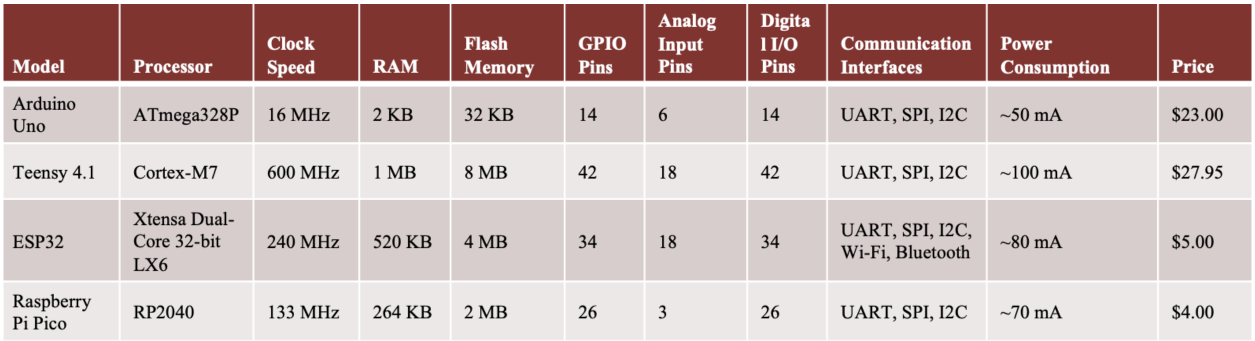


Figure 38. FrED Assembled PCB

3.1 Teensy 4.1 Microcontroller

A microcontroller is a small computer system that contains a central processing unit (CPU), memory, and programmable IO, within a single chip. There are multiple variants of microcontrollers available off the shelf, such as Arduino [17], Teensy [18], ESP32 [19] and RaspberryPi Pico [20]. A comparison of these microcontroller boards can be found in Table 2. The requirements for microcontroller is that it could support micro-ROS. micro-ROS is required to set up the architecture for deep reinforcement learned controls. All of Teensy, ESP32 and RaspberryPi Pico support micro-ROS architecture. The initial version of FrED uses a Teensy 3.5, which has been discontinued and updated to a newer version [21]. As of the project timeline, Teensy 4.1 is the most recent version [18]. The Teensy 4.1 is selected as it has been proven that it is capable to be used for controlling FrED using advanced techniques such as deep reinforced learning controls. Using an updated version of the Teensy board should ideally provide a smoother transition when compared to switching to a different board architecture. However, the cost of the Teensy 4.1 is relatively higher compared to the other microcontroller options. This leaves room for future work on exploring different microcontroller options for cost reduction.

Table 2. Comparison of Microcontrollers [17][18][19][20]



Model	Processor	Clock Speed	RAM	Flash Memory	GPIO Pins	Analog Input Pins	Digital I/O Pins	Communication Interfaces	Power Consumption	Price
Arduino Uno	ATmega328P	16 MHz	2 KB	32 KB	14	6	14	UART, SPI, I2C	~50 mA	$23.00
Teensy 4.1	Cortex-M7	600 MHz	1 MB	8 MB	42	18	42	UART, SPI, I2C	~100 mA	$27.95
ESP32	Xtensa Dual-Core 32-bit LX6	240 MHz	520 KB	4 MB	34	18	34	UART, SPI, I2C, Wi-Fi, Bluetooth	~80 mA	$5.00
Raspberry Pi Pico	RP2040	133 MHz	264 KB	2 MB	26	3	26	UART, SPI, I2C	~70 mA	$4.00

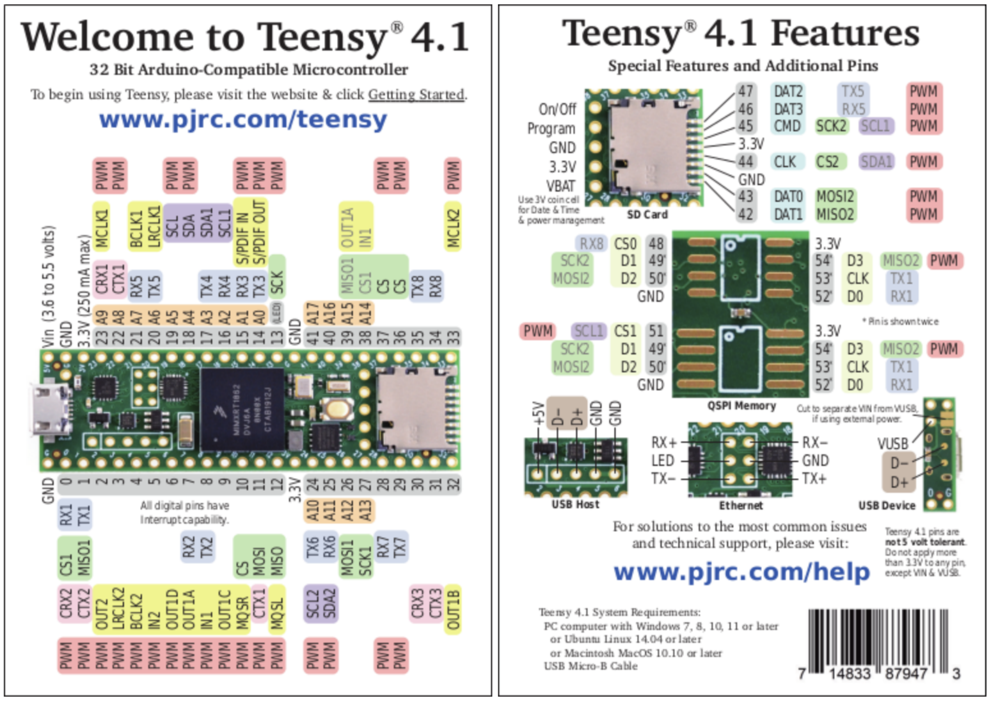
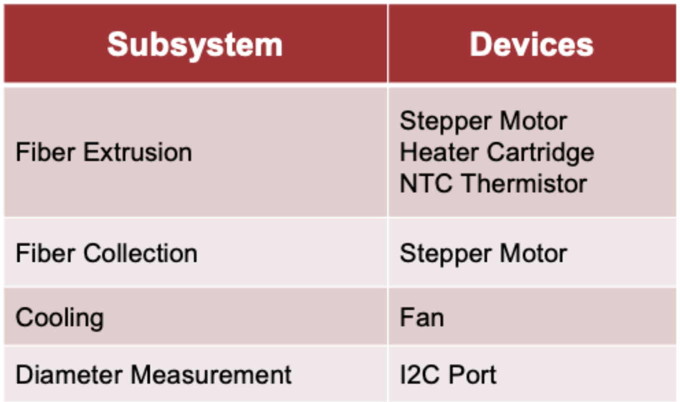


Figure 39. Teensy I/O [18]

3.2 Sensors and Actuators

Looking at the subsystems of FrED we would require a Stepper Motor for the Fiber Collection System, another Stepper Motor for the Extrusion System, a Heater Cartridge for the Extrusion System, a Thermistor for the Extrusion System and a fan for the Cooling System. These requirements are summarized in Table 3 below. The requirements for selecting actuators is as simple as being able to meet the mechanical design requirements in terms of dimensions and functionality, and to operate at 12V for the electronics design requirement.

Table 3. Device Requirements for FrED



Subsystem	Devices
Fiber Extrusion	Stepper Motor Heater Cartridge NTC Thermistor
Fiber Collection	Stepper Motor
Cooling	Fan
Diameter Measurement	I2C Port

Selecting a Stepper Motor

Stepper motors are widely available in different voltage, current and torque ratings. The search was narrowed down to NEMA 17 stepper motors used in desktop extrusion 3D printers. This is because they can be easily sourced and the cost has been significantly lowered due to the mass adoption of desktop extrusion 3D printers. The NEMA 17HS4401 stepper motor is selected [22]. It is the same model as those being used for desktop extrusion 3D printers such as the Creality Ender 3. The specifications of the motor can be seen in Figure 40.

Handson Technology

Data Specs

17HS4401S 1.7A Torque:43N.cm Stepper Motor

A stepper motor to satisfy all your 3D-Printer, robotics, Linear Motion projects needs! This 4-wire bipolar stepper has 1.8° per step for smooth motion and a nice holding torque. The motor was specified to have a max current of 1.7A/phase so that it could be driven easily with common motor shield for Arduino (or other motor driver) and a wall adapter or lead-acid battery. The motors are supplied with a 50cm long power cable with a 4-pin Harwin female connector already fitted - ready to plug and print!

Brief Data:

- Nema17 Bipolar.
- Number of Phase: 2.
- Step Angle: 1.8°.
- Phase Voltage: 2.6Vdc.
- Phase Current: 1.7A.
- Resistance/Phase: 1.5Ω ±10%.
- Inductance: 2.8mH ±20% (1KHz).
- Number of Wire: 4 (100cm Length).
- Holding Torque: 43Ncm.
- Shaft Diameter: Ø5mm.
- Motor Length: 40mm.
- Rotor Inertia: 54gcm^2.
- Temperature rise: 80°C Max.
- Insulation Class: B.
- Dielectric Strength: 500VAC/1-minute.
- Mass: 280g.

1 | www.handsontec.com

Figure 40. NEMA 17HS4401 stepper motor specification sheet [22]

Selecting a Heater Cartridge

A 12 Volts, 40 Watts heater cartridge was selected, shown in Figure 41. This heater cartridge is selected based on its popularity among desktop extrusion 3D printers. With similar reasons to the stepper motor selection, these heater cartridges are readily available at low costs. The design of the heater cartridge is very convenient, with the coils packaged in a cylindrical cartridge, this makes it easier for integration to designs just by inserting and fastening it to a hole. In addition to that, the cartridge is equipped with heat resistant cables, which eliminates the need for additional cable assemblies.

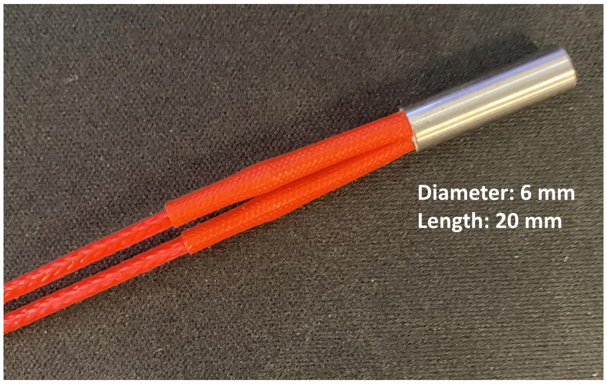


Figure 41. Heater Cartridge

Selecting a Thermistor

The thermistor selected is a NTC 3950 10K thermistor, meaning that it has resistance of 10k ohms at room temperature of 25degC and B coefficient of 3950. The thermistor is capable of measuring temperature with a range of -55 °C to 125 °C [23].

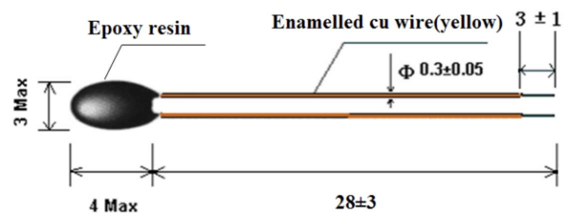


Figure 42. NTC Thermistor dimensions [23]

Selecting a Fan

A 4010 12V DC fan is selected due to its compact size and its capability to operate at 12 Volts [24]. These fans are commonly used for cooling in electronic devices.

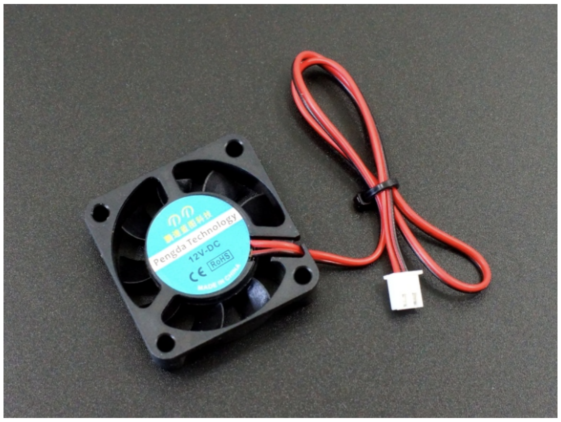


Figure 43. 12V 4010 Fan [24]

3.3 12V Power Supply Unit

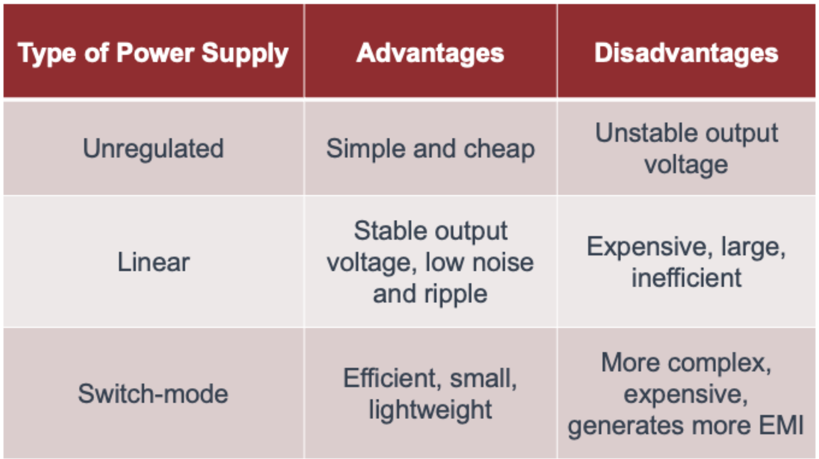
It was deciced that FrED runs on 12 Volts power. FrED require a power supply that takes in 100-120 Volts AC for use in countries such as United States and Japan, and 220-240 Volts AC for the rest of the world. The output should be 12 Volts DC and at least 61.7 Watts which converts to at least 5.14 Amperes, as shown in Table 4 below.

Table 4. Power Consumption of Electronic Devices in a FrED

Device	**Power (W)**
2 Stepper Motors	18
Heater Cartridge	40
Fan	1.2
Teensy	2.5
Total	**61.7**

A suitable power supply unit has to be chosen to power FrED. Industrial machinery uses mainly three types of power supply unit, unregulated power supply, linear power supply and switched-mode power supply (SMPS) [25]. A comparison of the three power supply can be found in Table 5. SMPS still remains the dominant type of power supply in industrial applications although a few specific applications still demands unregulated and linear power supply. Consumer electronics such as laptops and desktop computers use switching mode power supply. The mass adoption of SMPS in consumer electronics has made it cheap although it has a relatively complex architecture. SMPS is chosen to be the type of power supply used for FrED due to it’s low costs, high availability and suitability for the application.

Table 5. Comparison of Power Supply Types



Type of Power Supply	Advantages	Disadvantages
Unregulated	Simple and cheap	Unstable output voltage
Linear	Stable output voltage, low noise and ripple	Expensive, large, inefficient
Switch-mode	Efficient, small, lightweight	More complex, expensive, generates more EMI

There are two types of SMPS in consideration for FrED. One is housed in a metal housing, commonly used for DIY projects as shown in Figure 44. The other is housed in a plastic enclosure, commonly used for laptop chargers, as shown in Figure 45.

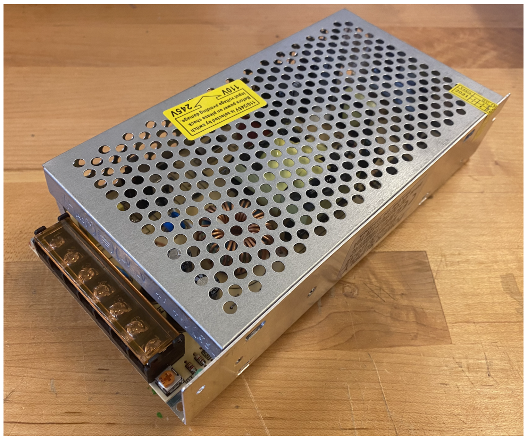


Figure 44. SMPS with Metal Casing

Figure 45. SMPS with Plastic Housing

It was decided that FrED will use the SMPS power supply that is housed in a plastic enclosure because it is more user friendly. It does not need any assembly and there are no exposed live AC wires. However, these type of power supply is only available in less than 200W ratings. This will not be a problem for the current FrED design, but will require changing if future power requirements of FrED increases. A 12V 10A power supply was sourced with a IEC-60320 C13 connector. This would allow the power supply to be used with multiple countries' electrical outlets, given a IEC-60320 C14 cable. IEC-60320 C14 cables can be purchased from electronic stores, in layman terms also known as 'power cord', shown in Figure 46.

Figure 46. IEC-60320 C14 power cord

3.4 Voltage Regulators 12V power and 3.3V and 5V electronics

The electronics of FrED operate at different voltages: 3.3V, 5.0V and 12.0V. 3.3 Volts is required for any I/O signal and power of the Teensy microcontroller. 5.0 Volts is required for I2C communication to a Raspberry Pi or most Arduino boards.12.0 Volts is required for powering most of the actuation devices such as stepper motors, heater cartridge and fan.

The input DC voltage from the SMPS is 12.0 Volts. This would need to be converted to both 3.3V and 5.0V. This is done through using a step down voltage regulator to create a 3.3V and 5.0V line on the PCB. Two step down circuits are built based using LM2596S-3.3 and LM2596S-5.0 step-down switching regulator IC for the 3.3V and 5.0V line respectively, shown in Figure 47 and Figure 48 [26]. Both step-down switching regulator ICs have similar architecture, but one has a 3.3V and the other has a 5.0V output. A capacitor and inductor is added to the output of the voltage regulator IC to smoothen the output voltage and current respectively.

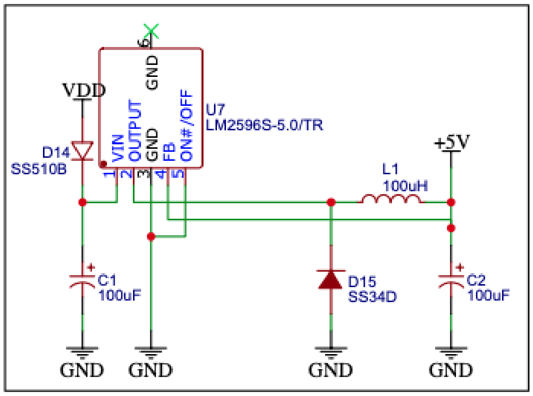


Figure 47. 12V to 5V Stepdown Circuit

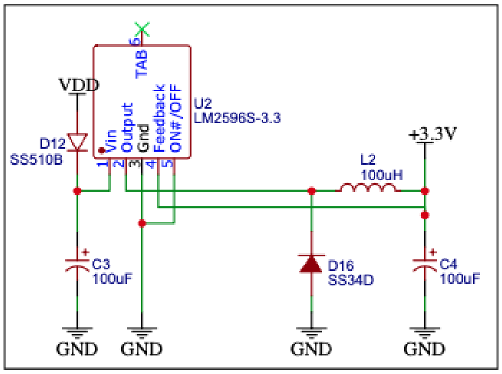


Figure 48. 12V to 3.3V Step Down Circuit

The limitations of these circuits is that they have a maximum 3.0A load rating. It means that the devices that draw power from the 3.3V and 5.0V line could not have a cumulative of 3.0A rating on each line.

3.5 Stepper Motor Drivers

The electronics subsystem is required to control two stepper motors. One for the fiber extrusion subsystem and another for the fiber collection subsystem. The NEMA 17 stepper motors that were selected run on at least 12 V and maximum of 1.7A. Stepper motor runs on a pulsing electric current and converts these pulses into step rotations. The standard step is 1.8 degrees, equivalent to 200 steps per rotation.

In order to be able to control and send pulses of current at 12 Volts to the stepper motor, we require a stepper driver to amplify the output signal from the microcontroller into 12 Volts pulses, at the same time limit the output current to not exceed the current rating of the stepper motor. The stepper driver DRV8825, Figure 49, is selected due to its capability to handle the specified voltage and current ratings [27]. The electronic subsystem requires two of these stepper drivers to control two stepper motors as one driver only controls one stepper motor. DRV8825 can be bought off the shelf as it is commonly used in filament 3d printers. It comes with 2.54 mm male header connectors. The PCB would need to accommodate these stepper drivers by having 2.54 mm female header connectors, as shown in Figure 50. The schematic of the DRV8825 connectivity within the PCB is shown in Figure 51.

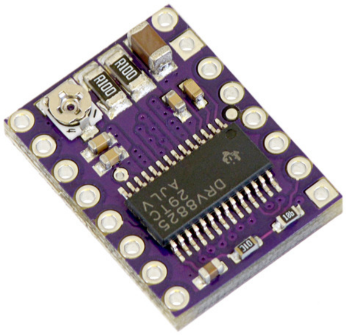


Figure 49. DRV8825 Stepper Driver [27]

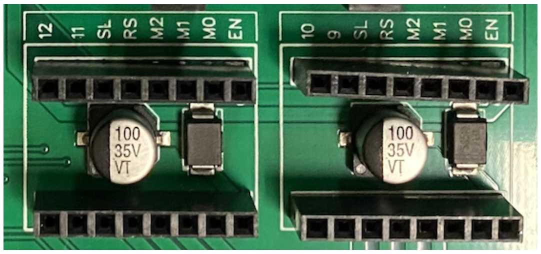


Figure 50. Female Header Connectors on PCB

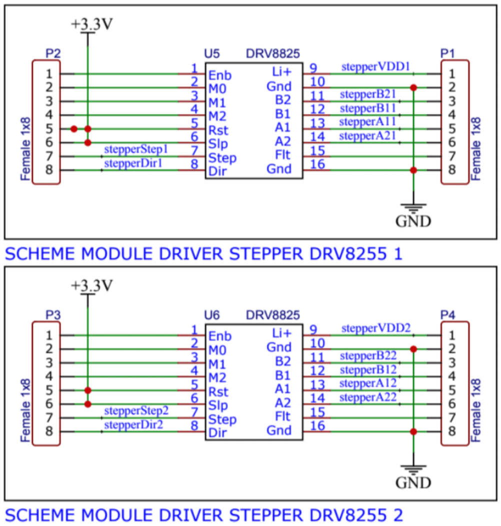


Figure 51. Schematic for Stepper Driver Connections

The stepper driver requires tuning to limit the amount of current flowing through the motor. This is done to prevent overflow of current which typically results to the overheating of the motor. Tuning is also done to ensure that there is enough current flowing through the motor to provide the required torque and speed. This can be done using a simple circuit as shown in Figure 52 [28], monitoring the current flow to the motor while adjusting the potentiometer in the driver module.

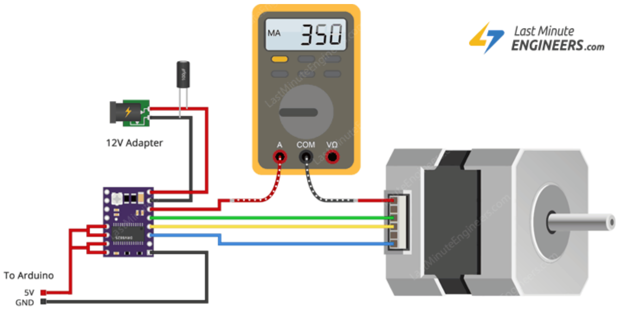


Figure 52. Tuning a Stepper Motor Driver [28]

3.6 PWM Drivers (Heater and Fan)

The heater cartridge and fan are loads. It is required that the electronics can control the intensity of the heating and the fan blowing to teach concepts such as PID controls. It would not be possible to teach PID control concepts with simple on-and-off controls on the heater cartridge and fan. Pulse width modulation (PWM) is needed to adjust the intensity of the heating and the fan blowing by varying the power output of the heater cartridge and fan.

Heater cartridge and fan can be considered as a fixed resistance in a Thevenin equivalent circuit. To adjust the power output of these loads, we can vary the relative voltage applied to the load given by Ohms law. This is achieved by rapidly turning on and off the 12V power supplied to the load, also known as pulse width modulation (PWM). The ratio of the amount that the power is on compared to the total time that the load is operational is called the duty cycle. The duty cycle is directly correlated with the relative voltage applied to the load. The extremes are that the power is off (0% duty cycle) and the power all at all time (100% duty cycle).

The microcontroller is capable of generating square wave PWM signals at 3.3V from its analog I/O pins. A pulse width modulation driver is required to amplify this 3.3V PWM signal into an equivalent 12V PWM output to the load. A PWM driver circuit is constructed as shown in Figure 53. The PWM driver circuit uses an optocoupler (PC817C-S) [29] and a MOSFET (IRLR7843TRPBF) [30]. The optocoupler isolates the high voltage circuit from the low voltage signals. The MOSFET acts as a switch that amplify voltages in circuits.

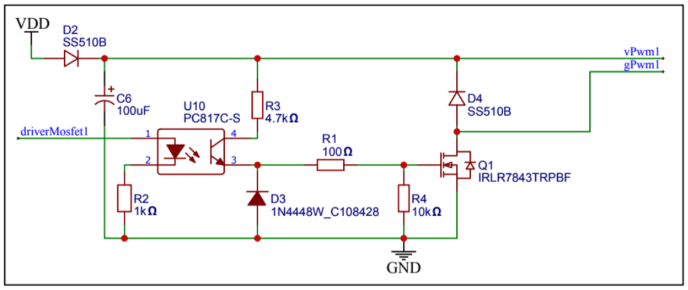


Figure 53. PWM Driver Circuit

3.7 Voltage Divider

The thermistor used is a negative temperature coefficient (NTC) thermistor. Its resistance decreases as its temperature increases. The temperature can be derived from the resistance value of the thermistor using the Steinhart-Hart equation. The microcontroller does not have the capability to read resistance value, only voltage values through its analog I/O. A voltage divider circuit is constructed to read the voltage drop across the thermistor, shown in Figure 54. The thermistor selected is a NTC 3950 10K thermistor, meaning that it has resistance of 10k ohms at room temperature of 25degC and B coefficient of 3950.

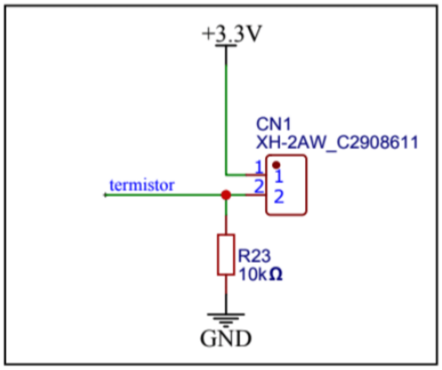


Figure 54. Voltage Divider Circuit for NTC Thermistor

Using the potential divider principles, the equation below is derived to convert the analog voltage input to the microcontroller to resistance value of the thermistor:

$$V_R = X_{AR} * \frac{V_{CC}}{1023}$$

$$R_T = (V_{cc} - V_R) * \frac{R}{V_R}$$

Where:
R_T is the resistance of the thermistor
R is the fixed resistance
V_{CC} is the voltage supplied
V_R is the voltage across resistor
X_{AR} is the analog reading (ranges 0-1023)

Figure 55. Equation to find resistance of thermistor

Re-arranging the Steinhart-Hart equation, we can find the temperature value using the resistance value derived from the prior equation.

$$T_X = \frac{1}{\left(\frac{\log_{10} R_T/R_{T0}}{\mathrm{B}}\right) + \left(\frac{1}{\mathrm{T}_0}\right)}$$

Where:
T_X is the temperature of the thermistor in Kelvin
R_T is the resistance of the thermistor
R_{T0} is the resistance of the thermistor at room temperature
B is the beta thermistor constant
T_0 is room temperature in Kelvin

Figure 56. Equation to find temperature reading of thermistor

3.8 TxRx Channels

Multiple Tx and Rx channels are readily available within the Teensy microcontroller to allow inter device communications. However, a problem may arise when the other devices runs at a different voltage than the Teensy microcontroller. One such example would be when interfacing a Teensy which runs at 3.3V with a Raspberry Pi which runs at 5.0V. To overcome this problem, a TxRx circuit that can interoperate with a 5.0V device was built, shown in Figure 57.

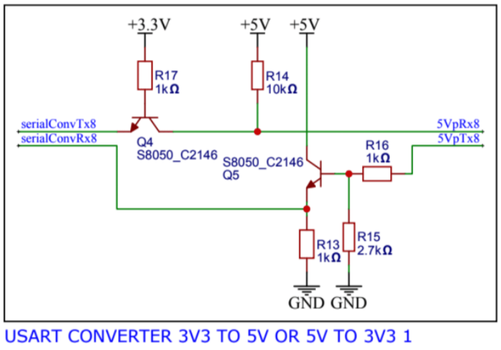


Figure 57. TxRx Schematic for Different Voltages

3.9 Connectors

Various electrical and signal connectors are designed on the PCB to ensure safe and reliable connections to the PCB. Various connectors are used in the electronics system:

1. JST XH Connectors, Figure 58 - These are used mainly to transmit signals. They are rated to 3A of maximum current. They provide a reliable connection for cables to PCB. This are used to connect devices such as the stepper motors, fan and thermistor.
2. 2.54mm Header Pins, Figure 59 - These are mainly to transmit signal. They are rated to 3A of maximum current. They provide a strong connection between PCB boards and can be soldered on. These are used to connect pre-built modules such as the Teensy microcontroller unit and the stepper drivers.
3. Terminal Blocks, Figure 60 - Terminal blocks are mainly used to transmit power. It provides a secure connection through the ability to tighten the connection with a screwdriver. It is used for connecting the main power supply to the PCB and transmitting power to the heater cartridge.
4. Ferrules, Figure 61 - Ferrules are used to reinforce strands of wire. Stranded-wire cables are reinforced with ferrules before connected to the terminal blocks to avoid accidents of stray wiring shorting.

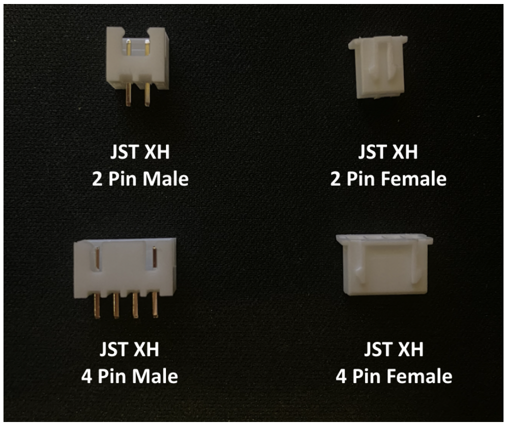


Figure 58. JST XH Connectors

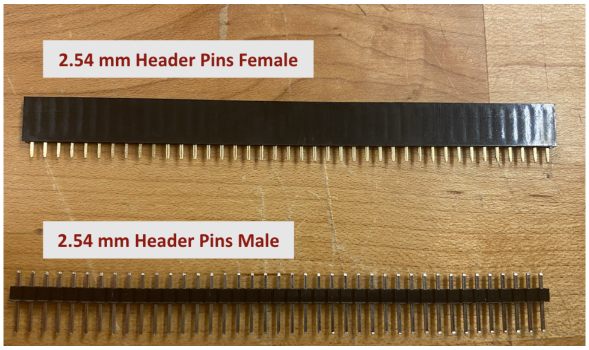


Figure 59. 2.54 mm header pins

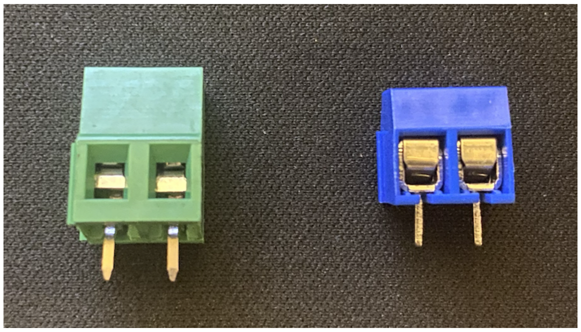


Figure 60. Terminal Blocks

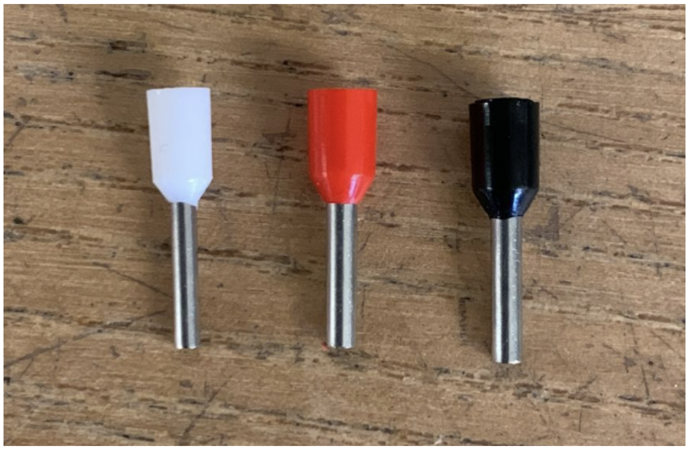


Figure 61. Ferrules

3.10 PCB Fabrication

PCB fabrication is outsourced to a Chinese contract manufacturer JLC PCB. This is due to their capability to deliver low cost PCB assembly (both manual and automated) at a short lead time. A PCBA was designed using the EasyEDA software that was provided by the contract manufacturer. The printed circuit board assembly (PCBA) required both automated assembly for the surface mount devices (SMD) and manual assembly for most of the connectors as they use through hole technology (THT). The specifications of the PCB is given below, in Tables 6 and 7.

Table 6. PCB Specifications

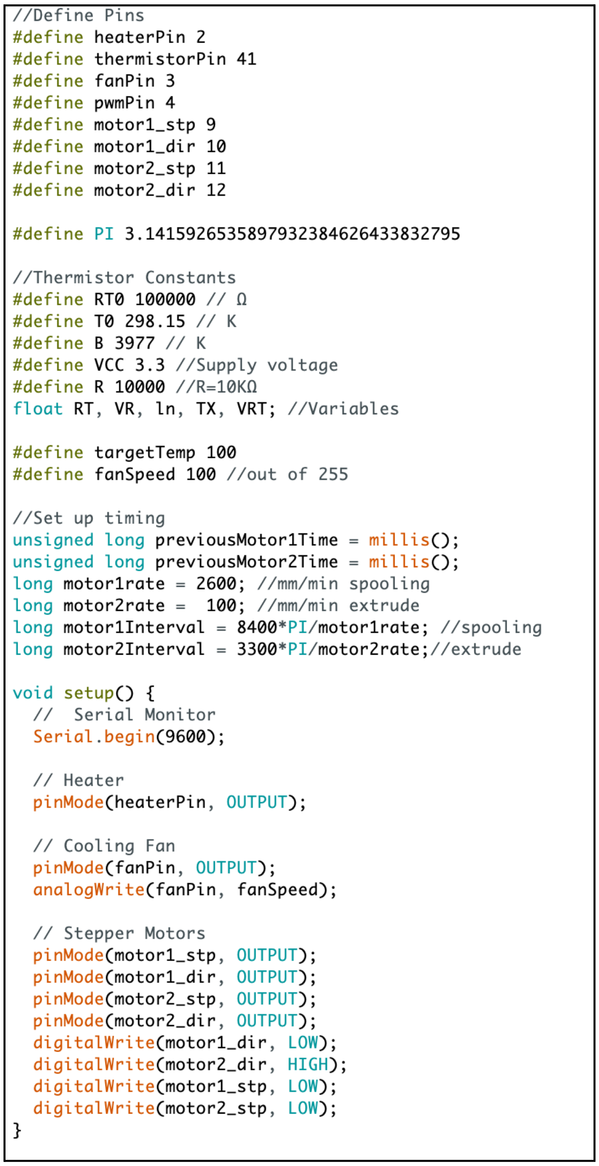
Gerber file:	Gerber_PCB_PCB_Russelbradley_2022-07…	Build Time:	2-3 days
Base Material:	FR-4	Layers:	2
Dimension:	105.4 mm* 102.9 mm ~~102.87mm* 105.41mm~~	PCB Qty:	5
Product Type:	Industrial/Consumer electronics	Different Design:	1
Delivery Format:	Single PCB	PCB Thickness:	1.6
Impedance Control:	no	Layer Sequence:	
PCB Color:	Green	Silkscreen:	White
Via Covering:	Tented	Surface Finish:	HASL(with lead)
Deburring/Edge rounding:	No	Outer Copper Weight:	1 oz
Gold Fingers:	No	Flying Probe Test:	Fully Test
Castellated Holes:	no	Remove Order Number:	No
4-Wire Kelvin Test:	No	Paper between PCBs:	No
Appearance Quality:	IPC Class 2 Standard	Confirm Production file:	No

Table 7. PCBA BOM

Comment	Designator	Footprint	JLCPCB Part #
PC817C-S	U10,U11,U12	SOP-4_L6.5-W4.6-P2.54-LS10.3-TL	C3008369
A2541WV-2X4P	H2,H4,H10	HDR-TH_8P-P2.54-V-R2-C4-S2.54_A2541WV-2X4P	C225519
KF301-5.0-2P	U13	CONN-TH_P5.00_KF301-5.0-2P	C474881
2.7kΩ	R15,R20	R0805	C352230
10kΩ	R4,R5,R12,R14,R21,R23	R0805	C328436
XYEK500-5.08-2P	U8,U9	CONN-TH_XYEK500-5.08-2P	C557687
4.7kΩ	R3,R6,R11	R0805	C328444
Header-Male-2.54_2x3	J1,J2,J3,J8	HDR-TH_6P-P2.54-V-M-R2-C3-S2.54-1	C65114
XH-2AW_C2908611	CN2,CN3,CN1	CONN-TH_XH-2AW_C2908611	C2908611
SS510B	D1,D2,D4,D5,D6,D7,D10,D13,D11,D12,D14	SMB_L4.6-W3.6-LS5.3-RD	C169413
1kΩ	R2,R7,R10,R13,R16,R17,R18,R19,R22	R0805	C881062
XH2.54-4AW	CN7,CN8	CONN-TH_XH2.54-4AW	C21273
100Ω	R1,R8,R9	R0805	C328380
1N4448W_C108428	D3,D8,D9	SOD-123_L2.8-W1.8-LS3.7-RD	C108428
Header-Female-2.54_1x5	H6,H7	HDR-TH_5P-P2.54-V-F	C50950
S8050_C2146	Q4,Q5,Q6,Q7	SOT-23-3_L3.0-W1.7-P0.95-LS2.9-BR	C2146
Header-Male-2.54_2x5	H8,H9,H5	HDR-TH_10P-P2.54-V-M-R2-C5-S2.54	C225520
100uH	L2,L1	IND-SMD_L7.5-W7.5_CYH74	C36970
X8821WR-03S-N0SN	CN4,CN6	CONN-TH_3P-P2.50_X8821WR-03S-N0SN	C388740
100uF	C5,C6,C7,C8,C11,C1,C2,C3,C4,C9	CAP-SMD_BD6.3-L6.6-W6.6-LS7.2-FD	C2887272
IRLR7843TRPBF	Q1,Q2,Q3	TO-252-2_L6.5-W6.1-P4.58-LS10.0-TR	C21988
Header-Female-2.54_2x8	J6,J7,J9,J10,J4,J5	HDR-TH_16P-P2.54-V-F-R2-C8-S2.54-1	C30734
LM2596S-3.3	U2	TO-263-5_L10.0-W8.4-P1.70-LS15.3-BR	C347420
Female1x8	P1,P2,P3,P4	HDR-TH_8P-P2.54-V-F-1	C27438
LM2596S-5.0/TR	U7	TO-263-5_L10.2-W8.6-P1.70-LS14.4-TL	C194349
SS34D	D15,D16	SMB_L4.6-W3.6-LS5.3-RD	C84634
X6511WV-24H-C30D60	H1,H3	HDR-TH_24P-P2.54-V-M	C725956

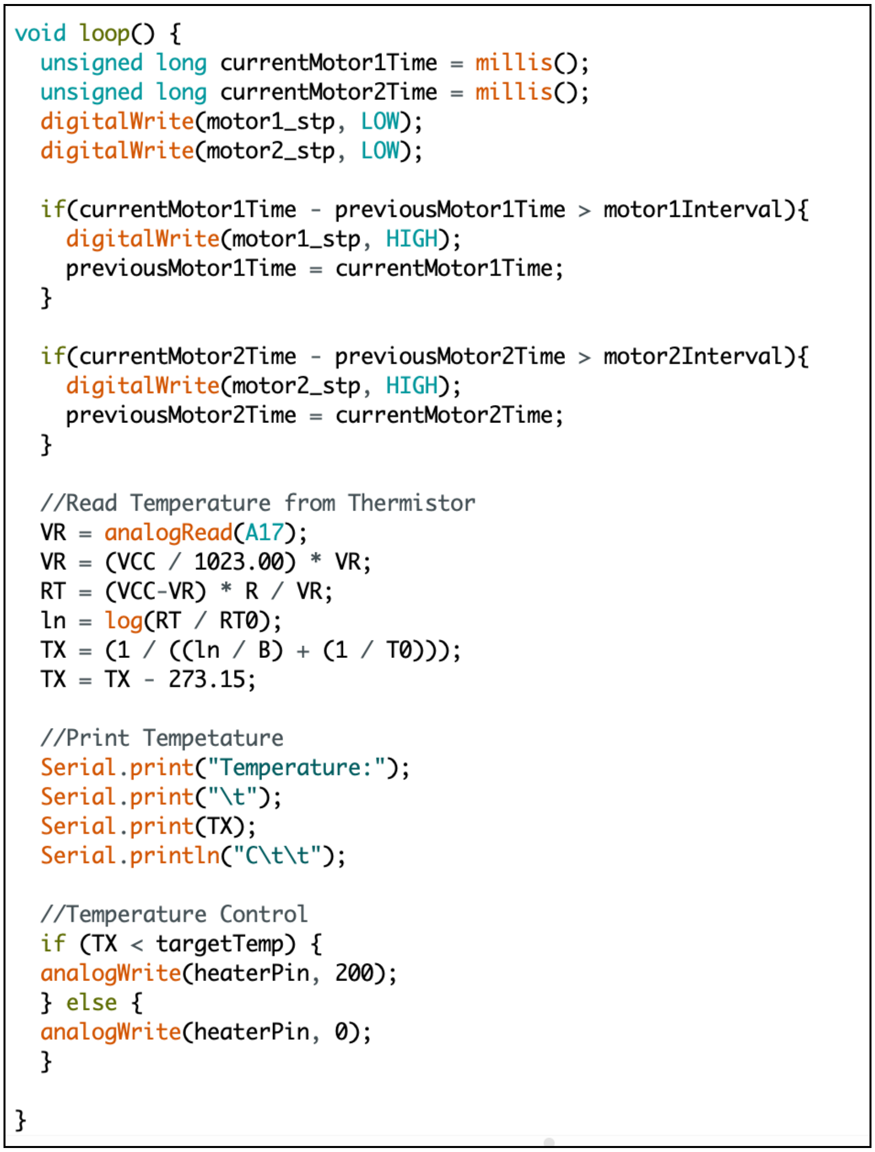
3.11 Code

A simple code was written to test FrED’s functional requirement, shown in Figure 62 and 63.



```
//Define Pins
#define heaterPin 2
#define thermistorPin 41
#define fanPin 3
#define pwmPin 4
#define motor1_stp 9
#define motor1_dir 10
#define motor2_stp 11
#define motor2_dir 12

#define PI 3.1415926535897932384626433832795

//Thermistor Constants
#define RT0 100000 // Ω
#define T0 298.15 // K
#define B 3977 // K
#define VCC 3.3 //Supply voltage
#define R 10000 //R=10KΩ
float RT, VR, ln, TX, VRT; //Variables

#define targetTemp 100
#define fanSpeed 100 //out of 255

//Set up timing
unsigned long previousMotor1Time = millis();
unsigned long previousMotor2Time = millis();
long motor1rate = 2600; //mm/min spooling
long motor2rate =  100; //mm/min extrude
long motor1Interval = 8400*PI/motor1rate; //spooling
long motor2Interval = 3300*PI/motor2rate;//extrude

void setup() {
  //  Serial Monitor
  Serial.begin(9600);

  // Heater
  pinMode(heaterPin, OUTPUT);

  // Cooling Fan
  pinMode(fanPin, OUTPUT);
  analogWrite(fanPin, fanSpeed);

  // Stepper Motors
  pinMode(motor1_stp, OUTPUT);
  pinMode(motor1_dir, OUTPUT);
  pinMode(motor2_stp, OUTPUT);
  pinMode(motor2_dir, OUTPUT);
  digitalWrite(motor1_dir, LOW);
  digitalWrite(motor2_dir, HIGH);
  digitalWrite(motor1_stp, LOW);
  digitalWrite(motor2_stp, LOW);
}
```

Figure 62. Simple Arduino Code (Setup)



```
void loop() {
  unsigned long currentMotor1Time = millis();
  unsigned long currentMotor2Time = millis();
  digitalWrite(motor1_stp, LOW);
  digitalWrite(motor2_stp, LOW);

  if(currentMotor1Time - previousMotor1Time > motor1Interval){
    digitalWrite(motor1_stp, HIGH);
    previousMotor1Time = currentMotor1Time;
  }

  if(currentMotor2Time - previousMotor2Time > motor2Interval){
    digitalWrite(motor2_stp, HIGH);
    previousMotor2Time = currentMotor2Time;
  }

  //Read Temperature from Thermistor
  VR = analogRead(A17);
  VR = (VCC / 1023.00) * VR;
  RT = (VCC-VR) * R / VR;
  ln = log(RT / RT0);
  TX = (1 / ((ln / B) + (1 / T0)));
  TX = TX - 273.15;

  //Print Tempetature
  Serial.print("Temperature:");
  Serial.print("\t");
  Serial.print(TX);
  Serial.println("C\t\t");

  //Temperature Control
  if (TX < targetTemp) {
  analogWrite(heaterPin, 200);
  } else {
  analogWrite(heaterPin, 0);
  }

}
```

Figure 63. Simple Arduino Code (Loop)

4. Design for Manufacturing and Assembly

This section discusses the design and manufacturing decisions that were made to streamline manufacturing and assembly operations of FrED.

4.1 Filament Additive Manufacturing (Process)

Filament additive manufacturing was selected because of the significant cost difference in low volume production settings, the ability to produce complex geometry, and the flexibility for design changes.

Assuming a demand for 500 FrEDs per year, which means that minimum 500 units of a unique part has to be made for FrED. At this quantity, processes such as injection molding still present a greater cost than additive manufacturing, due to the initial mold cost in injection molding. In addition to costs, lead time to produce the first part will be faster for additive manufacturing as no fixed tooling is required while injection molding requires the fabrication of a mold before even being able to produce the first part.

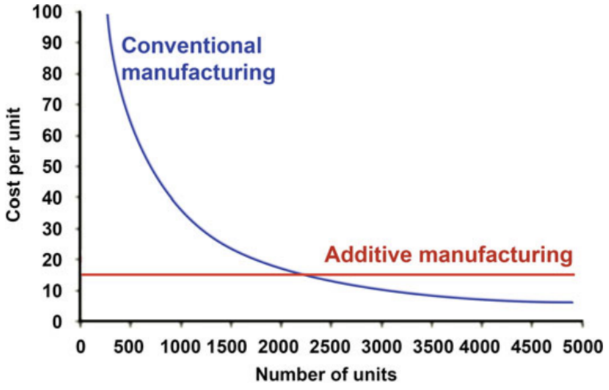


Figure 64. Cost per unit vs number of units for conventional and additive manufacturing [31]

In additive manufacturing, complexity is free. This means that a part with more features and more complex features may not have a significant cost difference than a simple part. This allows the designer additional freedom when designing FrED components. This also allows parts consolidation, combining assembly into a single part, which can help to minimize fasteners and assembly operations needed.

With additive manufacturing, making alterations to the design is relatively easy and cost-effective. Unlike injection molding, which requires the creation of fixed tooling that can be expensive and time-consuming to modify, additive manufacturing allows for quick and seamless design iterations.

There are many choices for additive manufacturing technology. This was narrowed down to fused filament fabrication (FFF) because the process uses polymer, cost, and the simplicity of operations. Polymer is used as the material for additively manufactured FrED components due to the cost of polymer printing technology as compared to metal additive manufacturing. Polymer would also meet the design requirements, so using metal would be an overkill. The cost of FFF additive manufacturing is very low, with machines producing high quality parts starting from about US$1000. Machines using stereolithography (SLA) and selective laser sintering (SLS) technology start at a higher price of about US$10000. The FFF workflow also requires minimal post processing, with the only necessary post processing needed is support removal. Post processing can be avoided by printing parts that do not require support. While SLA technology requires additional washing and curing, and SLS requires powder removal post printing.

The particular machines selected for FrED are the Prusa i3 Mk3S+ printers, shown in Figure 65 [32]. They are the latest version of Prusa machines as of Summer 2022. They produce high quality plastic parts with simple operations. This is due to their advanced technology in their control system, hardware and sensors. The Prusa machines feature automatic bed leveling, which solves the bed leveling issue that causes most process failures. This would also simplify day to day operations by eliminating the need for manual tuning and calibration before every print. The machines cost $749 as of Summer 2022.

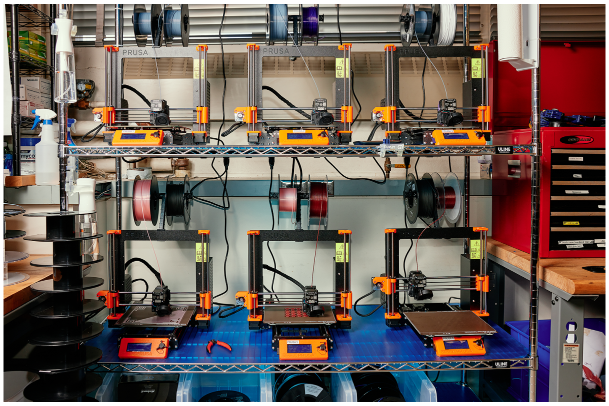


Figure 65. Prusa i3 Mk3S+ Machines

FrED requires small and detailed components such as gears. Gear teeth are very fine features that require relative precision for them to operate in a system. Such fine features would require a high process resolution, which is minimal difference between the CAD model and the actual part. The Z direction resolution is affected by layer height while the X-Y direction resolution is arguably limited by the nozzle size. The Z direction is affected by the layer height and the staircase effect, shown in Figure 66. The nozzle size limits the accuracy of the prints as it applies a radius and limits the feature size to it's diameter, shown in Figure 67. A machine was modified with a 0.25 mm nozzle to fulfill the requirements of printing fine gear teeth. Parts that require fine feature resolution were made using the machine with the 0.25mm nozzle.

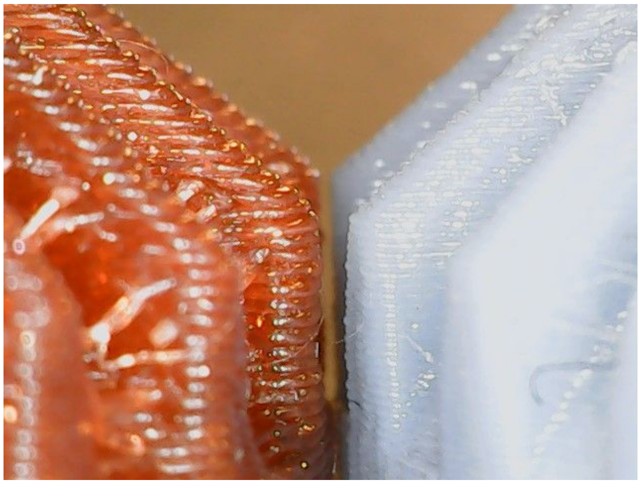


Figure 66. Gears printed with 0.4 mm (left) vs 0.25 mm (right) nozzle

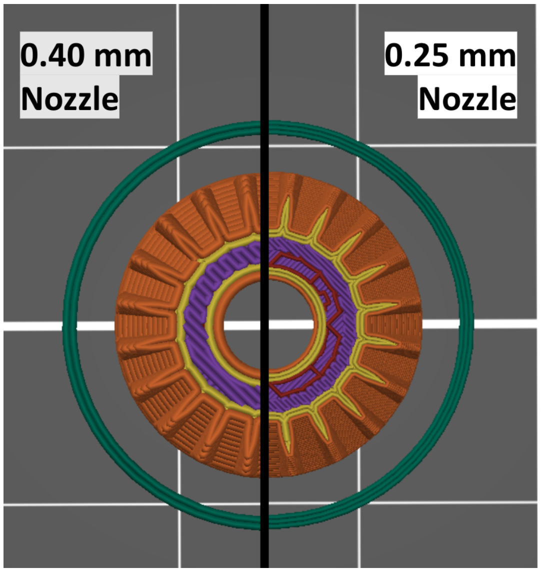


Figure 67. Gears sliced with 0.4 mm (left) vs 0.25 mm (right) nozzle

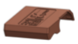
PLA and PETG are two common filament additive manufacturing materials, both possess material properties which makes them easy to print, but has slightly different mechanical properties. Both materials are compared and contrasted in Table 8. Both PETG and PLA are used for FrED parts. Generally parts that bear load are printed with PETG. The PETG used is grey and the PLA used is red in color, making a good contrast on aesthetics, and enforces the MIT branding.

A summary of parts and their 3D printing specifications is presented in Table 9.

Table 8. Comparison of PLA vs PETG filament additive manufacturing

Feature	PLA	PETG
Printability	Easy to print, low printing temperature	Slightly more challenging, higher temperature
Warping Resistance	Low warping, good for large prints	Moderate warping, requires careful setup
Strength	Lower tensile strength and impact resistance	Higher tensile strength and impact resistance
Flexibility	More rigid and brittle	More flexible and less prone to breaking
Heat Resistance	Low heat resistance, softens around 60-65˚C	Moderate heat resistance, softens around 80˚C
Moisture Resistance	Sensitive to moisture absorption	Resistant to moisture absorption
Chemical Resistance	Limited resistance to chemicals	Good resistance to chemicals
Transparency	Transparent and translucent options available	Generally opaque
Print Details and Accuracy	Good for fine details and intricate designs	Slightly less detailed, visible layer lines
Biodegradability	Biodegradable and derived from renewable sources	Not biodegradable, derived from petrochemicals

Table 9. 3D Printed FrED Parts Process Specification

Part ID	Image	QTY per FrED	Material	Nozzle Size (mm)	Cost ($)	Printing Time (min)	Max Height in Printing Orientation (in)	Base Area in Printing Orientation (mm^2)
FrED-C-002		1	PETG	0.4	0.73	168	2.72	2229.61
FrED-DM-001		1	PETG	0.4	2.98	640	4.14	3418.78
FrED-DM-002		1	PETG	0.4	0.14	27	0.47	769.79
FrED-DM-003		2	PLA	0.4	0.08	84	0.33	411.35
FrED-DM-004		1	PETG	0.4	0.11	16	0.06	2003.54
FrED-E-004		1	PETG	0.4	1.93	298	1.35	14754.73
FrED-E-005		1	PETG	0.4	1.54	233	0.23	9046.72
FrED-FC-005		1	PETG	0.25	0.21	190	0.48	1597.98
FrED-FC-006		1	PETG	0.4	0.53	103	1.25	2712.55
FrED-FC-008		1	PLA	0.4	0.71	132	2.63	505.92
FrED-FC-009		1	PLA	0.4	0.66	62	0.78	126.48
FrED-FC-010		1	PETG	0.25	0.06	61	0.38	383.41
FrED-FC-011		1	PETG	0.25	0.55	175	3.23	132.73
FrED-FC-015		1	PETG	0.25	0.04	43	0.47	207.35
FrED-FC-016		1	PETG	0.25	0.09	83	0.42	679.22
FrED-FC-017		1	PETG	0.25	0.08	84	0.48	589.15
FrED-FC-021		1	PLA	0.4	1.37	226	0.91	3836.42
FrED-FE-001		1	PETG	0.4	1.45	275	2.36	5243.47
FrED-FE-003		1	PETG	0.4	0.16	36	0.65	497.15
FrED-FE-004		1	PETG	0.4	0.04	12	0.33	197.65
FrED-FR-004		3	PETG	0.4	0.22	33	1.61	242.64
FrED-FR-005		3	PETG	0.4	0.25	51	0.95	999.51
FrED-TH-001		8	PLA	0.4	0.08	13	0.59	392.2
FrED-TH-002		8	PLA	0.4	0.05	8	0.28	392.2

4.2 Design for Additive Manufacturing (Design)

Knowing that the main process used for manufacturing FrED components is Filament Additive Manufacturing, the components were designed using DFAM principles in mind. Design for Additive Manufacturing leverages identifying strengths and limitations of the particular additive manufacturing process, Fused Filament Fabrication (FFF) to design parts.

The following are general Design for Additive Manufacturing principles for most additive manufacturing processes, taken from a book authored by Olaf Diegel, et. al. [31]:

1. It Depends! AM processes vary by process type, materials and machine. Finding specific design parameters and limitations can be found by printing test parts on the machine.
2. Should you be using AM in the first place? AM only brings benefits when the part is complex and for specific applications such as low production complexity. Simple parts that can be quickly and easily machined should not be made with AM in the first place.
3. It doesn't cost more to make things more beautiful. Complexity is free and the designer should use this advantage to enforce certain aesthetics to strengthen the product image/branding. Simple addition of features such as logo could be done at no cost.
4. Fillet all corners. It is good practice to fillet all sharp edges. This serves two purposes: making the product more ergonomic and easy to hold, and reduces the

stress concentrations that occur on sharp corners. In addition to that, fillets come at almost no cost with AM technology.

5. You cannot design for AM without thinking of part orientation. The quality (strength, material properties, surface quality, amount of support, etc.) of every AM part is directly related to the print orientation. Things to consider include anisotropy, roundness of holes, staircasing, overhangs.
6. Design to minimize large masses of material. Large masses of material are more common in CNC machined parts due to the additional time and cost needed to remove them. However, this is the contrary in additive manufacturing as more time, material and energy is needed to add material to the part.
7. Design to minimize support material. Support material is required for overhangs, but can be avoided by adding material to avoid overhangs to the design. Support material means more labor is needed for post processing, adding towards cost. Support material also affects part quality as support leaves marks at point of contact with the part. Overhanging surfaces tend to not print well.

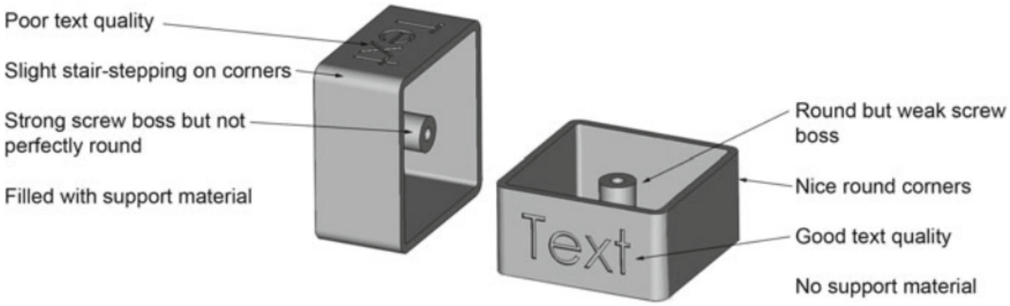


Figure 68. Print orientation affects part quality [31]

Expanding on the first rule of Design for Additive Manufacturing, specific Design for Fused Filament Fabrication guidelines for the Prusa machines were made, in conjunction with general guides from Olaf Diegel, et.al. [31]:

1. Accuracy & Tolerance

Accuracy is how close the part is to the CAD data. Tolerance is the acceptable degree of variation. The numbers for accuracy and tolerance of fused filament fabrication on the Prusa i3 Mk3S+ is summarized in Table 10 below.

Table 10. Accuracy and Tolerance for Prusa i3 Mk3S+ [31][32]

Layer thickness	0.05 – 0.3 mm
Accuracy	±0.03 mm per 25 mm
Tolerance	0.10 mm Z-Axis 0.30 mm XY-Axis
Smallest feature size	Around 1 mm

2. Support and Overhang

Supports are needed when overhangs are present, they allow overhanging features to be printed. Overhangs are defined as parts which extends horizontally beyond 45^{O}. Supports require additional post-processing to remove, so it is best to be avoided in the first place. Designs should consider elimination of overhangs through additions of 45 chamfers, print orientation changes, design changes.

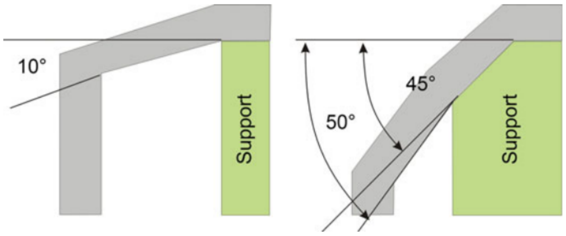


Figure 69. Overhang and Support in 3D printing [31]

3. Layer thickness

Layer thickness affects accuracy of the parts. This is due to the staircase effect seen in Figure 70. A larger layer height will result to a reduced accuracy. This particularly impacts external surfaces that are sloping. Sections of the part which has a series of layers with the same cross section would not be impacted as significantly. On the other hand lowering the layer height will result to a longer print time. This is due to the increased number of layers to be manufactured. The tradeoff between accuracy vs process time should be considered. Strategies such as variable slicing, where different sections of the part can have different layer heights can be considered.

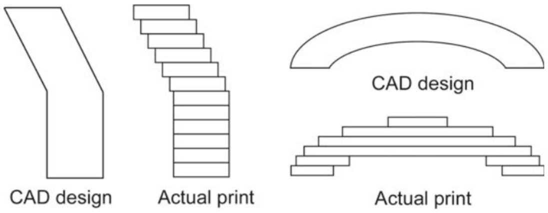


Figure 70. Layer thickness vs accuracy in extrusion 3D printing [31]

4. Nozzle Size

X-Y direction resolution is arguably limited by the nozzle size. The nozzle size limits the accuracy of the prints as it applies a radius and limits the feature size to it's diameter, shown in Figure 67. An analogy would be writing with a pen vs a marker.

The nozzle diameter also limits the layer height. A standard nozzle with diameter 0.4 mm can print layer thickness of 0.1 - 0.3 mm, a 0.25 mm nozzle can print layer thickness of 0.05 - 0.15 mm, and a 0.8 mm nozzle can print layer thickness of 0.3 - 0.55 mm.

Generally FrED parts do not require high accuracy unless they are assembled onto each other, such as a pin and hole mate. Hence, most of the parts can be made with a coarse resolution of 0.3mm layer thickness, which gives relatively faster process times.

5. Infill

Filament 3D printing allow the user to decide whether the part should be printed solid or as a 'sparse' part. The interior scaffolding of a 'sparse' part is called the infill. User can decide between multiple infill pattern and percentages options. Infill pattern affects the speed of the print and the directional strength of the part. Some infill allow strength in all three directions, but most infills only supports stress in two directions. Infill percentages can arguably be related to the strength of the part, although studies have shown that infill percentages above 50% can have diminishing returns. A denser infil takes a longer time to print and consumes more material.

FrED parts are generally made with 20% infill due to the satisfactory strength brought about by that infill density. Some parts such as gears may require the teeth to be printed solid. Instead of adjusting infill density, this is done by adjusting the shell thickness. FrED parts are also sliced with the gyroid infill as it provides strength in all three directions, it is also one of the fastest infill to print as the tool rarely needs to lift throughout the infill printing process.

Figure 71. Infill Density in Extrusion 3D Printing [31]

6. Shell Thickness

The shell thickness can arguably have more affect towards part strength compared to the infill density. The shell thickness refers to the amount of external solid contour lines that is printed before the infill, shown in Figure 72. A part with minimal infill density and a thicker shell would be preferred to get a strong part with the minimum amount of material and print time. FrED parts uses 4-5 layers of shell before the infill.

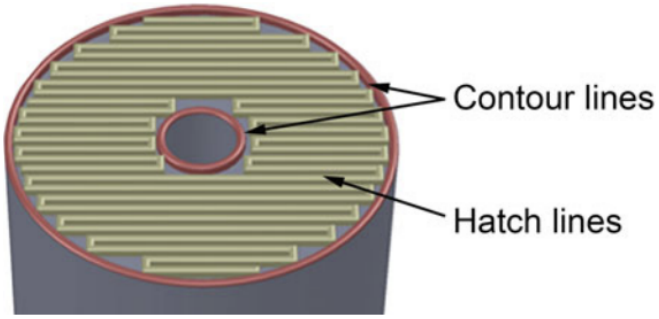


Figure 72. Infill (Hatch Lines) vs Shell (Contour Lines) [31]

7. Vertical wall thickness

The vertical wall thickness, Figure 73, is limited by two things, first the nozzle diameter. The theoretical thinnest wall possible would be a single nozzle pass, so that would be the nozzle diameter of 0.40 mm. In reality, this is not reccomended due to practical issues such as warpage and thermal gradients. It is recommended to go at least twice the nozzle diameter. The second factor is the layer height. A higher layer height would require a thicker wall, due to the inaccuracies. It is recommended to have a minimum wall thickness of four times the layer height. These are summarized in Table 11.

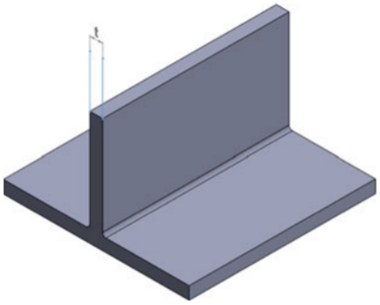


Figure 73. Vertical Wall Thickness Feature [31]

Table 11. Layer thickness vs minimum vertical wall thickness

Layer Thickness	**Theoretical Minimum**	**Recommended Minimum**
0.10 mm	0.20 mm	0.80 mm
0.20 mm	0.40 mm	0.80 mm
0.30 mm	0.60 mm	1.20 mm

8. Vertical holes

Vertical holes are generally built undersized, typically 0.4mm across the diameter smaller than the CAD design, using the Prusa i3 Mk3S+. This can be fixed by approximately offsetting the CAD model to represent a larger than intended hole. This can also be fixed by reaming the hole post printing. It might not be a good idea to have hole and pin connection between 3d printed parts, due to the misrepresentation error. Circles are represented as polygons in 3d printing, there might be a mismatch of polygon representation between the two mating parts.

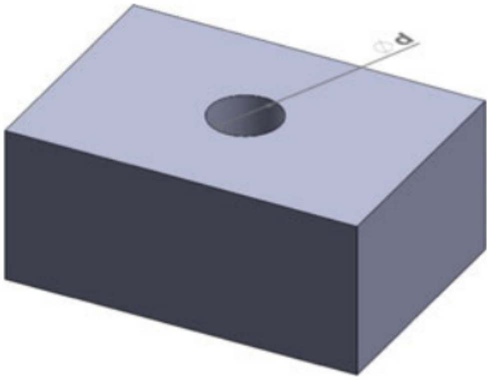


Figure 74. Vertical Circular Hole Feature [31]

9. Circular pins

Pins with small diameters, vertical ones in particular, are prone to breaking off if only supported at one end. Always fillet the pin where it joins the wall. Even 0.5 mm is enough to substantially strengthen the pin. Pins are better when printed vertically. Horizontal pins would be relatively less accurate than vertical pins.

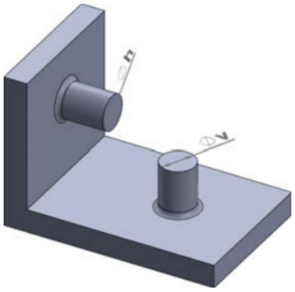


Figure 75. Vertical and Horizontal Circular Pins Feature [31]

10. No Fillets on the Base

Fillets on the base of the part should be avoided as midway printing fillets would result to thin features that encourages the warping of the part. Fillets on the base of a part significantly increases the chance of failure.

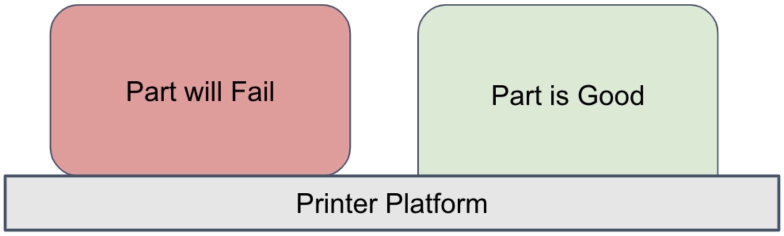


Figure 76. No Fillets on the Base

FrED parts were designed with DfAM in mind. A few examples are shown below. Out of 24 3D printed part types, only the spool requires support. All parts would print with minimal failure and minimal/no post processing.

One of the ways to prevent overhangs is to create teardrop shaped horizontal holes. Normal horizontal round holes would be considered as an overhang or bridge. These would normally require supports to print, otherwise it may not print perfectly and affect the fit of the hole. By shaping the top part of the hole into a right angled triangle, the hole is no longer an overhang and would print perfectly. This would not significantly effect the fit of the pin or screw into the hole. One such example is done on a hole on a gear that will be used to fasten the gear to a rod with a screw, shown in Figure 77.

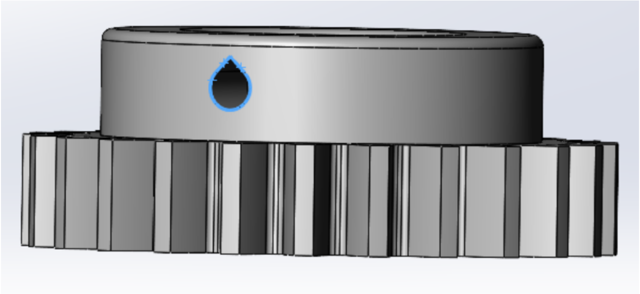


Figure 77. Gear showing modified hole for 3D printing

Another example of design for AM was done on the spool cap. The initial design of the spool cap, Figure 78, was designed ignoring any design for AM rules. It resulted to a part that was almost impossible to manufacture perfectly. The design was challenging to manufacture, multiple printing failures arose and yield was low due to bed adhesion issues. The design was oriented flat with a fillet and required supports to print. Removal of these support materials post-printing resulted to a part with multiple surface defects and slight warpage.

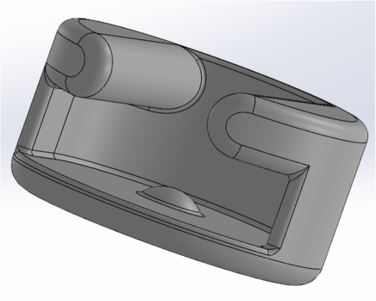


Figure 78. Spool cap without DfAM

A redesign was done to allow the spool cap to be printed upright, with minimal support, shown in Figure 79. The design resulted to better prints as it has a flat surface on the bed. However, support material is still required to print the internal overhanging structure. Support material needed is minimal and does not interface with surfaces critical to assembly. This design is good enough but not fully optimized.

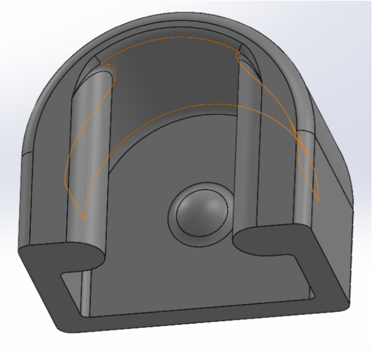


Figure 79. Revised spool cap printed upright

A final redesign was done on the spool cap, shown in Figure 80. The printing orientation was the reverse of the previous design. Instead of the external radius that will result in overhangs and the absence of a flat surface to print, a flat surface and chamfer is designed in place of the radius. The flat surface allows bed adhesion and the chamfer eliminates any overhangs. The current design can be printed without supports and has a high success rate.

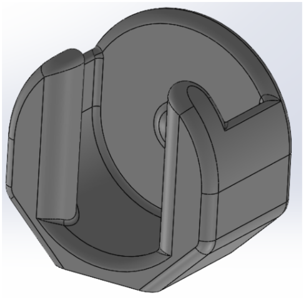


Figure 80. Final design of spool cap with DfAM rules

The fan support, shown in Figure 81 below, is one of the parts designed with DfAM rules in mind. It has a flat surface to be aligned to the printer platform. It has no overhangs. The potential overhang is the fan hole, which was designed in a teardrop shape to prevent overhangs. Excess material is removed, so that print time is reduced and it will cost less.

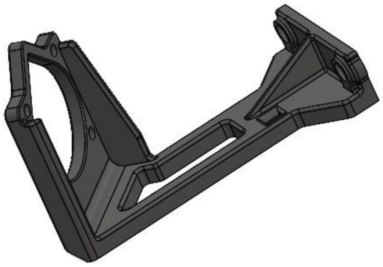


Figure 81. Fan support

4.3 Design for Assembly

Design for Manufacturing and Assembly (DFMA), a systematic methodology of improving manufacturing and assembly of products pioneered by Boothroyd and Dewhurst [33], was used to improve the manufacturability of FrED parts and the ease of assembly of FrED systems.

Some of the Design for Assembly rules are outlined below [33]:

1. Minimize Part Count: Reduce the number of individual parts in the design by consolidating components or utilizing multi-functional parts.
2. Standardize Parts: Use standardized parts whenever possible to simplify procurement, reduce inventory, and streamline assembly operations.
3. Design for Ease of Handling: Ensure parts have suitable features for easy handling during assembly, such as tabs, handles, or grip surfaces.
4. Design for Symmetry: Incorporate symmetry in the design to eliminate orientation constraints during assembly, allowing components to be inserted in multiple directions.
5. Use Self-Aligning Features: Design parts with self-aligning features, such as chamfers or tapered edges, to aid in accurate alignment during assembly.
6. Minimize Assembly Directions: Reduce the number of assembly directions or orientations required to assemble components by optimizing part design and alignment.

7. Avoid Complex Fastening: Simplify fastening methods by using standard fasteners and minimizing the number of unique fasteners required.
8. Design for Easy Access: Ensure that critical components or areas that may require maintenance, adjustment, or replacement are easily accessible during assembly and throughout the product's lifecycle.

It is not easy to apply all of these rules at once, some of the examples of these rules applied to FrED subassemblies are shown below. Figure 82 shows the diameter measurement holder, which enforces “Minimize Part Count”, “Minimize Assembly Directions”, “Design for Ease of Handling”, “Use Self-Aligning Features” and “Avoid Complex Fastening”. It minimizes part count by having components of the camera holder, pulley holders and card holder into a single part. It minimizes assembly directions as most of the parts are inserted top down, with the exception of the screws for the pulleys. It is designed for ease of handling due to it’s relatively larger sizes and the presence of multiple features that can be handling points. It has guides for the camera orientation and positioning and the slot in the card holder for the card to slide in, which are self aligning features. Fastening is either with a snap fit or a screw in the diameter measurement system assembly.

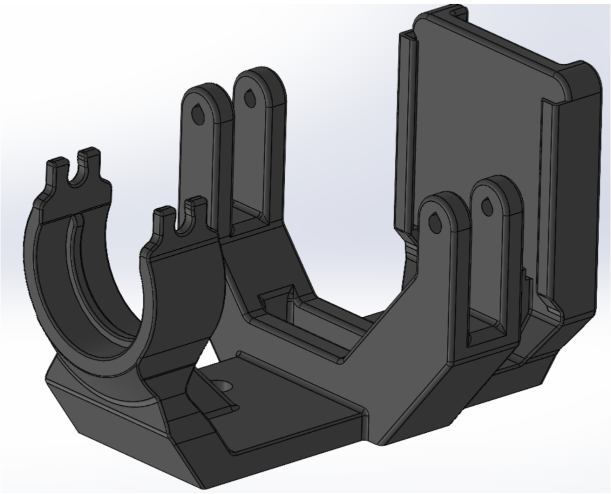


Figure 82. Diameter measurement holder

Another example where DFA is enforced but not in the best way is in the extrusion system, shown in Figure 83. Although the system is relatively complex, consist of many parts and may not be the easiest to assemble, it is assemled top down, which requires very minimal reorienting and holding of parts.

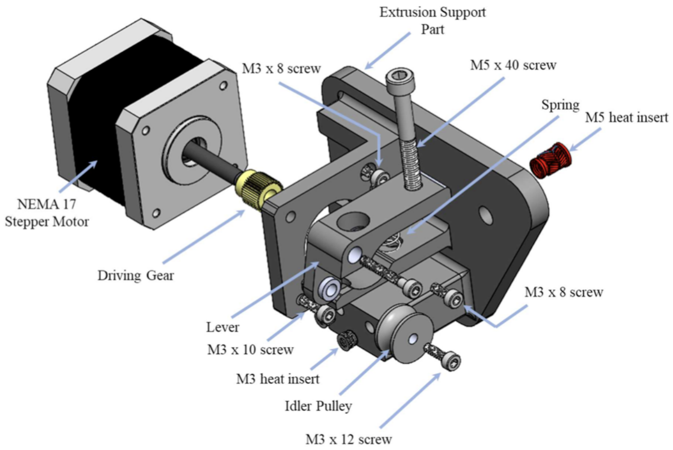


Figure 83. Extrusion system exploded view

4.4 Jigs and Fixtures

Jigs and fixtures are tools used in manufacturing and assembly processes to aid in the accurate and efficient production of parts and products. A jig is a device that holds and guides a tool or workpiece in a fixed position, ensuring consistent and precise positioning during operations such as drilling and machining. On the other hand, a fixture securely holds and locates workpieces during manufacturing processes, enabling repeatable and accurate assembly or inspection.

There are a few benefits of jigs and fixture. They enhance productivity by reducing human error and increasing the speed of operations. Jigs and fixtures provide a standardized setup, ensuring consistent results and reducing the time required for manual adjustments. They also improve quality control by maintaining precise positioning, resulting in fewer defects and better product consistency. They enable cost savings by reducing scrap and rework, optimizing production time, and facilitating the use of more efficient manufacturing techniques.

Jigs and Fixtures are made to guide FrED manufacturing and assembly processes. Among them are: Tube drilling jig, Fiber collection hammering jig, Thumb screws assembly fixture and clamp, Base assembly fixture. Further development of fixtures are encouraged to streamline factory processes. Access to rapid prototyping tools such as CAD, laser cutter and 3D printers has allowed development of jigs and fixtures at very minimal costs and flexibility of fixture design changes as the product evolves to updated versions.

Tube drilling jig, Figure 84, was made to guide the drilling of a small hole on a clear acrylic tube. Drilling a hole on the acrylic tube poses a few problems that led to the creation of the drilling jig. First, position along the tube is critical towards later assembly process. Second, it is hard to drill a curved surface. Third, it is difficult to hold the tube during the drilling process. The jig solves this problem by having a closed end that positions the rod relative to the drilling postition, the jig also holds the rod so that the position of the hole is centered on the rod. The jig has a pilot hole that is smaller than the actual hole on a flat surface, this is so that it is easy to drill and mantain positional accuracy during drilling. The jig also has flat surfaces on the side to make it easier to clamp to a vise. The jig can be made using 3d printing at low cost and is designed to be disposable after every use.

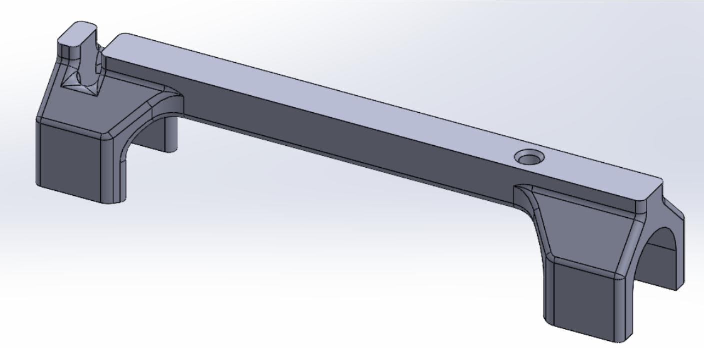


Figure 84. Filament collection tube drilling jig

Hammering fixture, shown in Figure 85, is used to accurately position the 2 gears that are press fit to a shaft using a mallet. The problem arises when it was difficult to press fit a plastic gear onto a shaft and accurately position it along the shaft. The fixture was designed that the gear is positioned to a certain height, the shaft is inserted in using a mallet until the end of the shaft reaches the end of the fixture. This results to the accurate positioning of the gear on the shaft. Two gears had to be inserted to the shaft and two independent fixtures are consolidated to a single fixture for two independent assembly operations.

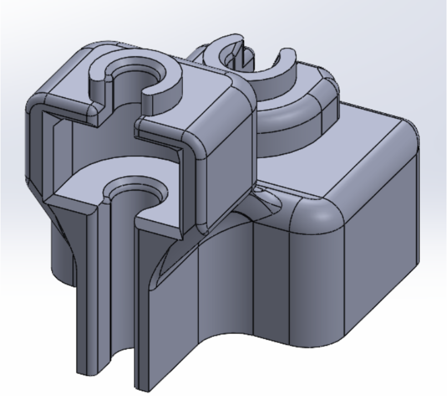


Figure 85. Fiber collection hammering fixture for press fit of gears on shaft

Thumb screws consists of a base, a hex head screw and a cap, shown in Figure 86. The assembly is fastened together with epoxy adhesive, which takes about 5 minutes to cure. In the curing period of time, the assembly has to be held together. Doing so manually would be inefficient as one person has only two hands to clamp two of these at one time.

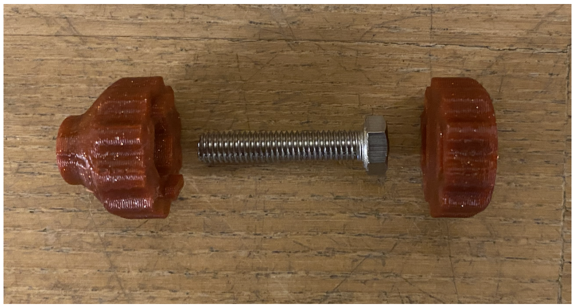


Figure 86. Thumb screw assembly

An assembly fixture is made to assemble 25 thumb screws at a time, shown in Figure 87. The fixture consists of a bottom base and a top cover, along with 4 fastening screws. First, thumb screw base is inserted to the fixture, Figure 88. Hex screws are inserted into the thumbscrew base and adhesive is applied, Figure 89. Thumb screw cap is inserted, Figure 90. Fixture is closed with the top cover and fastened with the fastening screws, Figure 91 and 92. The top cover of the fixture and the fixture base exerts a clamping force on the thumb screw assembly. This can be left for the next 5 minutes as the adhesive cures. This allows for a more efficient assembly process and does not require the operator to continuously and manually clamp the thumb screw assembly as the adhesive cures.

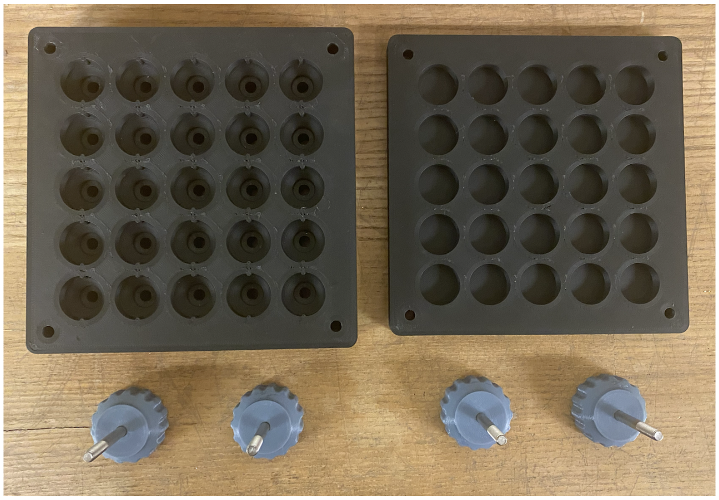


Figure 87. Thumb screws assembly fixture

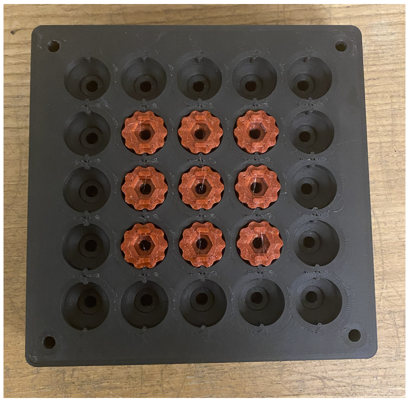


Figure 88. Thumb screws base inserted to fixture

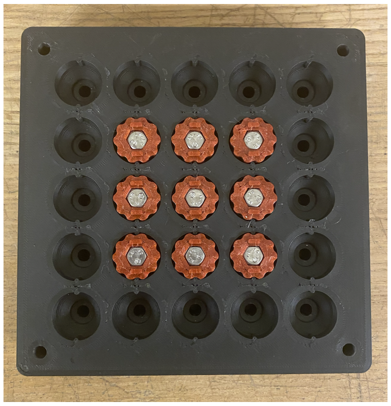


Figure 89. Hex screws inserted, adhesive applied

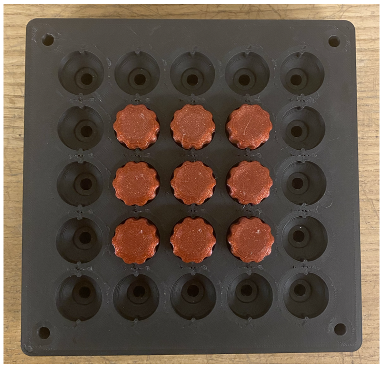


Figure 90. Thumb screws cap inserted to fixture

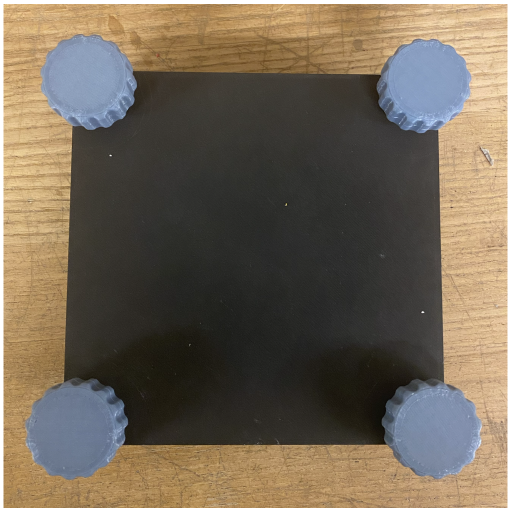


Figure 91. Fixture is closed and clamped (top view)

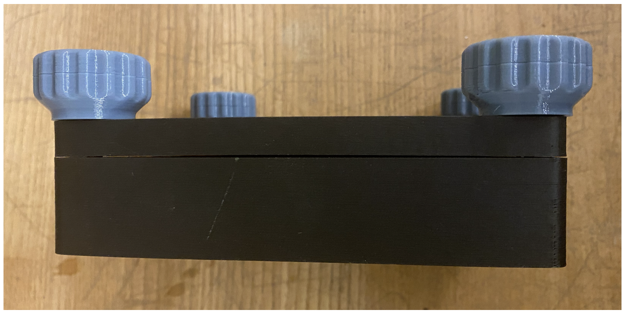


Figure 92. Fixture is closed and clamped (side view)

A base assembly fixture was made to improve the ease of assembling the base of FrED, shown in Figure 93 and 94. FrED's base consist of an acrylic base plate, three legs, a PCB drawer guide and a filament collection system. Assembly prior to the existence of the fixture was particularly challenging in part handling. It was hard to hold all the parts in place while having to screw and fasten the parts as there are no aligning features on the parts. The fixture allows for the assembly operator's hands to be free from holding parts during assembly. This significantly improves assembly time and consistency. Figure 95 shows the operator handling one part at a time, in that case, the base acrylic plate. Figure 96 shows the operator fastening a screw without the need of holding and positioning other parts in the assembly.

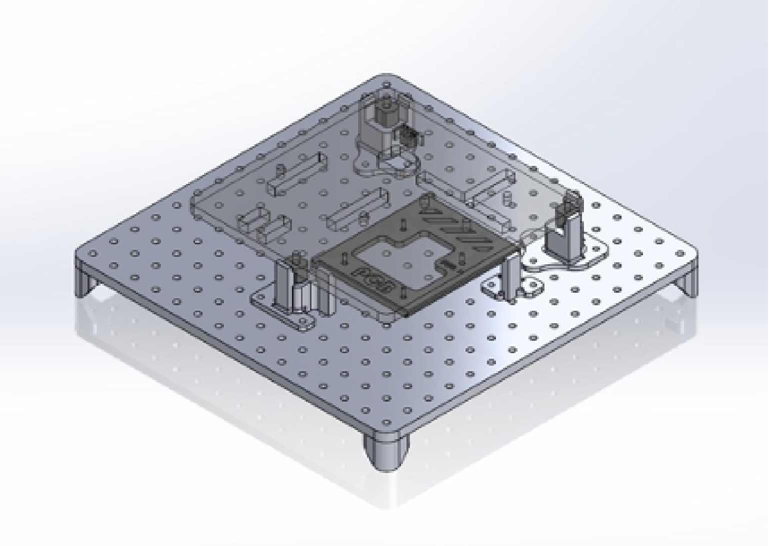


Figure 93. CAD of base assembly fixture

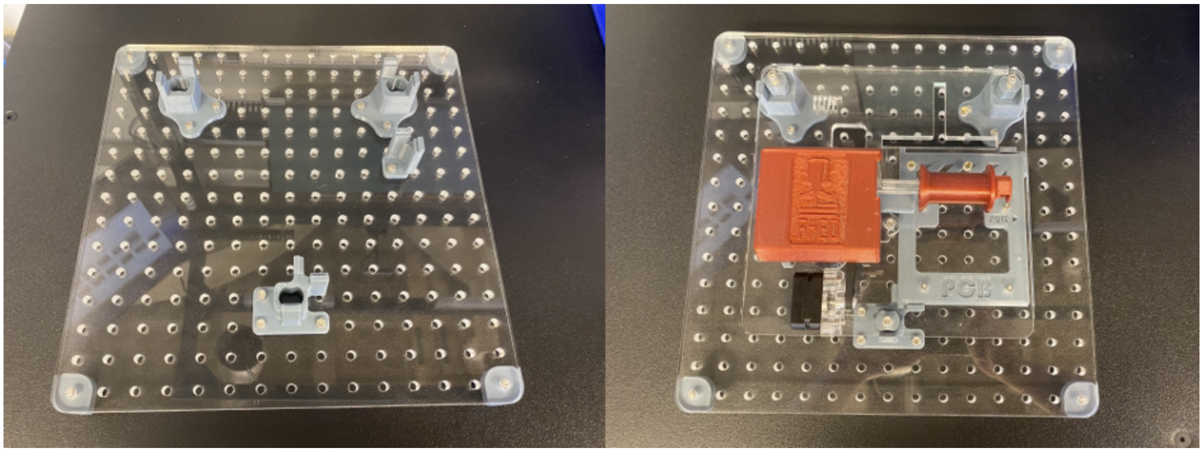


Figure 94. Base assembly fixture

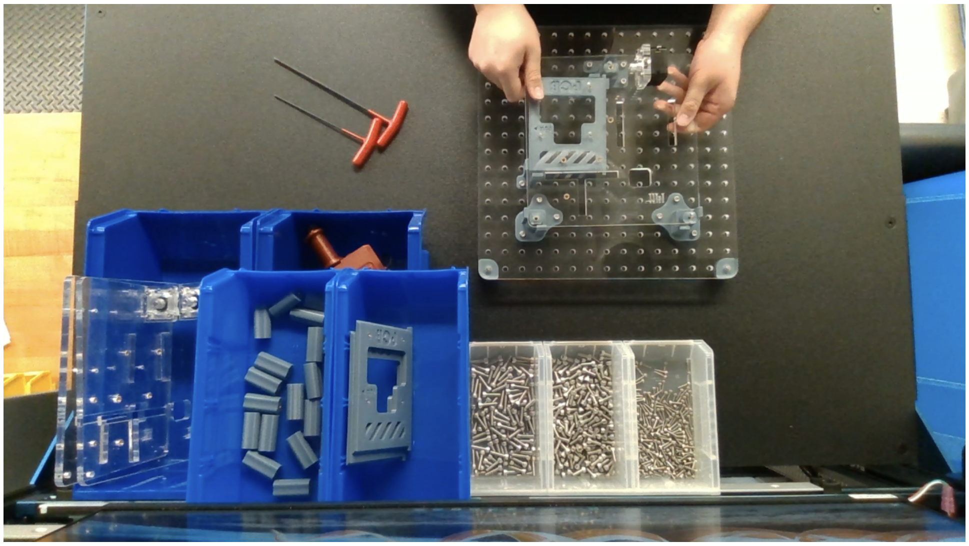


Figure 95. Assembly operator placing the base acrylic plate in the fixture

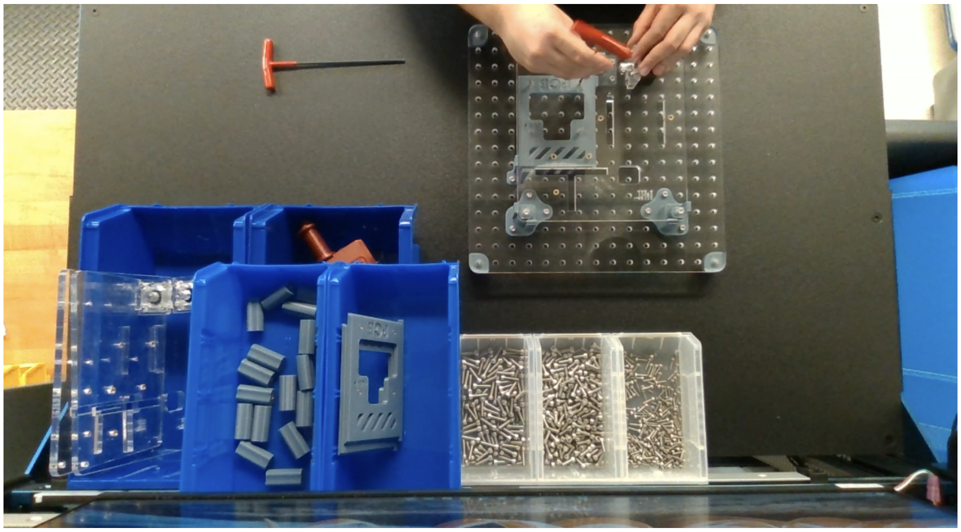


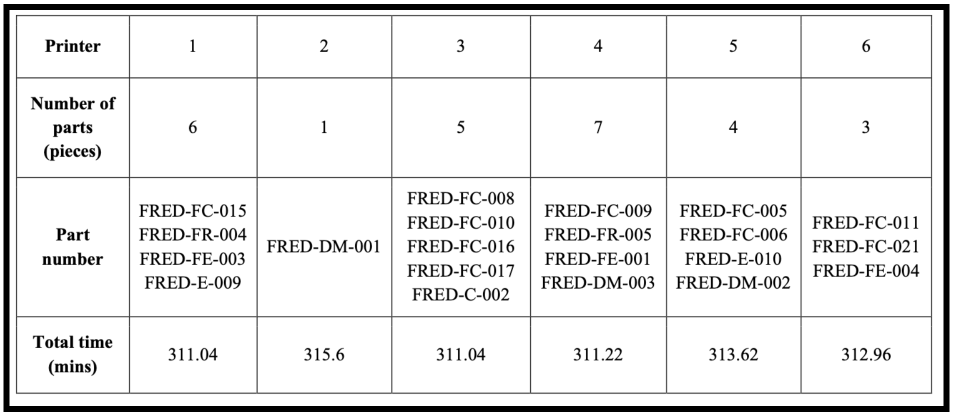
Figure 96. Assembly operator fastening a screw

5. FrED Smart Factory

The FrED Factory was built at the basement of MIT building 35. The facility duals as a teaching space, research space and a mass production facility for FrEDs. A digital transformation project in partnership with a local, MIT alumni founded startup Tulip Interfaces. Most of the work in this section was done collaboratively with undergraduate researchers Stanley Salim, Emily Ha, Mathew Reynolds and Sashlin Jagdessi, and Tulip Interfaces employees John Klaess, PhD, and Kyle Oberholtzer.

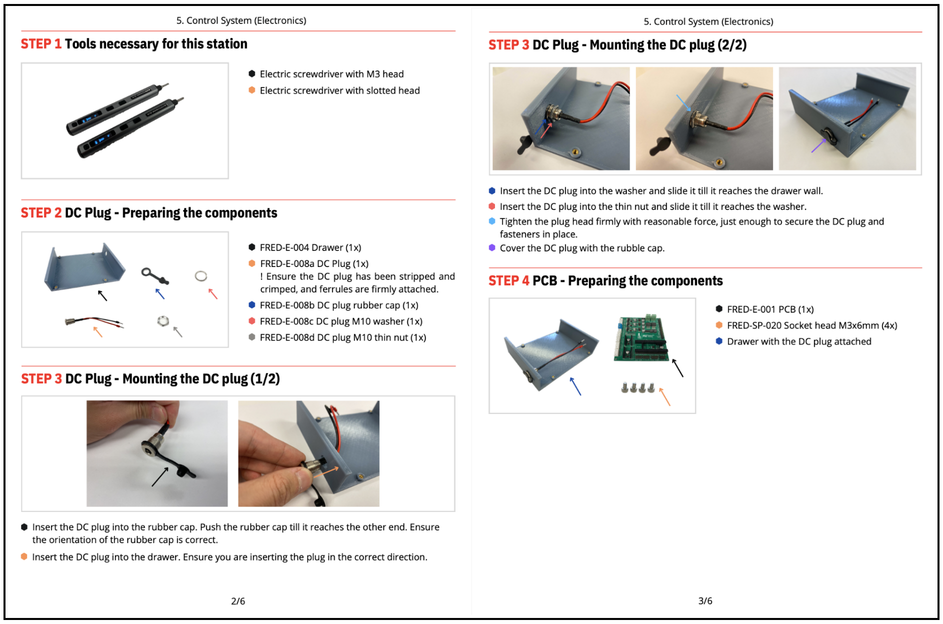
5.1 Motivation

T. Rojrungsasithorn's work [13] focuses heavily on the layout and operations of the factory. The factory was set up in a very short timeline, due to academic deadline reasons. Operations were run with paper manual, Excel spreadsheets and ad-hoc scheduling. It was good enough to produce the 25 FrED requirements by the end of Summer 2022. Figures 97, 98, 99, 100, 101 and 102 shows the current operations of FrED as of Summer 2022.



Printer	1	2	3	4	5	6
Number of parts (pieces)	6	1	5	7	4	3
Part number	FRED-FC-015 FRED-FR-004 FRED-FE-003 FRED-E-009	FRED-DM-001	FRED-FC-008 FRED-FC-010 FRED-FC-016 FRED-FC-017 FRED-C-002	FRED-FC-009 FRED-FR-005 FRED-FE-001 FRED-DM-003	FRED-FC-005 FRED-FC-006 FRED-E-010 FRED-DM-002	FRED-FC-011 FRED-FC-021 FRED-FE-004
Total time (mins)	311.04	315.6	311.04	311.22	313.62	312.96

Figure 97. Excerpt from scheduling spreadsheet



5. Control System (Electronics)

STEP 1 Tools necessary for this station

- Electric screwdriver with M3 head
- Electric screwdriver with slotted head

STEP 2 DC Plug - Preparing the components

- FRED-E-004 Drawer (1x)
- FRED-E-008a DC Plug (1x)
  ! Ensure the DC plug has been stripped and crimped, and ferrules are firmly attached.
- FRED-E-008b DC plug rubber cap (1x)
- FRED-E-008c DC plug M10 washer (1x)
- FRED-E-008d DC plug M10 thin nut (1x)

STEP 3 DC Plug - Mounting the DC plug (1/2)

- Insert the DC plug into the rubber cap. Push the rubber cap till it reaches the other end. Ensure the orientation of the rubber cap is correct.
- Insert the DC plug into the drawer. Ensure you are inserting the plug in the correct direction.

2/6

5. Control System (Electronics)

STEP 3 DC Plug - Mounting the DC plug (2/2)

- Insert the DC plug into the washer and slide it till it reaches the drawer wall.
- Insert the DC plug into the thin nut and slide it till it reaches the washer.
- Tighten the plug head firmly with reasonable force, just enough to secure the DC plug and fasteners in place.
- Cover the DC plug with the rubble cap.

STEP 4 PCB - Preparing the components

- FRED-E-001 PCB (1x)
- FRED-SP-020 Socket head M3x6mm (4x)
- Drawer with the DC plug attached

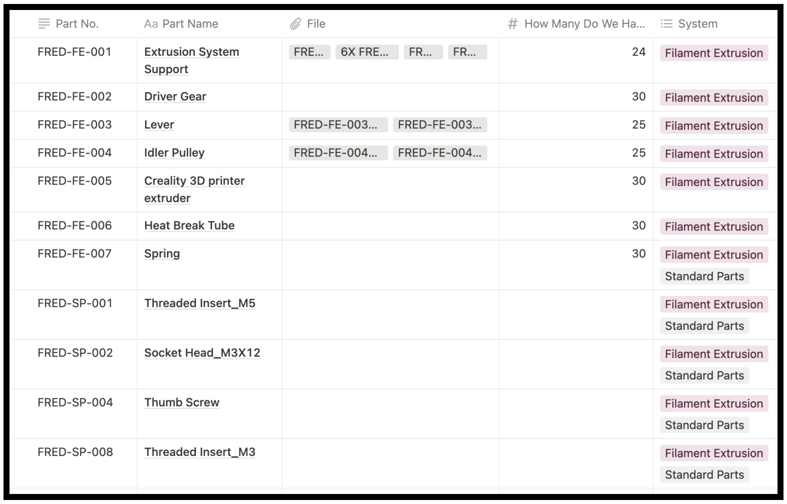
3/6

Figure 98. Exerpt from paper assembly manual

Figure 99. Fiber collection manual assembly station

Figure 100. Fiber extrusion manual assembly station

Figure 101. Inventory shelves



Part No.	Part Name	File	How Many Do We Ha...	System
FRED-FE-001	Extrusion System Support	FRE... 6X FRE... FR... FR...	24	Filament Extrusion
FRED-FE-002	Driver Gear		30	Filament Extrusion
FRED-FE-003	Lever	FRED-FE-003... FRED-FE-003...	25	Filament Extrusion
FRED-FE-004	Idler Pulley	FRED-FE-004... FRED-FE-004...	25	Filament Extrusion
FRED-FE-005	Creality 3D printer extruder		30	Filament Extrusion
FRED-FE-006	Heat Break Tube		30	Filament Extrusion
FRED-FE-007	Spring		30	Filament Extrusion Standard Parts
FRED-SP-001	Threaded Insert_M5			Filament Extrusion Standard Parts
FRED-SP-002	Socket Head_M3X12			Filament Extrusion Standard Parts
FRED-SP-004	Thumb Screw			Filament Extrusion Standard Parts
FRED-SP-008	Threaded Insert_M3			Filament Extrusion Standard Parts

Figure 102. Excerpt of inventory tracking spreadsheet

The situation motivates for a project to improve FrED factory operations. One of them being the digital transformation of the FrED factory. Digital transformation of the FrED factory is critical in two areas. First, to streamline factory operations through digital tools and a unified database. Second, as a data source and showcase of Industry 4.0 concepts on discrete assembly lines, for pedagogical purposes. Three critical areas for digitalization were identified: Machines, Assembly Stations and Inventory.

5.2 Value Proposition

Manufacturers who has adopted Industry 4.0 worldwide have seen multiple benefits such as productivity increases, cost reductions, sustainability, agility, etc. as shown on the survey done with McKinsey [34], Figure 103.

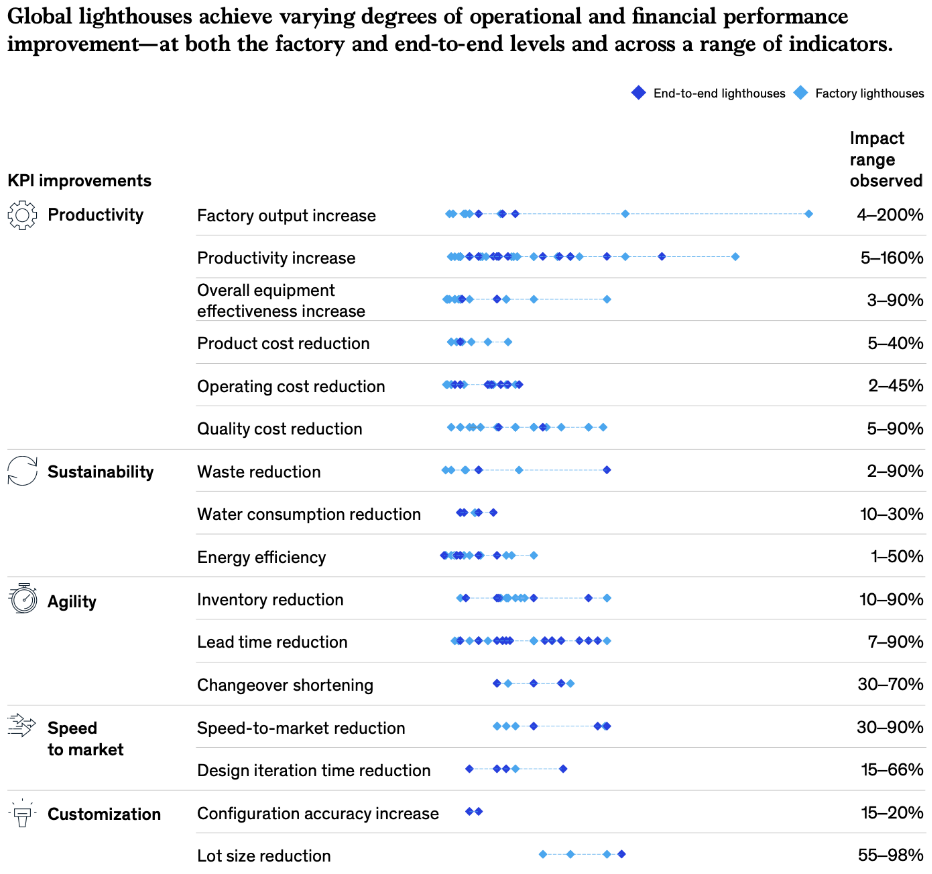


Figure 103. Performance improvement of manufacturers adopting Industry 4.0 technology [34]

An analysis by McKinsey on digital transformation for small-lot discrete manufacturing [35] have shown use cases on three areas: data-driven overall equipment efficiency (OEE) optimization, digital enablement of workers, and intgrated product data model from engineering to commissioning.

Data driven OEE optimization is achieved through use cases such as automated machine setup and feeding, digital process optimization based on machine and quality data, and manufacturing IT integration for digital performance management for critical bottleneck machinery. OEE optimization can generate significant value in cases where companies rely heavily on internal manufacturing. OEE optimization increases the utilization of machines and reduces waste in manufacturing processes [35].

Digital enablement of workers is enabled by use cases such as real-time tracking of assembly times per step and progress, digital documentation, drawings, trouble- shooting guides, and checklists, digital work orders containing detailed task description and sequence. The digital enablement of workers becomes a key value driver when faced with an increasing number of temporary workers and an overall decline in the skilled workforce. Solutions can either help to rapidly train employees or to break the tasks at hand into small steps that are easily manageable for unskilled laborers [35].

Intgrated product data model from engineering to commissioning is enabled by the integration of quality data into digital tool chain, engineering and design software supplying latest information to shop floor and building the digital thread. This becomes a key value as it results to efficient production on sites throughout the supply chain as well as an efficient path to manage increasing product complexity [35].

A set of value proposition was built for the FrED Factory Digitalization based on industry trends and internal requirements and processes:

Machine Monitoring

- Data driven solutions to investigating defects
- Reduce waste through early defect detection and automatic stopping
- Maximize printer utilization through data driven scheduling
- Being agile through making faster operational decisions

Digital Inventory Management

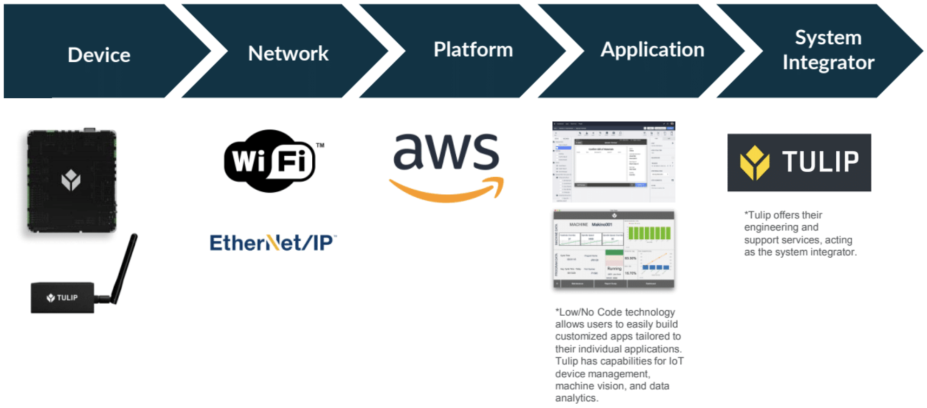
- Improved inventory accuracy
- Detecting trends and providing visibility in stock levels to reduce stockouts
- Providing traceability of parts through the digital thread

Smart Assembly Stations

- Assembly time savings
- Reduce errors in assembly through foolproofing
- People analytics - collect actual data on assembly, better predict labor needs
- Find variation in assembly time per worker for targeted performance development

5.3 Tulip Interfaces

Tulip Interfaces is a company that provides a platform for digital manufacturing and operations [38][39]. The Tulip platform is designed to help manufacturers digitize their operations, improve efficiency, and gain real-time visibility into their processes. They combine hardware, software, and analytics capabilities to enable companies to create and deploy custom applications for their specific manufacturing needs. They aim to empower workers on the shop floor with the tools and information they need to be more efficient, productive, and quality-focused.



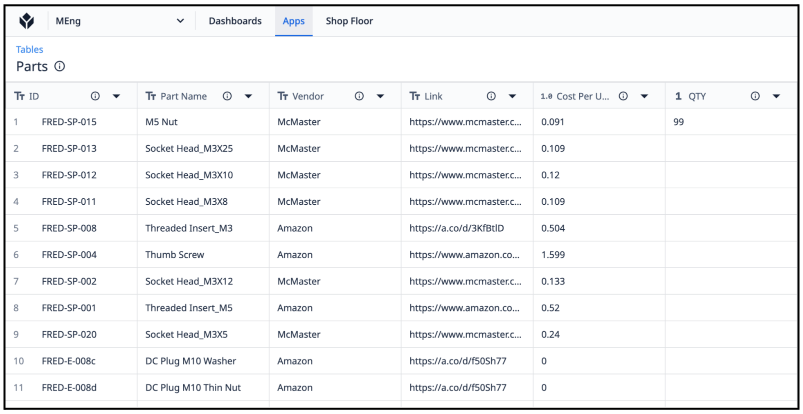
*Low/No Code technology allows users to easily build customized apps tailored to their individual applications. Tulip has capabilities for IoT device management, machine vision, and data analytics.

*Tulip offers their engineering and support services, acting as the system integrator.

Figure 104. Tulip Platform Implementation Layers

The Tulip platform allows manufacturers to create interactive shop floor applications without extensive coding knowledge. They provide a low/no code visual development environment where users can drag and drop pre-built components to build custom applications. These applications can be used to guide operators through assembly instructions, capture data and quality checks, monitor machine performance, and track production metrics in real-time.

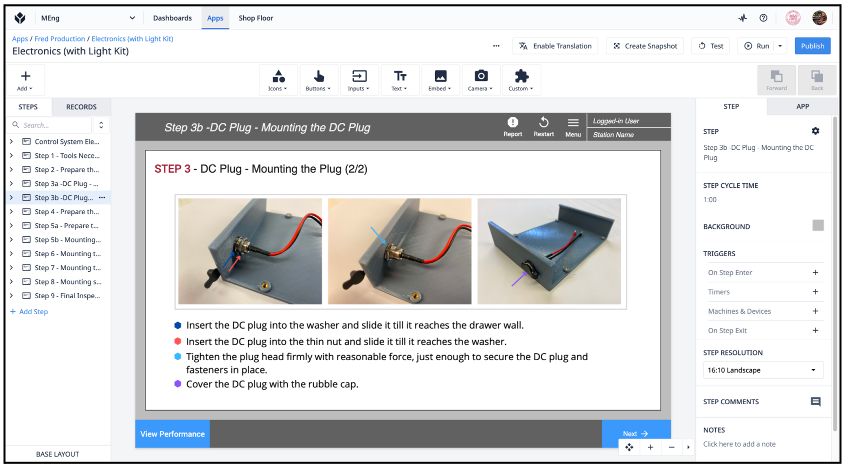
With Tulip, manufacturers can connect machines, sensors, and other devices to gather real-time data from the shop floor. The platform enables data collection, analysis, and visualization, empowering users to identify bottlenecks, optimize processes, and make data-driven decisions to improve productivity and quality. The platform is designed to be flexible and scalable, allowing manufacturers to adapt and scale their digital operations as needed.



Parts

	ID	Part Name	Vendor	Link	Cost Per U...	QTY
1	FRED-SP-015	M5 Nut	McMaster	https://www.mcmaster.c...	0.091	99
2	FRED-SP-013	Socket Head_M3X25	McMaster	https://www.mcmaster.c...	0.109	
3	FRED-SP-012	Socket Head_M3X10	McMaster	https://www.mcmaster.c...	0.12	
4	FRED-SP-011	Socket Head_M3X8	McMaster	https://www.mcmaster.c...	0.109	
5	FRED-SP-008	Threaded Insert_M3	Amazon	https://a.co/d/3KfBtlD	0.504	
6	FRED-SP-004	Thumb Screw	Amazon	https://www.amazon.co...	1.599	
7	FRED-SP-002	Socket Head_M3X12	McMaster	https://www.mcmaster.c...	0.133	
8	FRED-SP-001	Threaded Insert_M5	Amazon	https://www.amazon.co...	0.52	
9	FRED-SP-020	Socket Head_M3X5	McMaster	https://www.mcmaster.c...	0.24	
10	FRED-E-008c	DC Plug M10 Washer	Amazon	https://a.co/d/f50Sh77	0	
11	FRED-E-008d	DC Plug M10 Thin Nut	Amazon	https://a.co/d/f50Sh77	0	

Figure 105. Data Tables in Tulip Platform



Electronics (with Light Kit)

- Control System Ele...
- Step 1 - Tools Nece...
- Step 2 - Prepare th...
- Step 3a -DC Plug - ...
- Step 3b -DC Plug...
- Step 4 - Prepare th...
- Step 5a - Prepare t...
- Step 5b - Mounting...
- Step 6 - Mounting t...
- Step 7 - Mounting t...
- Step 8 - Mounting s...
- Step 9 - Final Inspe...
- + Add Step

Step 3b -DC Plug - Mounting the DC Plug

STEP 3 - DC Plug - Mounting the Plug (2/2)

- Insert the DC plug into the washer and slide it till it reaches the drawer wall.
- Insert the DC plug into the thin nut and slide it till it reaches the washer.
- Tighten the plug head firmly with reasonable force, just enough to secure the DC plug and fasteners in place.
- Cover the DC plug with the rubble cap.

STEP: Step 3b -DC Plug - Mounting the DC Plug

STEP CYCLE TIME: 1:00

STEP RESOLUTION: 16:10 Landscape

NOTES: Click here to add a note

Figure 106. Tulip Interfaces No/Low Code Platform

FrED Factory partners with Tulip as the application for the digital transformation project. This is because we do not have internal information technology (IT) capability to develop or implement IT infrastructure to converge with our operational technology (OT). Tulip provides a seamless implementation of IT technology applied to operations, furthermore, the low/no code platform lowers the barrier to learn the system. Tulip will also act as a better tool than an manufacturing operations management (MOM) software suite in terms of teaching how data flows in a factory because it is possible to go under the hood and analyze what is happening in the system.

5.4 Use Cases: Smart Assembly Stations

The first use case is Smart Assembly Stations, shown in Figure 106 and 107. The goal of the smart assembly stations is to be able to augment the assembly worker to perform daily tasks and complex processes more efficiently and with fewer errors. At the same time, the smart assembly station acts as a tool to collect data on assembly processes.

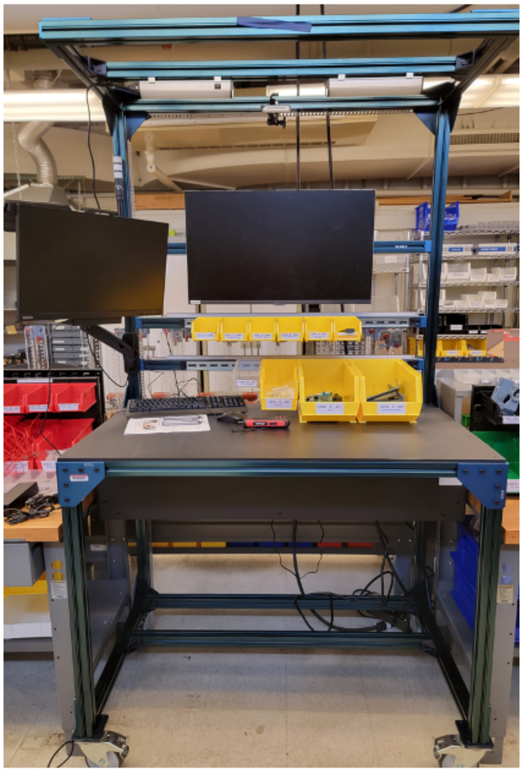


Figure 107. Front view of smart assembly station

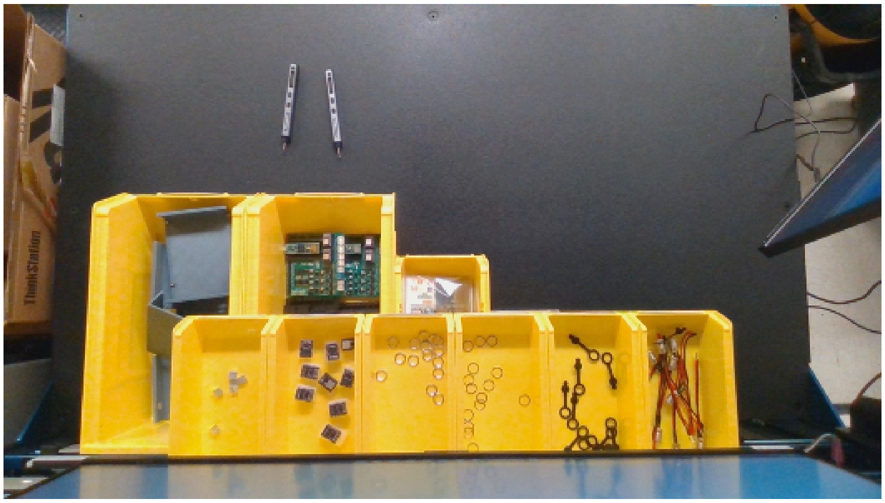
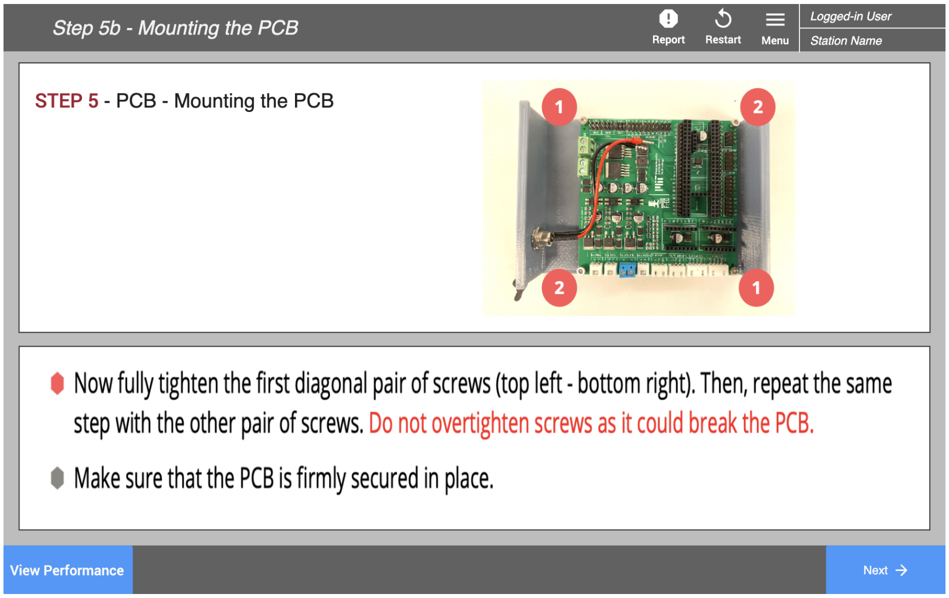


Figure 108. Top view of smart assembly station

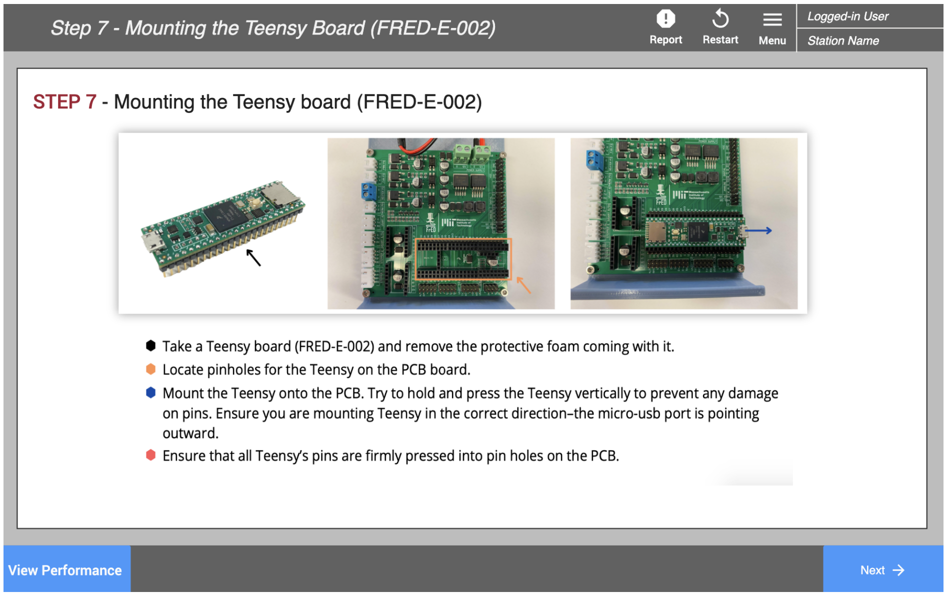
The station is equipped with a touchscreen PC which displays work instructions and an graphical user interface to transition to next steps of the assembly. The digital work instructions allows rich media such as images and videos that can better guide the assembly worker, shown in Figures 109 and 110. The digital work instructions can also include user inputs such as checkboxes or serial numbers from a barcode. A sample implementation of checkboxes, shown in Figrure 110, shows how the digital work instructions can ensure that tools are present in the station before a worker starts their shift.



STEP 5 - PCB - Mounting the PCB

- Now fully tighten the first diagonal pair of screws (top left - bottom right). Then, repeat the same step with the other pair of screws. Do not overtighten screws as it could break the PCB.
- Make sure that the PCB is firmly secured in place.

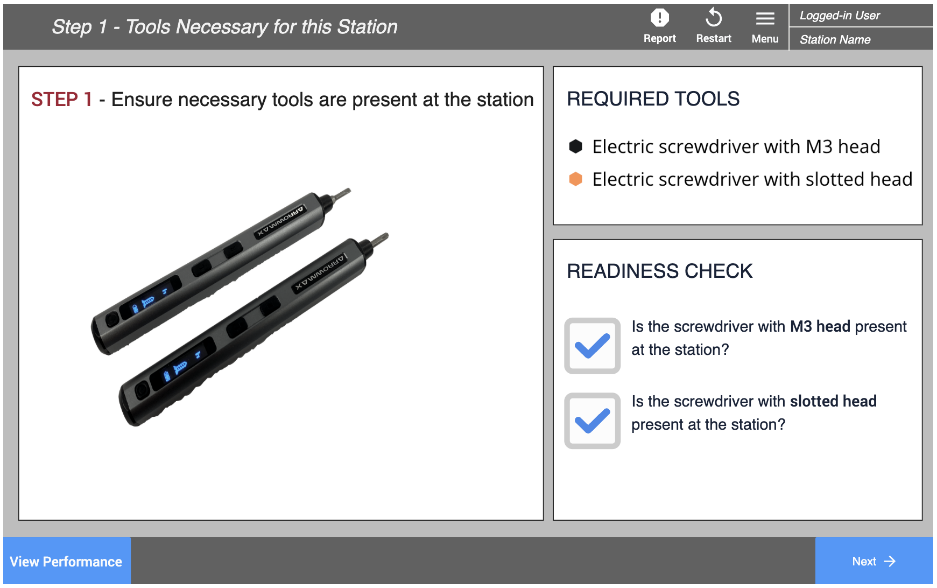
Figure 109. Sample page on digital work instruction



STEP 7 - Mounting the Teensy board (FRED-E-002)

- Take a Teensy board (FRED-E-002) and remove the protective foam coming with it.
- Locate pinholes for the Teensy on the PCB board.
- Mount the Teensy onto the PCB. Try to hold and press the Teensy vertically to prevent any damage on pins. Ensure you are mounting Teensy in the correct direction–the micro-usb port is pointing outward.
- Ensure that all Teensy's pins are firmly pressed into pin holes on the PCB.

Figure 110. Sample page on digital work instruction



STEP 1 - Ensure necessary tools are present at the station

REQUIRED TOOLS

- Electric screwdriver with M3 head
- Electric screwdriver with slotted head

READINESS CHECK

☑ Is the screwdriver with **M3 head** present at the station?

☑ Is the screwdriver with **slotted head** present at the station?

Figure 111. Checkboxes to ensure tools are present

The station is also equipped with a depth camera, Intel RealSense D415, to track the hand motion and position of the assembly worker, shown in Figure 112. This can be used to implement time studies and measure workers’ performance. The camera, which tracks the worker’s hands position in real time, can be combined with a programmable LED strip to provide visual guidance during assembly. Figure 113 shows a green LED lit over a bin to indicate part to be picked. Figure 114 shows a fool proofing alert, a red LED lit over a bin to indicate the wrong part being picked.

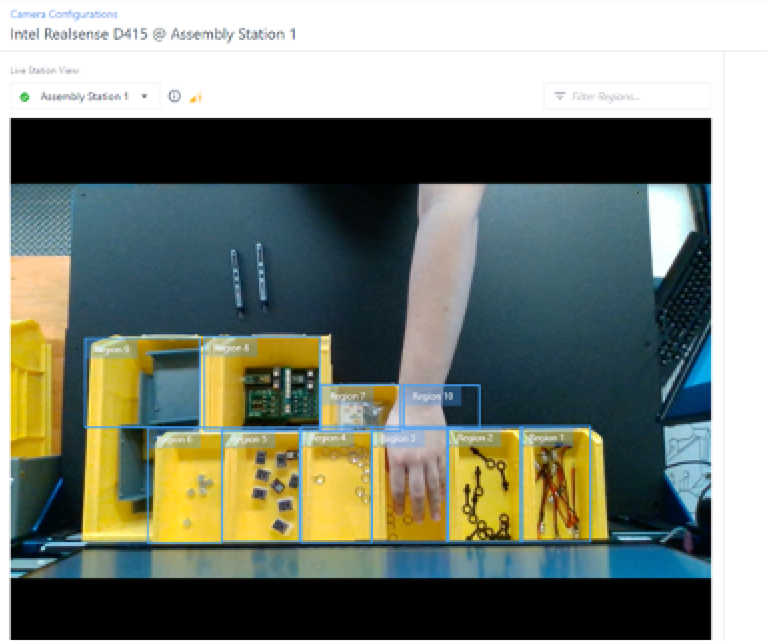


Figure 112. Image captured from Intel RealSense depth camera

Figure 113. LED guiding worker to pick parts

Figure 114. LED alerting worker picking wrong part

5.5 Use Cases: Digital Inventory Management

The second use case is digital inventory management. There are two main goal in this use case. First, to be able to monitor and manage FrED factory inventory levels. Second, to be able to provide tracability of parts and assembly made in the factory.

The most basic application that can be built allows workers to check in and check out parts from different inventory points of the factory. This would enforce updating of inventory level data. More sophisticated methods such as using IoT enabled inventory scales, computer vision, etc. is proposed, but requires extensive development and implementation efforts. This will be future work as we currently do not have enough development capacity.

An concept that uses barcode scanner and a graphical user interface (GUI) was ideated. Each bin would contain a single part type and is assigned a barcode. A worker would need to scan the corresponding barcode of the bin to check-out or check-in parts throughout various bins and shelves. The worker could see the data and specification of the parts and adjust the quantity of parts to refill or remove through the GUI.

Figure 115. Digital Inventory Shelf with GUI

The inventory shelves can be equipped with LED strips, shown in Figure 116. The idea is that the LED strip visualizes real time inventory level data from the database. It visually displays inventory level with color coding: Good = Green, Running low = Orange, Stockout = Red. This will be a good way for workers to be aware of the inventory levels without physically counting parts in the bin or checking inventory dashboard/application. The LED strip can dual as an indicator of bin location, shown in Figure 117, to allow workers to easily find and lookup parts.

Figure 116. Inventory shelf with LED strip

Figure 117. LED indicating bin position

The concept of tracability of parts is built on the concept of the digital thread. The concept is to build a seamless flow of digital information throughout the entire product lifecycle, from design and engineering to manufacturing, assembly, and beyond. It involves linking and correlating data from different sources, systems, and processes to provide a comprehensive and accurate representation of the product's history, specifications, configurations, and associated data.

This is done by first deciding the granularity of the data to be collected and minor modification to physical processes and standard operating procedures to support data collection. For example, every batch of parts from a printer would have to be labelled with a unique ID, so that every manufactured part can be traced to the date, machine and process parameters that it was made on. A similar approach can be done with assemblies, where it would be possible to trace the exact datetime of assembly, operator who assembled, and video of the assembly. The digital thread would also allow us to track versions of parts on the factory floor. If design changes and revision are made, we can ensure which subassemblies receive which part version and maintain a record of which version of FrED a customer receives.

5.6 Use Cases: Machine Monitoring and Analytics

The third use case is machine monitoring and analytics. The goal is to be able to monitor the 3D printer fleet operations and processes. One aspect of machine operation is the state of the machine, such as: idle, down, printing, repair, error, etc. This can be used to measure the machine’s Overall Equipment Effectiveness (OEE), a performance metric used in manufacturing to measure the efficiency and productivity of equipment and machinery. Process data includes temperature data, sensor data, vibration, etc. that is collected during printing and can potentially be a proxy to quality of parts, machine drifts, etc. Some of the features that are going to be built includes: real time data acquisition, data visualization and dashboards, predictive analytics for failures and maintenance, perscriptive analytics for scheduling, remote monitoring and automated alarm for print failures.

Data from the printer is aquired through a Raspberry Pi connected to the printer's control board. The connection is done through a universal serial bus, and using the RESTful API on top of the HTTP protocol to fetch operational and process data from the machines. The Raspberry Pi is a single board computer that runs a software called Octoprint in order to be able to establish the connection with the printer's control board. The Raspberry Pi is also connected to a database server, where it pushes and stores the data collected.

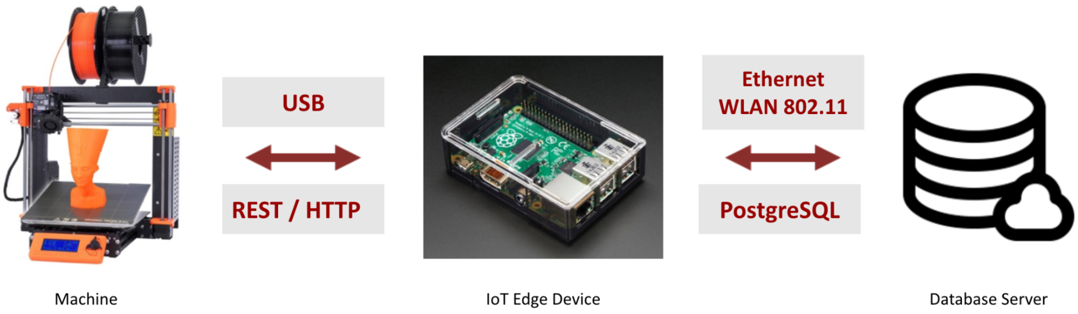


Figure 118. Data collection architecture

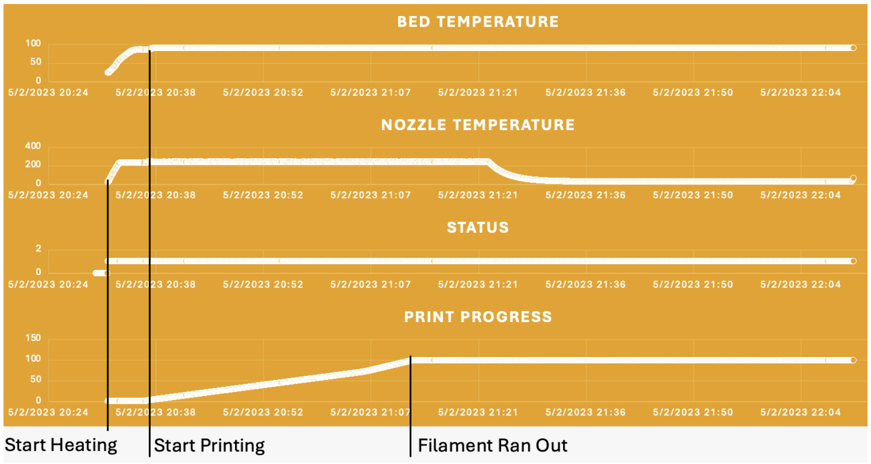


Figure 119. Process and operational data collected from 3D printer

Once data is in one location, it can be easily extended into applications. One such applications is a dashboard to monitor the machine's OEE and productivity. It is still a work in progress. A mockup of the dashboard can be seen in the figures below. Another application that can be developed is early stopping when defect is detected. This would require predictive algorithms that could predict potential or ongoing failure and could automatically send alerts and stop machines.

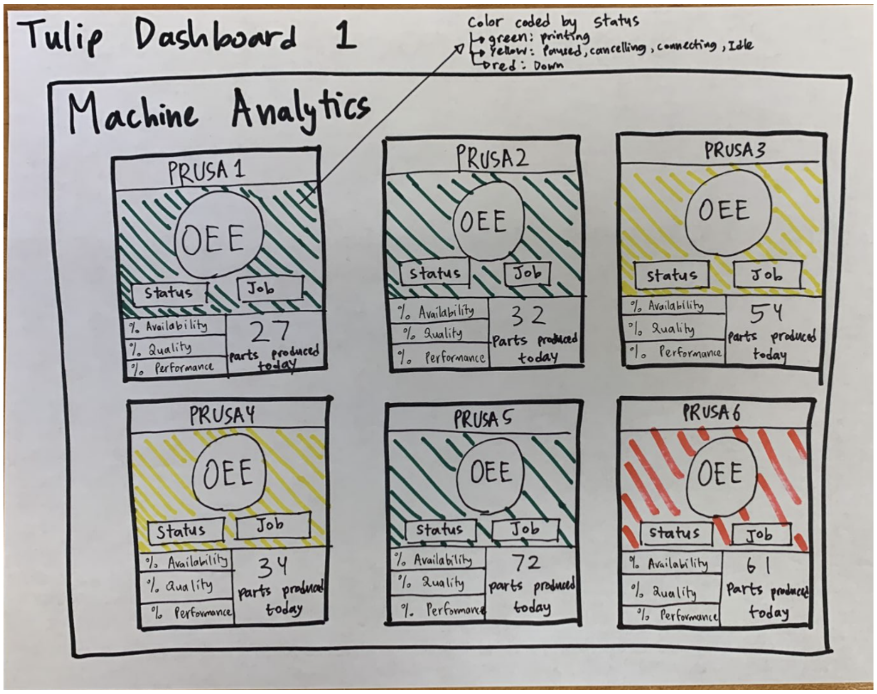


Figure 120. Dashboard showing individual machine performance in printer fleet

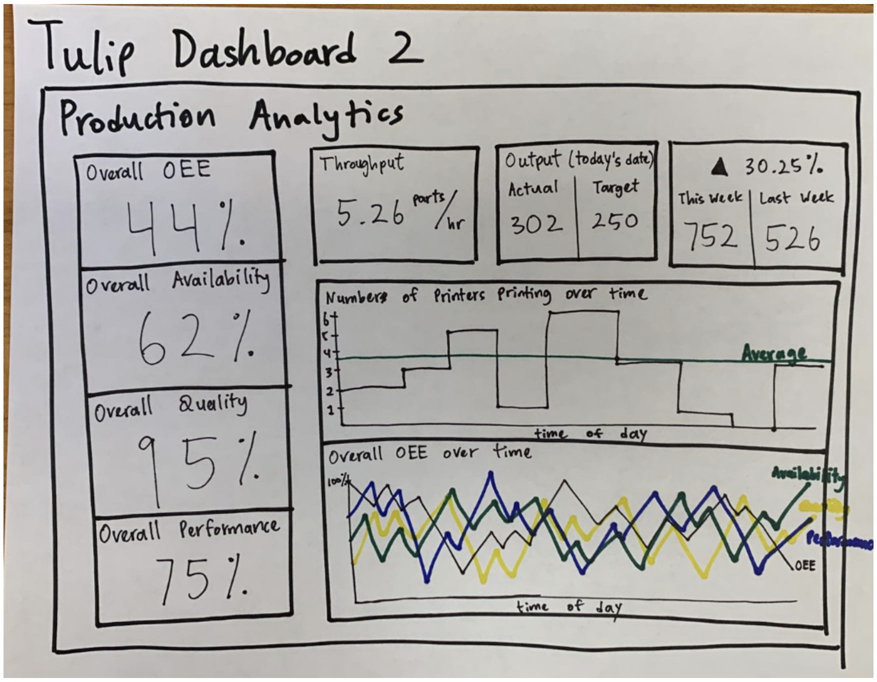


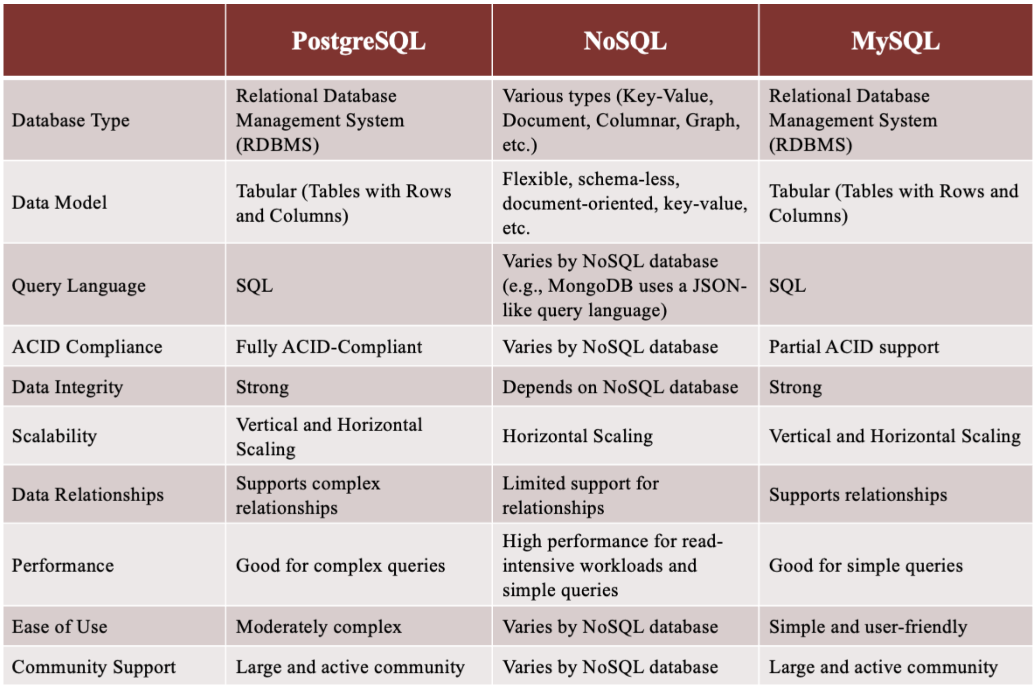
Figure 121. Summary dashboard for printer fleet

5.7 Data Base Management System

Multiple literatures agrees that the key to a successful digital transformation is to have a solid data foundation [34][36][37]. Furthermore, we realise that the 'database' in Tulip plafrom, also known as Tulip Tables, is not as powerful as relational databases that have been used in most existing enterprise software. It was decided that FrED factory should have an independent relational database server. The relational database can later be connected to the Tulip platform as the database.

Standard Query Language (SQL) is a programming language used to manipulate relational databases. There are various flavors of SQL, to name a few: postgreSQL, NoSQL, MySQL. A comparison of these are presented in Table 12. PostgreSQL, an object-relational database, is selected as it best represents the data to be collected in the FrED factory. Data is represented in tables, relations between tables can be made and it has the ability to store complex data types such as documents, images and videos. The database created is hosted on Microsoft Azure cloud as it provides great flexibility, allowing a wide range of available services for future use. It also supports Timescale DB, a time series extension to PostgreSQL that handles time series data streams better, such as the in process data coming from the 3D printers.

Table 12. Comparison of Different Flavors of SQL



	PostgreSQL	**NoSQL**	**MySQL**
Database Type	Relational Database Management System (RDBMS)	Various types (Key-Value, Document, Columnar, Graph, etc.)	Relational Database Management System (RDBMS)
Data Model	Tabular (Tables with Rows and Columns)	Flexible, schema-less, document-oriented, key-value, etc.	Tabular (Tables with Rows and Columns)
Query Language	SQL	Varies by NoSQL database (e.g., MongoDB uses a JSON-like query language)	SQL
ACID Compliance	Fully ACID-Compliant	Varies by NoSQL database	Partial ACID support
Data Integrity	Strong	Depends on NoSQL database	Strong
Scalability	Vertical and Horizontal Scaling	Horizontal Scaling	Vertical and Horizontal Scaling
Data Relationships	Supports complex relationships	Limited support for relationships	Supports relationships
Performance	Good for complex queries	High performance for read-intensive workloads and simple queries	Good for simple queries
Ease of Use	Moderately complex	Varies by NoSQL database	Simple and user-friendly
Community Support	Large and active community	Varies by NoSQL database	Large and active community

A database schema was designed for the FrED factory, shown in Figure 122. The idea of the schema is to provide a data foundation on FrED factory operations. The table headers in blue shows the foundation of the database that is the Bill of Materials (BOM). The bill of materials provides complete information on the components needed to assemble a FrED as well as the assembly structure. Data such as vendor, cost, etc. is also stored in the Bill of Materials. The Bill of Materials schema can be further extended to form an Order Management System (OMS) shown in green and a Manufacturing Execution System (MES) schema shown in orange. A Material Requirement Planning system (MRP) can also be built on top of the schema.

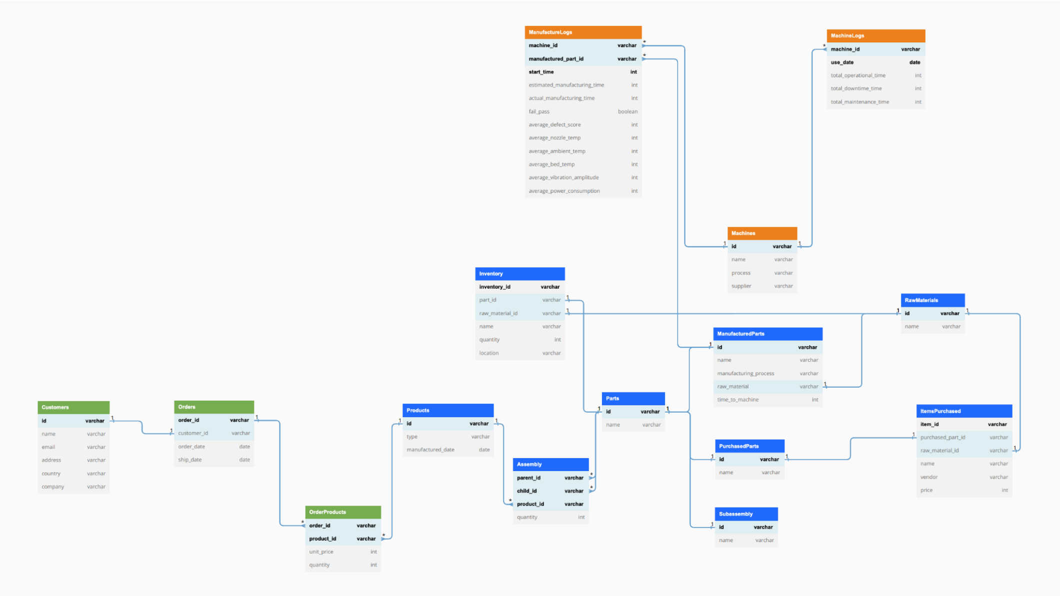


Figure 122. Schema Diagram of FrED Factory Database

Figure 123 shows how data can be pulled from the current schema to build an MRP system. An MRP system uses information such as sales forecasts, production schedules, and inventory levels to calculate the materials and components needed to meet production goals.

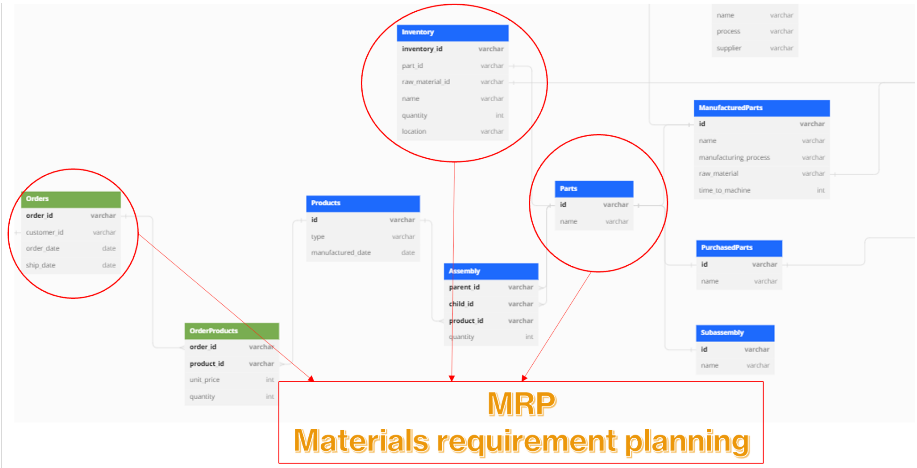
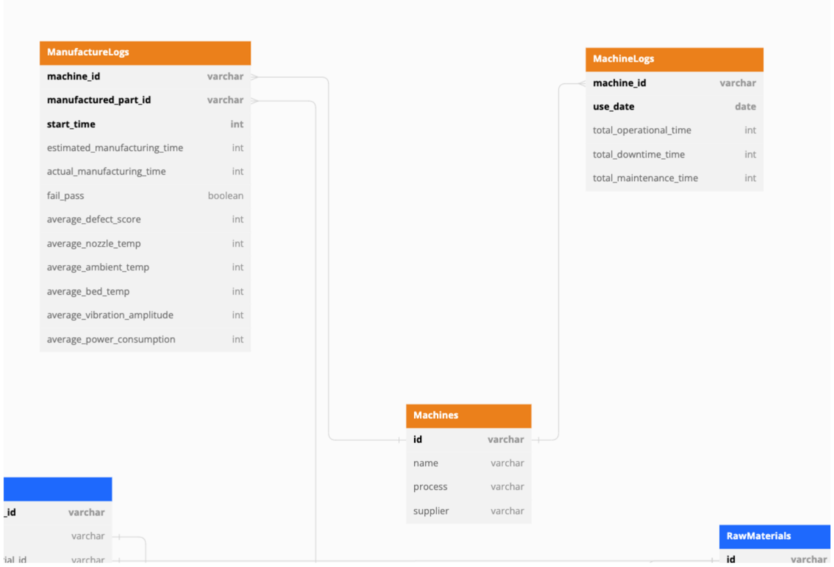


Figure 123. Materials Requirement Planning

Figure 124 shows how a Manufacturing Execution System schema can extend from the bill of materials schema. A Manufacturing Execution System is a software system that manages and controls manufacturing operations on the shop floor, providing real-time visibility, tracking, and control over production processes.



ManufactureLogs	
machine_id	**varchar**
manufactured_part_id	**varchar**
start_time	**int**
estimated_manufacturing_time	int
actual_manufacturing_time	int
fail_pass	boolean
average_defect_score	int
average_nozzle_temp	int
average_ambient_temp	int
average_bed_temp	int
average_vibration_amplitude	int
average_power_consumption	int

MachineLogs	
machine_id	**varchar**
use_date	**date**
total_operational_time	int
total_downtime_time	int
total_maintenance_time	int

Machines	
id	**varchar**
name	varchar
process	varchar
supplier	varchar

Figure 124. Manufacturing Execution System schema

6. Educational Activities in the FrED Ecosystem

Various educational activities were run with the support of the FrED ecosystem at both MIT and Tec de Monterrey. Two senior undergraduate classes were taught at Tec de Monterrey on Mechatronics Design and Manufacturing Automation. A class at MIT uses FrED Factory as a use case for an operations improvement project. An online, self-paced augmented and virtual reality class, was run over MIT's Independent Activity Period. Multiple undergraduate research has been done at the FrED factory.

6.1 Tec de Monterrey Mechatronics Design + VR Class

A mechatronics design capstone class was taught during the Fall semester of 2022 and Spring of 2023. The goal of the class is for students to apply theory into practice through the designing and making a mechatronic device. FrED is a good use case for this, it consists of multiple systems: mechanical, electrical/electronics and controls. The scope was extended to cover a development of Virtual FrED that is to be deployed in Augmented Reality and Virtual Reality (AR/VR) applications.

During the course of Fall 2022 semester, Tec de Monterrey students have built an alternate version of FrED, shown in Figure 125 and 126. The FrED was designed based on the low-cost FrED that was designed in MIT. They took a different approach to the FrED redesign, considering material and process availability in Mexico.

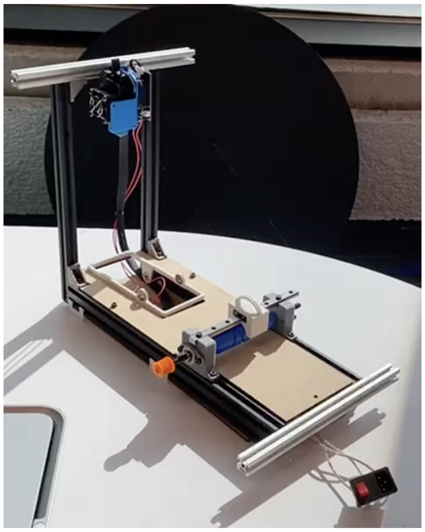
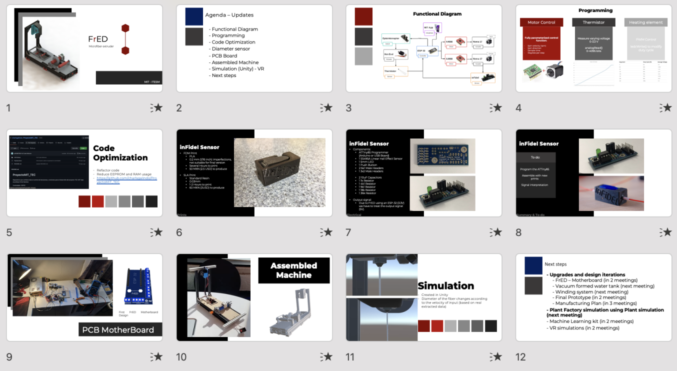


Figure 125. Partially completed Tec de Monterrey FrED

Figure 126. CAD model of Tec de Monterrey FrED

Every other week, MIT faculty, graduate students, and post-doc would meet the students to provide insights and feedback on their design. The students prepare a slide deck to present their progress to MIT.



FrED

Microfiber extruder

MIT - ITESM

Agenda – Updates

- Functional Diagram
- Programming
- Code Optimization
- Diameter sensor
- PCB Board
- Assembled Machine
- Simulation (Unity) - VR
- Next steps

Functional Diagram

Programming

Motor Control

Thermistor

Heating element

Code Optimization

- Refactor code
- Reduce EEPROM and RAM usage
- https://github.com/charlsgalindo/ProyectoMIT_TEC

inFidel Sensor

- FDM Print
  - PLA
  - 0.2 mm (1/16 inch) imperfections, not suitable for final version
  - Several Hours to print
  - 50 MXN (2.5 USD) to produce
- SLA Print
  - Standard Resin
  - 0.03mm
  - 1-2 Hours to print
  - 60 MXN (3USD) to produce

inFidel Sensor

inFidel Sensor

To do:

Program the ATTiny85

Assemble with new prints

Signal interpretation

PCB MotherBoard

Assembled Machine

Simulation

- Created in Unity
- Diameter of the fiber changes according to the velocity of input (based on real extracted data)

Next steps

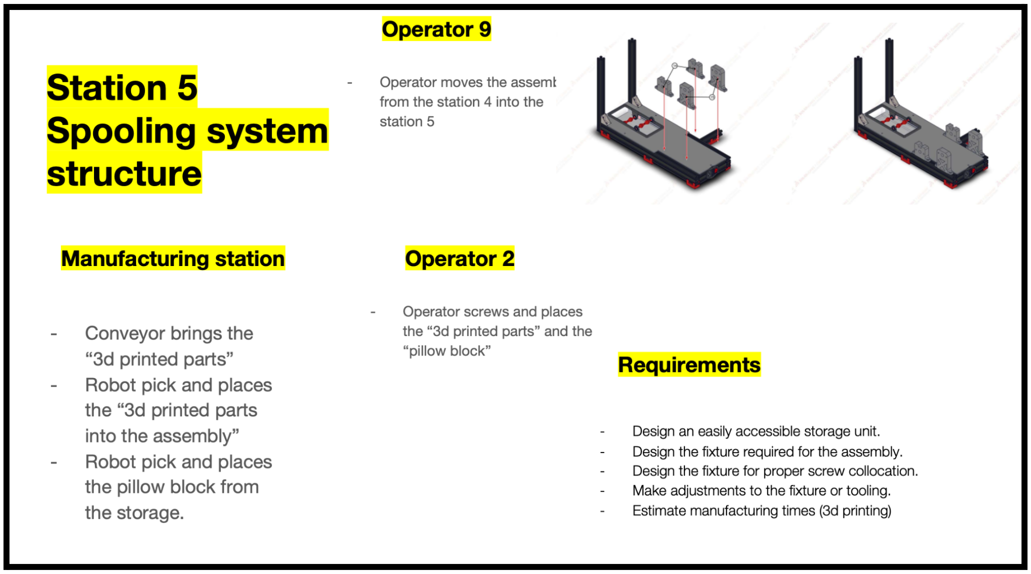
- Upgrades and design iterations
  - FrED – Motherboard (in 2 meetings)
  - Vacuum formed water tank (next meeting)
  - Winding system (next meeting)
  - Final Prototype (in 2 meetings)
  - Manufacturing Plan (in 3 meetings)
- Plant Factory simulation using Plant simulation (next meeting)
- Machine Learning kit (in 2 meetings)
- VR simulations (in 2 meetings)

Figure 127. Example of a slide deck prepared by Tec de Monterrey students

6.2 Tec de Monterrey Manufacturing Automation Class

A manufacturing automation class was conducted in Tec de Monterrey. The course project was to build a FrED production line using collaborative robots, PLCs, HMIs, sensors, and actuators. The class is split to multiple teams that will be responsible for a part of the manufacturing line where the entire class will ultimately come together to create a FrED device. By bringing a real industrial application to the lab, students will have the opportunity to gain hands-on experience and develop practical solutions to the challenges of modern manufacturing.

Figure 128. Cobots Lab at Tec de Monterrey



Operator 9

- Operator moves the assemb from the station 4 into the station 5

Station 5 Spooling system structure

Manufacturing station

- Conveyor brings the "3d printed parts"
- Robot pick and places the "3d printed parts into the assembly"
- Robot pick and places the pillow block from the storage.

Operator 2

- Operator screws and places the "3d printed parts" and the "pillow block"

Requirements

- Design an easily accessible storage unit.
- Design the fixture required for the assembly.
- Design the fixture for proper screw collocation.
- Make adjustments to the fixture or tooling.
- Estimate manufacturing times (3d printing)

Figure 129. Sample problem statement for a team

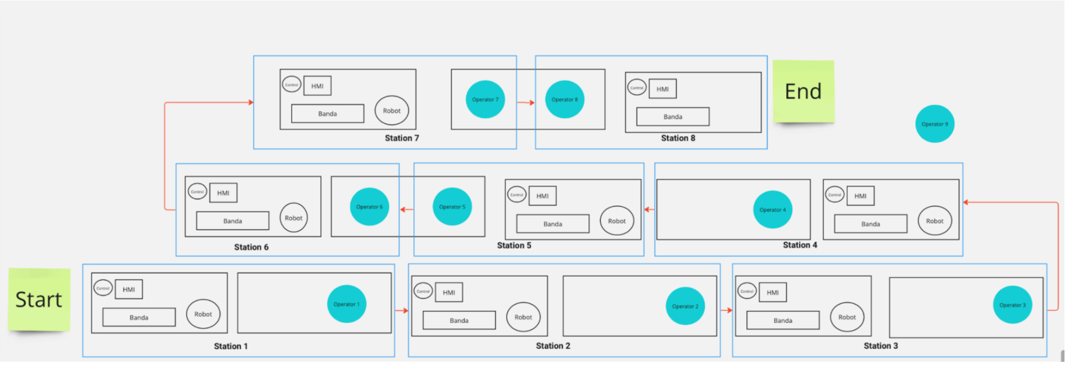
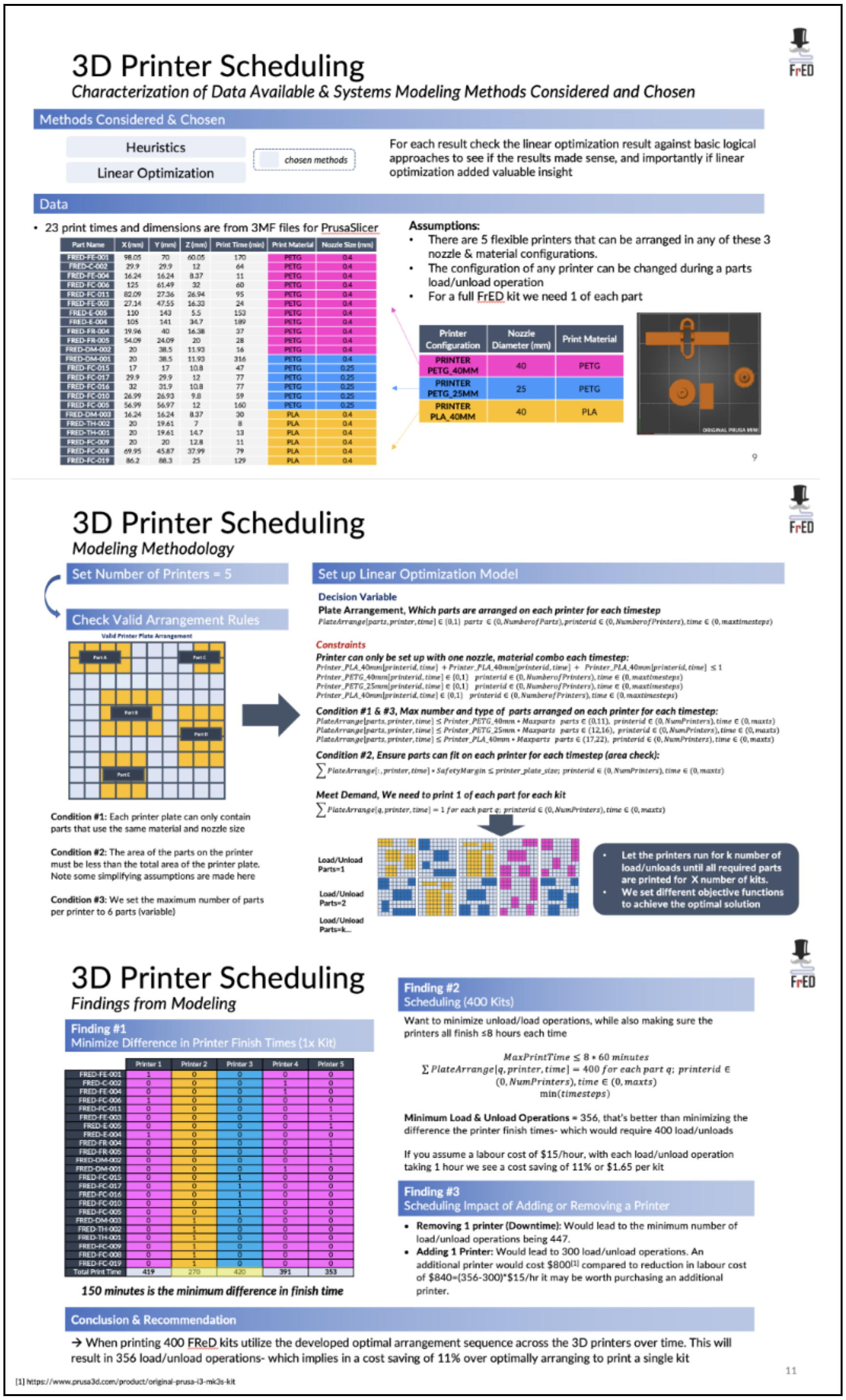


Figure 130. Final proposed layout for factory

6.3 On Campus Manufacturing Systems Course

An on campus manufacturing systems course, 2.853 and 2.854, was run during the Fall semester of 2022. The class uses FrED as an example to teach advanced process control for manufacturing, similar to what has been done in the Professional Education course [7]. FrED was further used in a class project where a student team solved four problems around the FrED factory: Inventory Management, Assembly Steps Optimization, 3D Printer Scheduling and Discrete Event Simulator.



3D Printer Scheduling

Characterization of Data Available & Systems Modeling Methods Considered and Chosen

Methods Considered & Chosen

- Heuristics
- Linear Optimization

chosen methods

For each result check the linear optimization result against basic logical approaches to see if the results made sense, and importantly if linear optimization added valuable insight

Data

- 23 print times and dimensions are from 3MF files for PrusaSlicer

Part Name	X (mm)	Y (mm)	Z (mm)	Print Time (min)	Print Material	Nozzle Size (mm)
FRED-FE-001	98.05	70	60.05	170	PETG	0.4
FRED-C-002	29.9	29.9	12	64	PETG	0.4
FRED-FE-004	16.24	16.24	8.37	11	PETG	0.4
FRED-FC-006	125	61.49	32	60	PETG	0.4
FRED-FC-011	82.09	27.36	26.94	95	PETG	0.4
FRED-FE-003	27.14	47.55	16.33	24	PETG	0.4
FRED-E-005	110	143	5.5	153	PETG	0.4
FRED-E-004	105	141	34.7	189	PETG	0.4
FRED-FR-004	19.96	40	16.38	37	PETG	0.4
FRED-FR-005	54.09	24.09	20	28	PETG	0.4
FRED-DM-002	20	38.5	11.93	16	PETG	0.4
FRED-DM-001	20	38.5	11.93	316	PETG	0.4
FRED-FC-015	17	17	10.8	47	PETG	0.25
FRED-FC-017	29.9	29.9	12	77	PETG	0.25
FRED-FC-016	32	31.9	10.8	77	PETG	0.25
FRED-FC-010	26.99	26.93	9.8	59	PETG	0.25
FRED-FC-005	56.99	56.97	12	160	PETG	0.25
FRED-DM-003	16.24	16.24	8.37	30	PLA	0.4
FRED-TH-002	20	19.61	7	8	PLA	0.4
FRED-TH-001	20	19.61	14.7	13	PLA	0.4
FRED-FC-009	20	20	12.8	11	PLA	0.4
FRED-FC-008	69.95	45.87	37.99	79	PLA	0.4
FRED-FC-019	86.2	88.3	25	129	PLA	0.4

Assumptions:

- There are 5 flexible printers that can be arranged in any of these 3 nozzle & material configurations.
- The configuration of any printer can be changed during a parts load/unload operation
- For a full FrED kit we need 1 of each part

Printer Configuration	Nozzle Diameter (mm)	Print Material
PRINTER PETG_40MM	40	PETG
PRINTER PETG_25MM	25	PETG
PRINTER PLA_40MM	40	PLA

3D Printer Scheduling

Modeling Methodology

Set Number of Printers = 5

Check Valid Arrangement Rules

Condition #1: Each printer plate can only contain parts that use the same material and nozzle size

Condition #2: The area of the parts on the printer must be less than the total area of the printer plate. Note some simplifying assumptions are made here

Condition #3: We set the maximum number of parts per printer to 6 parts (variable)

Set up Linear Optimization Model

Decision Variable

Plate Arrangement, *Which parts are arranged on each printer for each timestep*

$PlateArrange[parts, printer, time] \in \{0,1\}$ $parts \in (0, NumberofParts), printerid \in (0, NumberofPrinters), time \in (0, maxtimesteps)$

Constraints

Printer can only be set up with one nozzle, material combo each timestep:

$Printer\_PLA\_40mm[printerid, time] + Printer\_PLA\_40mm[printerid, time] + Printer\_PLA\_40mm[printerid, time] \leq 1$

$Printer\_PETG\_40mm[printerid, time] \in \{0,1\}$ $printerid \in (0, NumberofPrinters), time \in (0, maxtimesteps)$

$Printer\_PETG\_25mm[printerid, time] \in \{0,1\}$ $printerid \in (0, NumberofPrinters), time \in (0, maxtimesteps)$

$Printer\_PLA\_40mm[printerid, time] \in \{0,1\}$ $printerid \in (0, NumberofPrinters), time \in (0, maxtimesteps)$

Condition #1 & #3, Max number and type of parts arranged on each printer for each timestep:

$PlateArrange[parts, printer, time] \leq Printer\_PETG\_40mm * Maxparts$ $parts \in (0,11), printerid \in (0, NumPrinters), time \in (0, maxts)$

$PlateArrange[parts, printer, time] \leq Printer\_PETG\_25mm * Maxparts$ $parts \in (12,16), printerid \in (0, NumPrinters), time \in (0, maxts)$

$PlateArrange[parts, printer, time] \leq Printer\_PLA\_40mm * Maxparts$ $parts \in (17,22), printerid \in (0, NumPrinters), time \in (0, maxts)$

Condition #2, Ensure parts can fit on each printer for each timestep (area check):

$\sum PlateArrange[:, printer, time] * SafetyMargin \leq printer\_plate\_size;$ $printerid \in (0, NumPrinters), time \in (0, maxts)$

Meet Demand, We need to print 1 of each part for each kit

$\sum PlateArrange[q, printer, time] = 1$ $for\ each\ part\ q;$ $printerid \in (0, NumPrinters), time \in (0, maxts)$

- Let the printers run for k number of load/unloads until all required parts are printed for X number of kits.
- We set different objective functions to achieve the optimal solution

3D Printer Scheduling

Findings from Modeling

Finding #1
Minimize Difference in Printer Finish Times (1x Kit)

	Printer 1	Printer 2	Printer 3	Printer 4	Printer 5
FRED-FE-001	1	0	0	0	0
FRED-C-002	0	0	0	1	0
FRED-FE-004	0	0	0	1	0
FRED-FC-006	1	0	0	0	0
FRED-FC-011	0	0	0	0	1
FRED-FE-003	0	0	0	0	1
FRED-E-005	0	0	0	0	1
FRED-E-004	1	0	0	0	0
FRED-FR-004	0	0	0	0	1
FRED-FR-005	0	0	0	0	1
FRED-DM-002	0	0	0	0	1
FRED-DM-001	0	0	0	1	0
FRED-FC-015	0	0	1	0	0
FRED-FC-017	0	0	1	0	0
FRED-FC-016	0	0	1	0	0
FRED-FC-010	0	0	1	0	0
FRED-FC-005	0	0	1	0	0
FRED-DM-003	0	1	0	0	0
FRED-TH-002	0	1	0	0	0
FRED-TH-001	0	1	0	0	0
FRED-FC-009	0	1	0	0	0
FRED-FC-008	0	1	0	0	0
FRED-FC-019	0	1	0	0	0
Total Print Time	419	270	420	391	353

150 minutes is the minimum difference in finish time

Finding #2
Scheduling (400 Kits)

Want to minimize unload/load operations, while also making sure the printers all finish ≤8 hours each time

$$MaxPrintTime \leq 8 * 60\ minutes$$
$$\sum PlateArrange[q, printer, time] = 400\ for\ each\ part\ q;\ printerid \in (0, NumPrinters), time \in (0, maxts)$$
$$\min(timesteps)$$

Minimum Load & Unload Operations = 356, that's better than minimizing the difference the printer finish times- which would require 400 load/unloads

If you assume a labour cost of $15/hour, with each load/unload operation taking 1 hour we see a cost saving of 11% or $1.65 per kit

Finding #3
Scheduling Impact of Adding or Removing a Printer

- **Removing 1 printer (Downtime):** Would lead to the minimum number of load/unload operations being 447.
- **Adding 1 Printer:** Would lead to 300 load/unload operations. An additional printer would cost $800[1] compared to reduction in labour cost of $840=(356-300)*$15/hr it may be worth purchasing an additional printer.

Conclusion & Recommendation

→ When printing 400 FReD kits utilize the developed optimal arrangement sequence across the 3D printers over time. This will result in 356 load/unload operations- which implies in a cost saving of 11% over optimally arranging to print a single kit

[1] https://www.prusa3d.com/product/original-prusa-i3-mk3s-kit

Figure 131. Sample analysis from student project (Credits to Samuel Abel)

6.4 Developing Immersive Technologies for Manufacturing and Engineering Workshop

Talis Reks, a game-development and big-data technologist at MIT.nano Immersion Lab, led a short self-paced online workshop on AR and VR applications for manufacturing over MIT Independent Activities Period (IAP). The worshop is a beginners guide to VR/AR development with a focus on engineering and manufacturing. The course teaches concepts on game design, CAD, physics, AR/VR and scripts using state of the art software tools. FrED is used as a model and application example throughout the workshop.

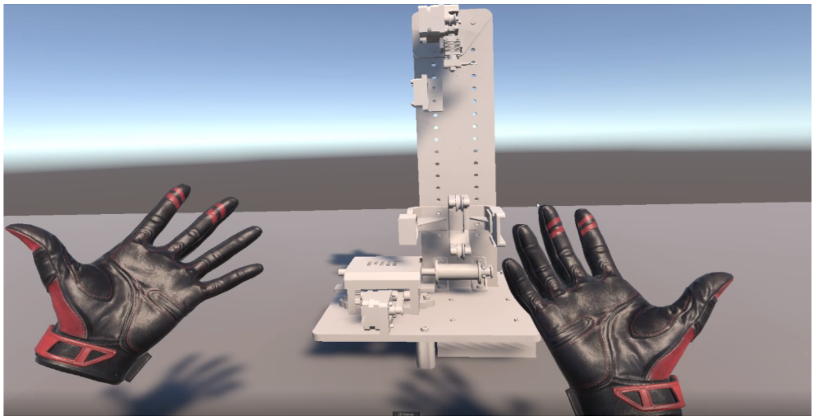
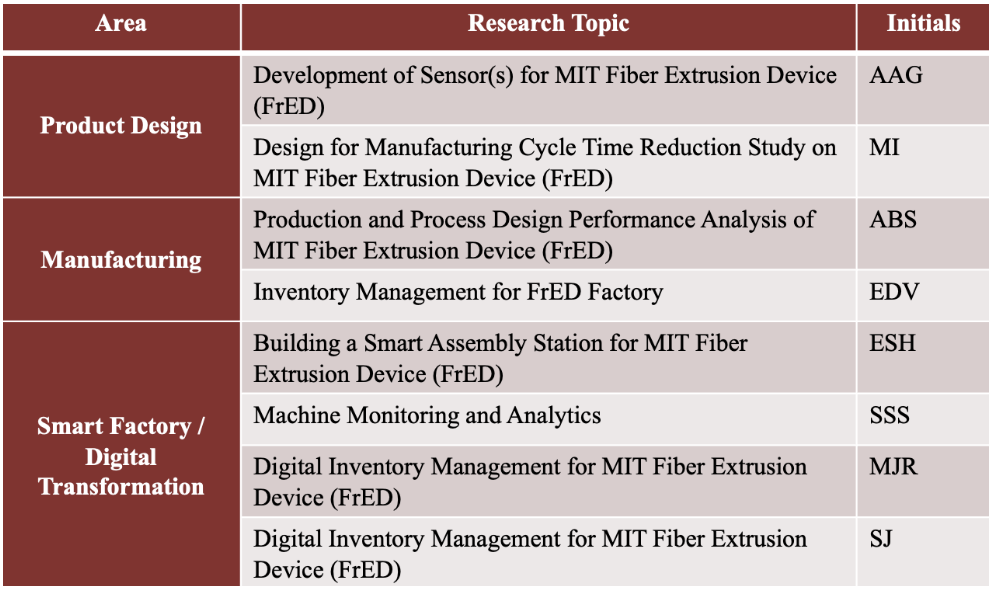


Figure 132. Virtual FrED used in the workshop

6.5 Undergraduate Research Opportunities Program (UROP)

Various undergraduate research was done in the FrED factory over the academic year. FrED factory aims to be a platform for undergraduate research and learnign in design and manufacturing. Various research topics was conducted on areas such as product design, manufacturing and digital transformation. A list of research topics conducted is presented in Table 13.

Table 13. Undergraduate research topic conducted in FrED Factory



Area	Research Topic	Initials
Product Design	Development of Sensor(s) for MIT Fiber Extrusion Device (FrED)	AAG
	Design for Manufacturing Cycle Time Reduction Study on MIT Fiber Extrusion Device (FrED)	MI
Manufacturing	Production and Process Design Performance Analysis of MIT Fiber Extrusion Device (FrED)	ABS
	Inventory Management for FrED Factory	EDV
Smart Factory / Digital Transformation	Building a Smart Assembly Station for MIT Fiber Extrusion Device (FrED)	ESH
	Machine Monitoring and Analytics	SSS
	Digital Inventory Management for MIT Fiber Extrusion Device (FrED)	MJR
	Digital Inventory Management for MIT Fiber Extrusion Device (FrED)	SJ

7. Future Work

Further work has to be done to bring low-cost FrED to market. The priority is completing a fully functional FrED design. The current FrED design lacks a functional diameter measurement sensor. Manufacturing and Assembly can be further optimized through best practices and an SOP that covers a wide enough scope.

Inbound and outbound supply chain plan has to be made. A supplier base for FrED material and components has to be compiled. An outbound delivery plan to customers has to be made.

Alternate Versions of FrED could also be developed to serve different purposes. A few completed examples include the Tec de Monterrey FrED and an Improved Research version FrED developed by Shreya Dhar [41].

The smart factory project is ongoing. The vision is to have a connected factory where all data can be linked together for meaningful analysis and streamlined operations. After the infrastructure is completed, data has to be collected for a few manufacturing runs.

Teaching content has to be further developed for on-campus manufacturing systems class. The goal is to have more practical aspect of the class from use case and case studies that come out of the FrED factory.

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Appendix

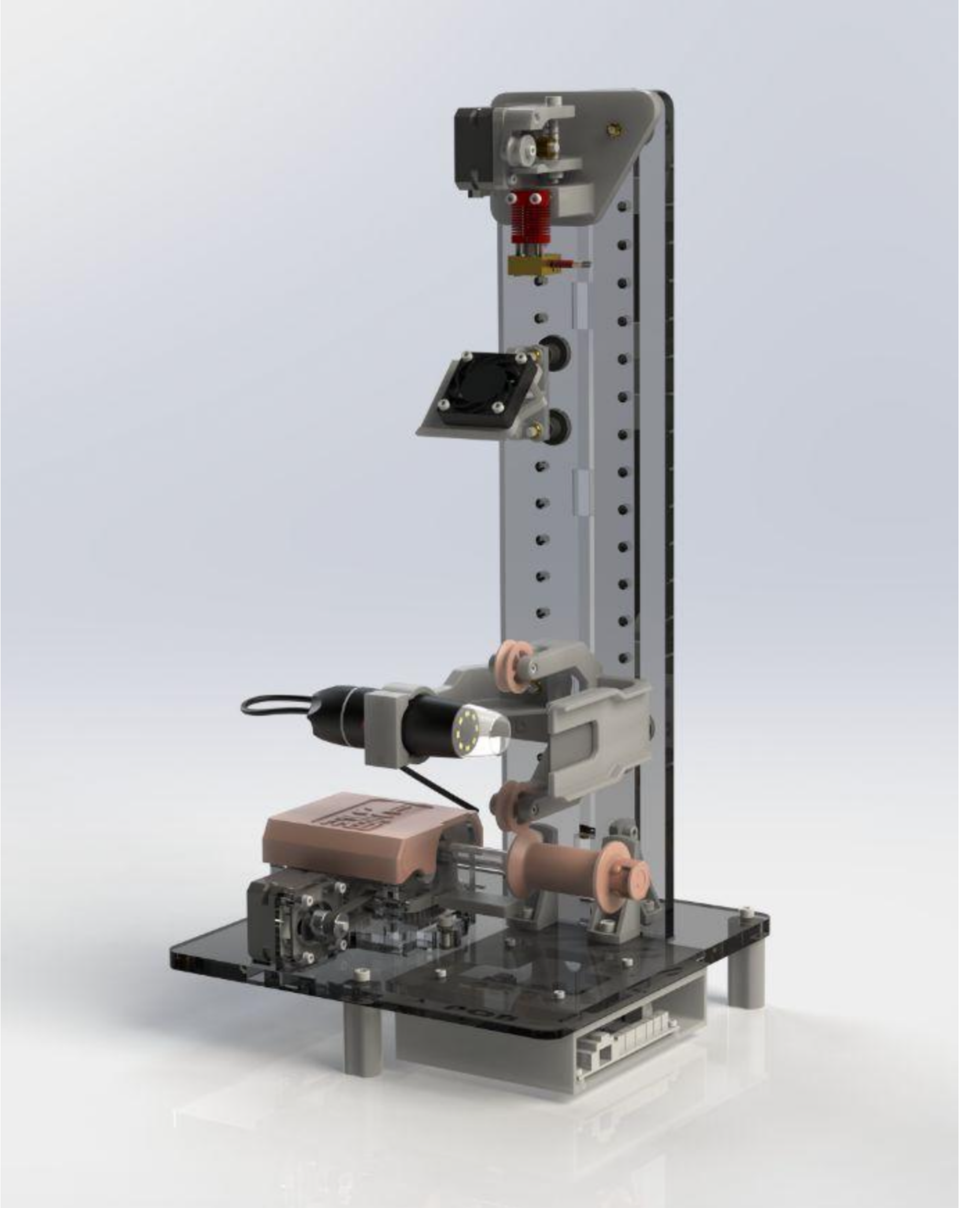


Figure A1. Render of FrED Final Design

Figure A2. FrED Logo

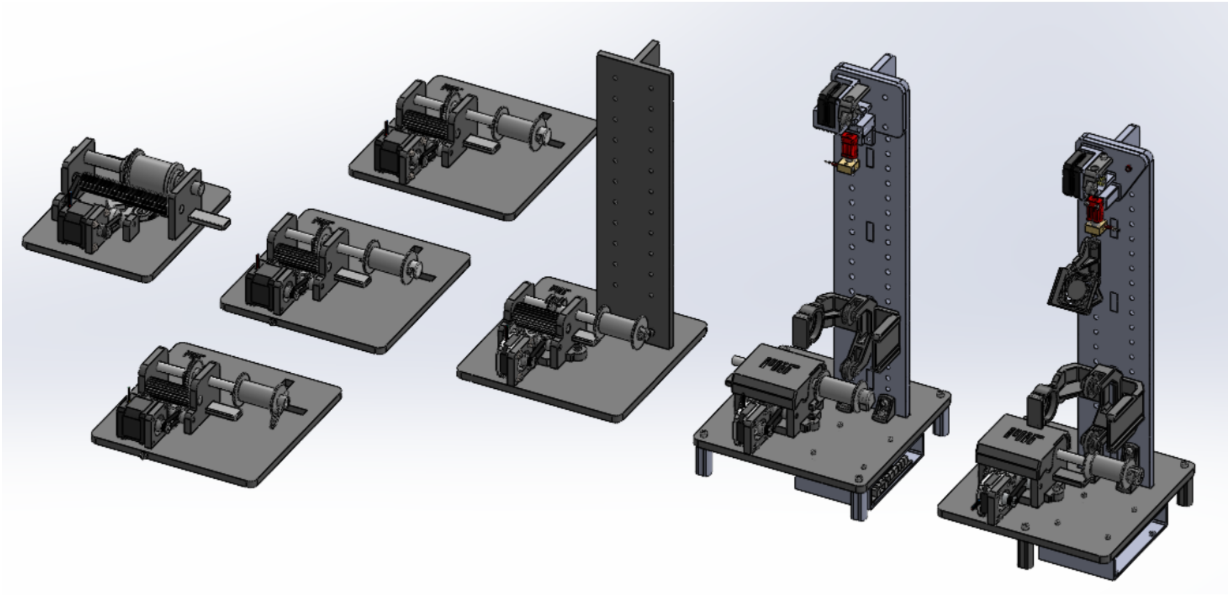


Figure A3. FrEDvolution

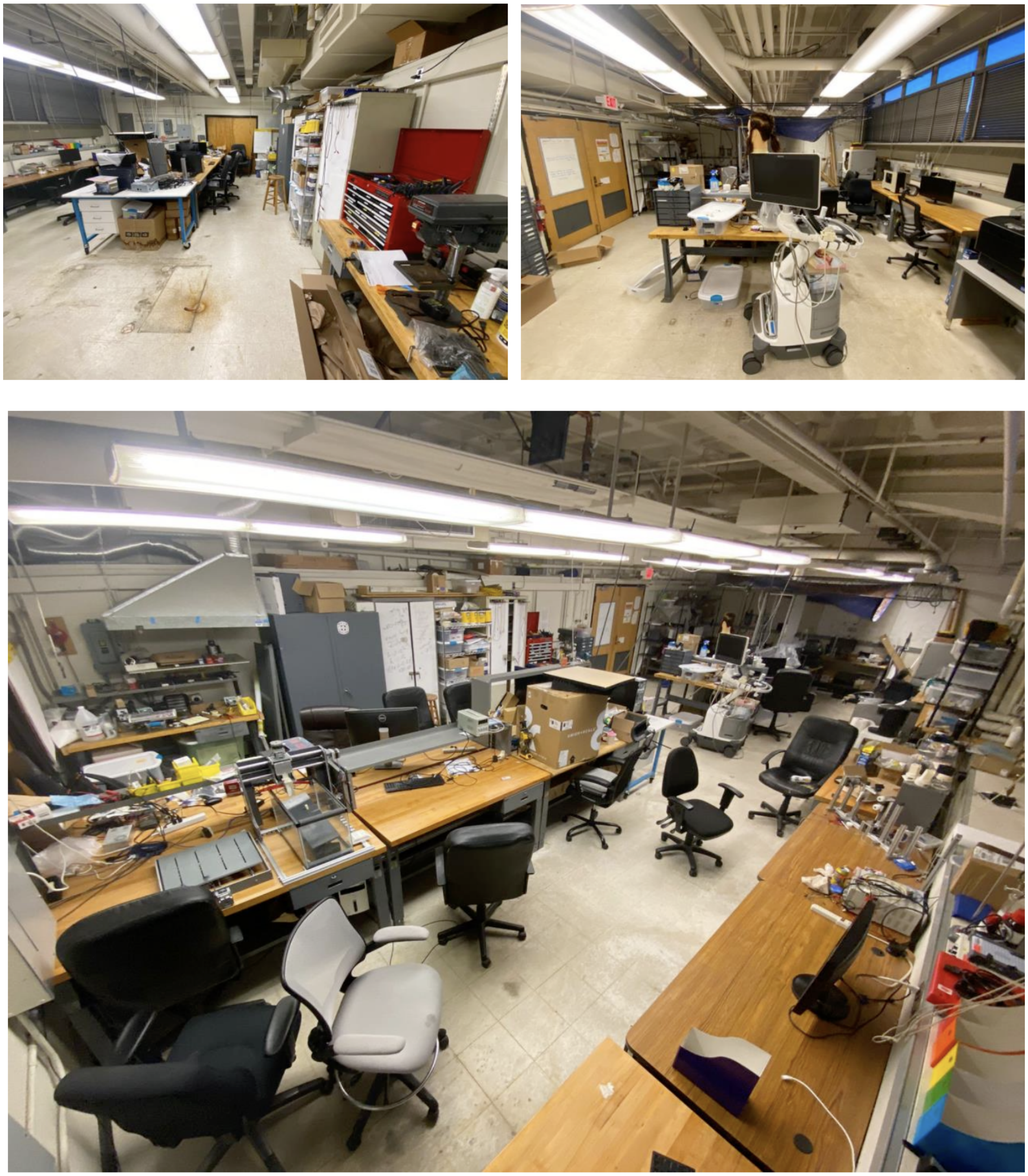


Figure A4. Previous State of Room 35-017

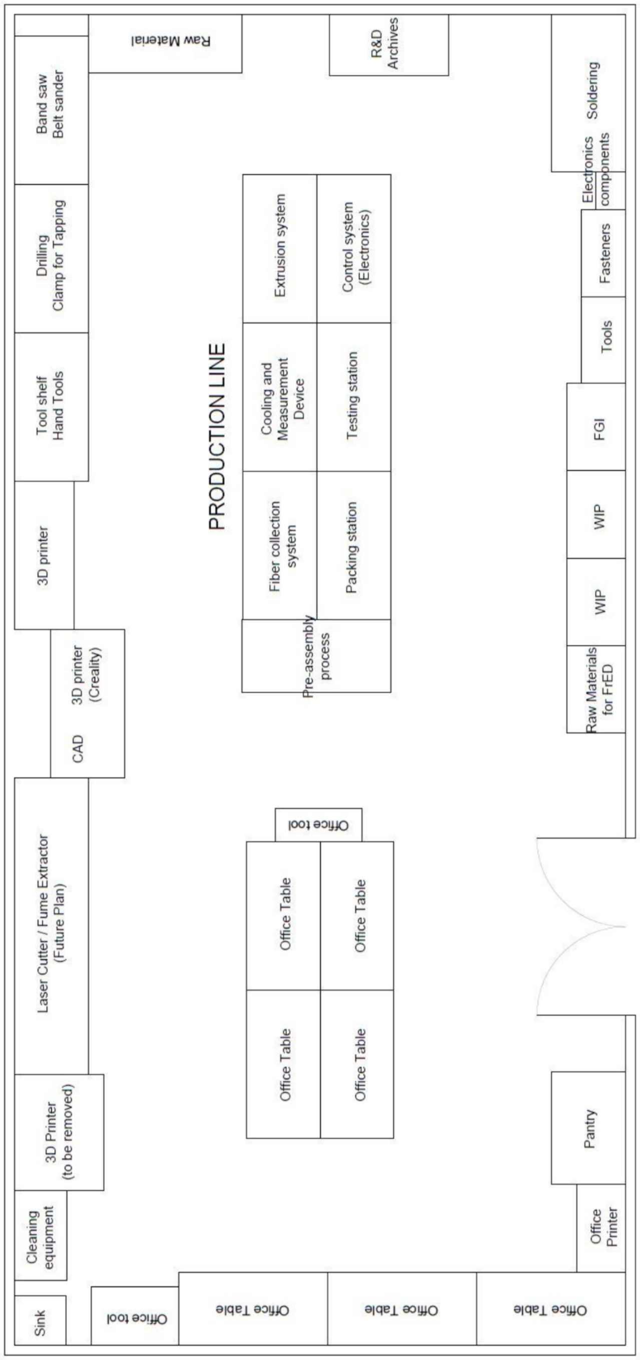


Figure A5. FrED Factory Layout

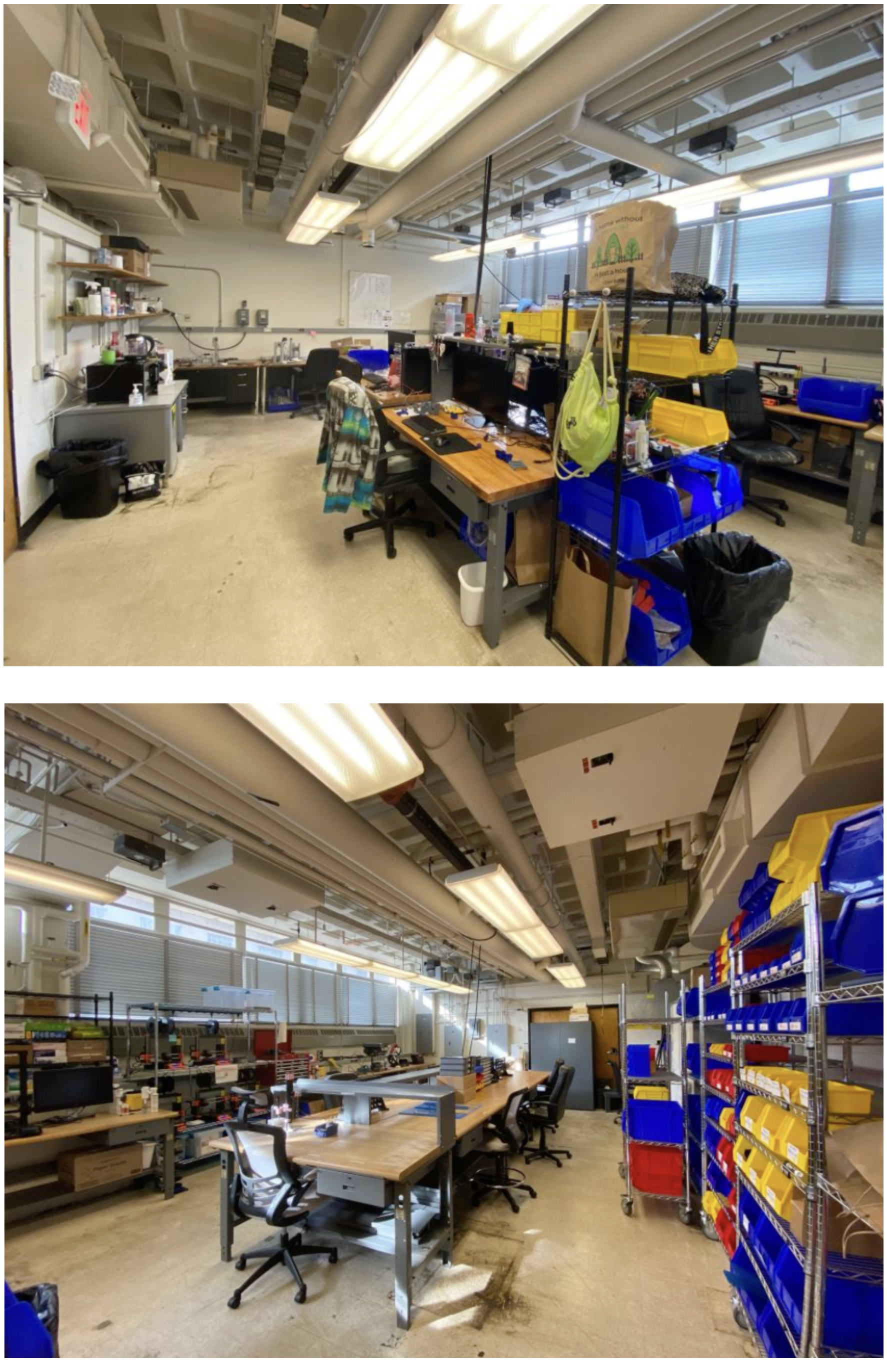


Figure A6. FrED Factory

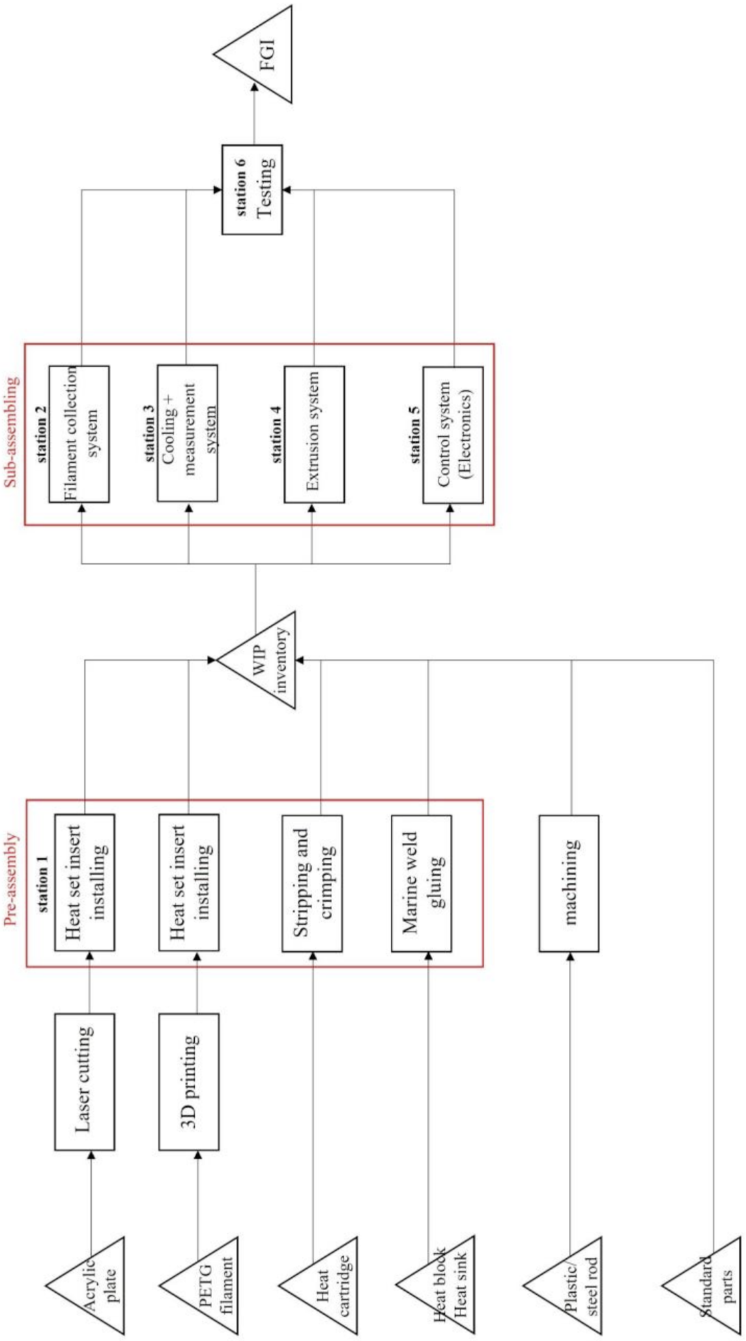


Figure A7. FrED Factory Process Flow Diagram

Table A1. FrED Bill of Materials

Part No.	Part Name	System	# Quantity	Material	Mfg Process	# Unit Weight (g)	Σ Total Weight (g)	# Mfg Time per unit (hr)	Σ Total Mfg Time (hr)	# Envelope Width (mm)	# Envelope Length (mm)	Σ Envelope Area (mm^2)	Vendor	# Cost/Pack	# Units/Pack	Σ Estimated Unit Cost	# Unit Cost	Σ Total Cost	PIC
FRED-FC-001	Modular Plate	Filament Collection	1	3/8" Acrylic Plate	Laser Cutting		0		0	116.55	85.5	9965.025	McMaster	$56.43	371612.16	0.000151851866		1.513207640987	Ray Li
FRED-FC-002	Main Axle Plate	Filament Collection	2	3/8" Acrylic Plate	Laser Cutting		0		0	77.4	69.05	5344.47	McMaster	$56.43	371612.16	0.000151851866		1.623135484562	Ray Li
FRED-FC-003	Motor Plate	Filament Collection	1	3/8" Acrylic Plate	Laser Cutting		0	0.016	0.016	50.2	51.73	2596.846	McMaster	$56.43	371612.16	0.000151851866		0.394335910815	Ray Li
FRED-FC-004	Rotary shaft_L80	Filament Collection	1	316 Stainless Steel	Bandsaw		0	0.017	0.017			0	McMaster	$83.82	10	8.382		8.382	Ray Li
FRED-FC-005	Scotch Yolk Wheel	Filament Collection	1	PETG	FDM	7.62	7.62	0.73	0.73			0					$0.19	0.19	Ray Li
FRED-FC-006	Slider	Filament Collection	1	PETG	FDM	15.06	15.06	1.35	1.35			0					$0.37	0.37	Ray Li
FRED-FC-007	Round Tube Stock_L185	Filament Collection	1	Polycarbonate Plastic	Bandsaw		0	0.033	0.033			0	McMaster	$8.07	13	0.620769230769		0.620769230769	Ray Li
FRED-FC-008	Spool	Filament Collection	1	PETG	FDM	29.8	29.8	2.6	2.6			0					$0.73	0.73	Ray Li
FRED-FC-009	Spool Cap	Filament Collection	1	PETG	FDM	1.93	1.93	0.367	0.367			0					$0.06	0.06	Ray Li
FRED-FC-010	Axle Gear_D25	Filament Collection	1	PETG	FDM	2.84	2.84	0.3	0.3			0					$0.07	0.07	Ray Li
FRED-FC-011	Spur Gear Stock_D20x62	Filament Collection	1	PETG	FDM	17.84	17.84	2.083	2.083			0					$0.44	0.44	Ray Li
FRED-FC-012	Timing Belt	Filament Collection	1	Neoprene	-		0	0	0			0	McMaster				$6.80	6.8	Ray Li
FRED-FC-013	Rotary Shaft_D5_L20	Filament Collection	1	316 Stainless Steel	Bandsaw		0	0.017	0.017			0	McMaster	$83.82	40	2.0955		2.0955	Ray Li
FRED-FC-014	Timing Belt Pulley	Filament Collection	2	Aluminum	-		0	0	0			0					$6.04	12.08	Ray Li
FRED-FC-015	Plastic Miter Gear	Filament Collection	1	PETG	FDM	2.08	2.08	34	34			0					$0.05	0.05	Ray Li

FRED-FC-016	Modified Miter Gear	Filament Collection	1	PETG	FDM	3.75	3.75	0.4	0.4			0					$0.09	0.09	Ray Li
FRED-FC-017	Plastic Spur Gear_D28	Filament Collection	1	PETG	FDM	3.17	3.17	49	49			0	McMaster				$0.08	0.08	Ray Li
FRED-FC-018	Round Tube Stock_L14.5	Filament Collection	1	Polycarbonate Plastic	Bandsaw		0	0.017	0.017			0	McMaster	$8.07	168	0.048035714286		0.048035714286	Ray Li
FRED-FC-019	Gear Housing	Filament Collection	1	PETG	FDM	37.85	37.85	3	3			0					$0.94	0.94	Ray Li
FRED-SP-002	Socket Head_M3X12	Filament Collection Standard Parts	4	18-8 Stainless Steel	-		0	0	0			0	McMaster	$13.31	100	0.1331		0.5324	Ray Li
FRED-SP-003	Washer_M3	Filament Collection Standard Parts	4	18-8 Stainless Steel	-		0	0	0			0	McMaster	$2.99	100	0.0299		0.1196	Ray Li
FRED-SP-007	Stepper Motor Nema 17 JST-XH 17HS4023	Filament Collection Standard Parts	1				0		0			0	Amazon	$36.99	5	7.398		7.398	Russel B
FRED-SP-016	Socket Head_M5X20	Filament Collection Standard Parts	2	18-8 Stainless Steel	-		0	0	0			0	McMaster	$16.66	100	0.1666		0.3332	Ray Li
FRED-SP-017	Flat Head Screw_M2X8	Filament Collection Standard Parts	1	18-8 Stainless Steel	-		0	0	0			0	McMaster	$6.60	25	0.264		0.264	Ray Li
FRED-FR-001	Base	Frame	1	3/8" Acrylic Plate	Laser Cutting		0		0	240	230	55200	McMaster	$56.43	371612.16	0.000151851866		8.3822230032	Ray Li
FRED-FR-002	T-frame	Frame	1	3/8" Acrylic Plate	Laser Cutting		0	0.087	0.087	100	460	46000	McMaster	$56.43	371612.16	0.000151851866		6.985185836	Aviva Levi
FRED-FR-003	T-frame rib	Frame	1	3/8" Acrylic Plate	Laser Cutting		0	0.032	0.032	59	460	27140	McMaster	$56.43	371612.16	0.000151851866		4.12125964324	Aviva Levi
FRED-FR-004	Legs	Frame	3	PETG	FDM	4.63	13.89	0.46	1.38			0					$0.12	0.36	Ray Li
FRED-FR-005	Bracket	Frame	3	PETG	FDM	3.87	11.61	0.55	1.65			0					$0.10	0.3	Ray Li
FRED-SP-001	Threaded Insert_M5	Frame Standard Parts	11	Brass C3604	-		0	0	0			0	Amazon	$12.99	50	0.2598		2.8578	Ray Li
FRED-SP-005	Socket Head_M5X14	Frame Standard Parts	9	18-8 Stainless Steel	-		0	0	0			0	McMaster	$9.34	50	0.1868		1.6812	Ray Li
FRED-FE-001	Extrusion System Support	Filament Extrusion	1	PETG	FDM	54.65	54.65	2.67	2.67			0		$1.52	1	1.52		1.52	Aviva Levi

FRED-SP-005	Socket Head_M5X14	Frame Standard Parts	9	18-8 Stainless Steel	-		0	0	0			0	McMaster	$9.34	50	0.1868		1.6812	Ray Li
FRED-FE-001	Extrusion System Support	Filament Extrusion	1	PETG	FDM	54.65	54.65	2.67	2.67			0		$1.52	1	1.52		1.52	Aviva Levi
FRED-FE-002	Driver Gear	Filament Extrusion	1	Brass	-		0		0			0		$9.99	5	1.998		1.998	Aviva Levi
FRED-FE-003	Lever	Filament Extrusion	1	PETG	FDM	5.89	5.89	0.37	0.37			0					$0.16	0.16	Aviva Levi
FRED-FE-004	Idler Pulley	Filament Extrusion	1	PETG	FDM	1.75	1.75	0.133	0.133			0		$0.05	1	0.05	$0.05	0.05	Aviva Levi
FRED-FE-005	Creality 3D printer extruder	Filament Extrusion	1	Aluminum	Drill press		0		0			0	Amazon	$13.99	2	6.995		6.995	Aviva Levi
FRED-FE-006	Heat Break Tube	Filament Extrusion	1	316 Stainless Steel	Bandsaw		0		0	1	11	11	McMaster	$18.75	1828.8	0.010252624672		0.112778871392	Aviva Levi
FRED-FE-007	Spring	Filament Extrusion	1	Zinc plated music wire steel	-		0		0			0	McMaster	$4.98	5	0.996		0.996	Aviva Levi
FRED-SP-001	Threaded Insert_M5	Filament Extrusion Standard Parts	2	Brass C3604	-		0	0	0			0	Amazon	$12.99	50	0.2598		0.5196	Aviva Levi
FRED-SP-002	Socket Head_M3X12	Filament Extrusion Standard Parts	1	18-8 Stainless Steel	-		0	0	0			0	McMaster	$13.31	100	0.1331		0.1331	Aviva Levi
FRED-SP-007	Stepper Motor Nema 17 JST-XH 17HS4023	Filament Extrusion Standard Parts	1		-		0		0			0	Amazon	$36.99	5	7.398		7.398	Aviva Levi
FRED-SP-004	Thumb Screw	Filament Extrusion Standard Parts	2	Plastic and Metal	-		0	0	0			0	Amazon	$11.99	15	0.799333333333		1.598666666666	Aviva Levi
FRED-SP-008	Threaded Insert_M3	Filament Extrusion Standard Parts	3	Brass	-		0	0	0			0	McMaster	$16.81	100	0.1681		0.5043	Aviva Levi
FRED-SP-010	Socket Head_M3X16	Filament Extrusion Standard Parts	2	18-8 Stainless Steel	-		0		0			0	McMaster	$7.09	100	0.0709		0.1418	Aviva Levi

FRED-SP-011	Socket Head_M3X8	Filament Extrusion Standard Parts	2	18-8 Stainless Steel	-		0		0			0	McMaster	$5.45	100	0.0545		0.109	Aviva Levi
FRED-SP-012	Socket Head_M3X10	Filament Extrusion Standard Parts	1	18-8 Stainless Steel	-		0		0			0	McMaster	$6.00	100	0.06		0.06	Aviva Levi
FRED-SP-013	Socket Head_M3X22	Filament Extrusion Standard Parts	1	18-8 Stainless Steel	-		0		0			0	McMaster	$5.45	100	0.0545		0.0545	Aviva Levi
FRED-SP-014	Socket Head_M5X40	Filament Extrusion Standard Parts	1	18-8 Stainless Steel	-		0		0			0	McMaster	$7.32	25	0.2928		0.2928	Aviva Levi
FRED-SP-015	M5 Nut	Filament Extrusion Standard Parts	1	18-8 Stainless Steel	-		0		0			0	McMaster	$9.14	100	0.0914		0.0914	Aviva Levi
FRED-E-001	Custom PCB	Electronics	1				0		0			0		$20.00	1	20		20	Russel B
FRED-E-002	Teensy 4.1	Electronics	1				0		0			0		$40.00	1	40		40	Russel B
FRED-E-003	Stepper Motor Driver DRV8825	Electronics	2				0		0			0	Amazon	$17.99	6	2.998333333333		5.996666666666	Russel B
FRED-E-004	Drawer	Electronics	1	PETG	FDM	41.66	41.66	2.867	2.867			0					$1.04	1.04	Ray Li
FRED-E-005	Drawer Guide	Electronics	1	PETG	FDM	39.66	39.66	2.717	2.717			0					$0.99	0.99	Ray Li
FRED-E-006a	18AWG 8mm Ferrules RED	Electronics	1				0		0			0	Amazon	$9.99	380	0.026289473684		0.026289473684	Russel B
FRED-E-006b	18AWG 8mm Ferrules BLK	Electronics	1				0		0			0	Amazon	$9.99	380	0.026289473684		0.026289473684	Russel B
FRED-E-007	20AWG 8mm Ferrules	Electronics					0		0			0						0	
FRED-E-008a	5.5x2.1mm DC Plug Female	Electronics	1				0		0			0	Amazon	$10.99	8	1.37375		1.37375	Russel B
FRED-E-008b	DC Plug Rubber Cap	Electronics	1				0		0			0	Amazon					0	Russel B
FRED-E-008d	DC Plug M10 Thin Nut	Electronics	1				0		0			0	Amazon					0	Russel B
FRED-E-008c	DC Plug M10 Washer	Electronics	1				0		0			0	Amazon					0	Russel B

FRED-E-009	Micro USB Cable 3ft	Electronics	1				0		0			0	Amazon	$14.99	12	1.249166666667		1.249166666667	Russel B
FRED-E-010	DC Power Supply 12V10A 120W 5.5mm	Electronics	1				0		0			0	Amazon	$89.99	5	17.998		17.998	Russel B
FRED-SP-008	Threaded Insert_M3	Electronics Standard Parts	8	Brass	-		0	0	0			0	McMaster	$16.81	100	0.1681		1.3448	Ray Li
FRED-SP-009	Socket Head_M3X14	Electronics Standard Parts	4	18-8 Stainless Steel	-		0	0	0			0	McMaster	$7.63	100	0.0763		0.3052	Ray Li
FRED-SP-015	Heater Cartridge 12V40W 5x20mm	Electronics Filament Extrusion	1				0		0			0	Amazon	$14.99	10	1.499		1.499	Russel B
FRED-SP-016	Thermistor Cartridge NTC3950 100K 3x15mm	Electronics Filament Extrusion	1				0		0			0	Amazon	$12.99	10	1.299		1.299	Russel B
FRED-DM-001	Diameter Measurement Holder	Diameter Measurement	1	PETG	FDM	59.56	59.56	5.26	5.26			0					$2.16	2.16	Ray Li
FRED-DM-002	Diameter Measurement Holder Lock	Diameter Measurement	1	PETG	FDM	4.74	4.74	0.43	0.43			0					$0.12	0.12	Ray Li
FRED-DM-003	Pulley_ID20	Diameter Measurement	2	PETG	FDM	2.41	4.82	0.25	0.5			0					$0.06	0.12	Ray Li
FRED-DM-004	USB Microscope	Diameter Measurement	1		-	198.45	198.45	0	0			0	Amazon	$21.24	1	21.24		21.24	Tanach R
FRED-DM-005	Black Card	Diameter Measurement	1				0		0	45	45	2025						0	
FRED-SP-008	Threaded Insert_M3	Diameter Measurement Standard Parts	2	Brass	-		0	0	0			0	McMaster	$16.81	100	0.1681		0.3362	Ray Li
FRED-SP-001	Threaded Insert_M5	Diameter Measurement Standard Parts	2	Brass C3604	-		0	0	0			0	Amazon	$12.99	50	0.2598		0.5196	Ray Li
FRED-SP-004	Thumb Screw	Diameter Measurement Standard Parts	2	Plastic and Metal	-		0	0	0			0	Amazon	$11.99	15	0.799333333333		1.598666666666	Ray Li
FRED-SP-006	Socket Head_M3X20	Diameter Measurement	1	18-8 Stainless Steel	-		0	0	0			0	McMaster	$5.45	50	0.109		0.109	Ray Li

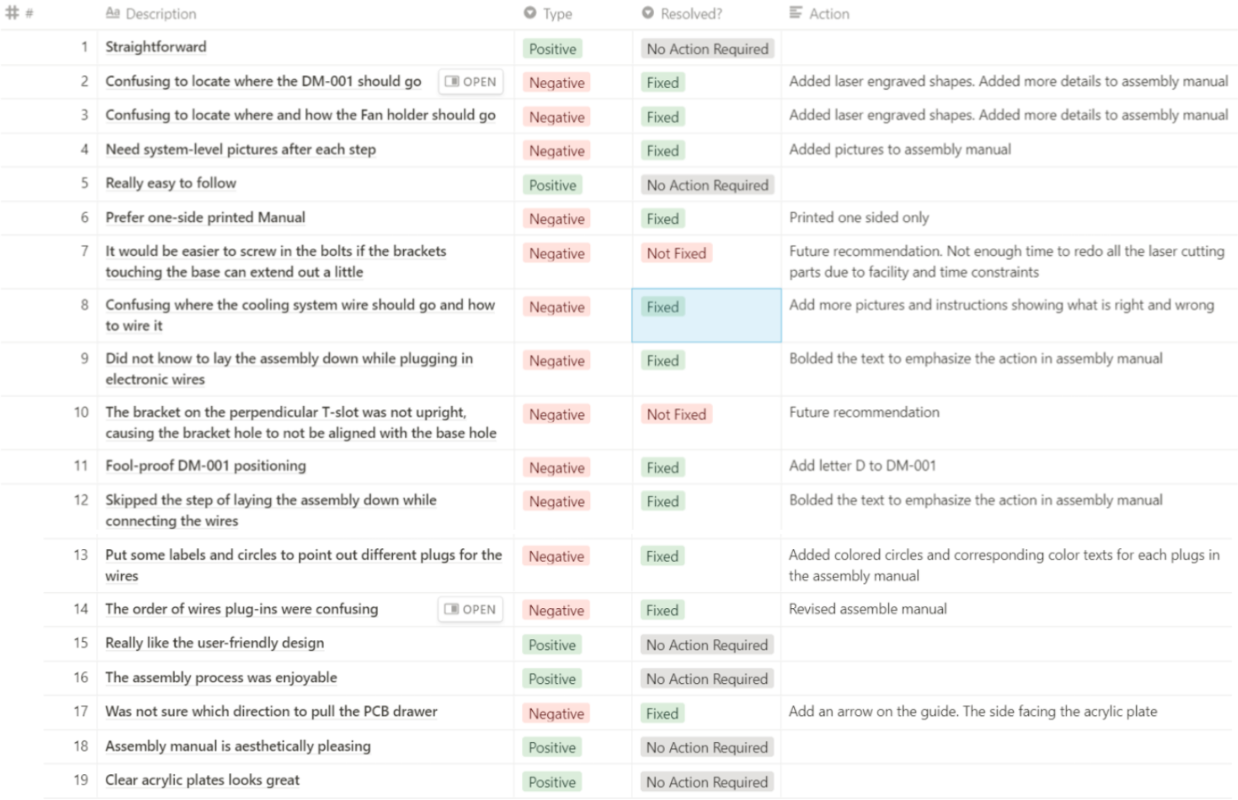
	Raspberry Pi?	Diameter Measurement Electronics	1				0		0			0		$50.00	1	50		50	
FRED-C-001	40 x 40 x 10 Fan	Filament Cooling	1	Plastic and Metal	-		0		0			0	Amazon	$3.00	1	3		3	Aviva Levi
FRED-C-002	Fan Support	Filament Cooling	1	PETG	FDM	22.37	22.37	1.067	1.067			0		$0.62	1	0.62		0.62	Aviva Levi
FRED-SP-009	Socket Head M3X14	Filament Cooling Standard Parts	4	18-8 Stainless Steel	-		0		0			0	McMaster	$7.63	100	0.0763		0.3052	Aviva Levi
FRED-SP-008	Threaded Insert M3	Filament Cooling Standard Parts	4	Brass	-		0		0			0	McMaster	$16.81	100	0.1681		0.6724	Aviva Levi
FRED-SP-004	Thumb Screw	Filament Cooling Standard Parts	2	Plastic and Metal			0		0			0	Amazon	$11.99	15	0.799333333333		1.598666666666	Aviva Levi
FRED-SP-001	Threaded Insert M5	Filament Cooling Standard Parts	2	Brass C3604	-		0		0			0	Amazon	$12.99	50	0.2598		0.5196	Aviva Levi

Table A2. Pilot Run Results

Pilot Run Results

Name	Background	Total Time (s)	Work ex (Years)	Feedbacks	Manual Version	Test Date	Video Link	Note
Mohamed O	Mfg M.Eng.	346.5	10	1 2 3 4	V1	August 1, 2022		Without electronics
Sherman L	Mfg M.Eng.	796.54	1	5 6 7 10 1 18	V2	August 3, 2022		
Charlie L	Mfg M.Eng.	989.47	1	7 1 8 9 10 11 12 13 14	V2	August 3, 2022		
Ryan L	Mfg M.Eng.	744.93	1	15 16 17 8 1 19	V3	August 3, 2022		

Table A3. Pilot Run Results Summarized



#	Description	Type	Resolved?	Action
1	Straightforward	Positive	No Action Required	
2	Confusing to locate where the DM-001 should go	Negative	Fixed	Added laser engraved shapes. Added more details to assembly manual
3	Confusing to locate where and how the Fan holder should go	Negative	Fixed	Added laser engraved shapes. Added more details to assembly manual
4	Need system-level pictures after each step	Negative	Fixed	Added pictures to assembly manual
5	Really easy to follow	Positive	No Action Required	
6	Prefer one-side printed Manual	Negative	Fixed	Printed one sided only
7	It would be easier to screw in the bolts if the brackets touching the base can extend out a little	Negative	Not Fixed	Future recommendation. Not enough time to redo all the laser cutting parts due to facility and time constraints
8	Confusing where the cooling system wire should go and how to wire it	Negative	Fixed	Add more pictures and instructions showing what is right and wrong
9	Did not know to lay the assembly down while plugging in electronic wires	Negative	Fixed	Bolded the text to emphasize the action in assembly manual
10	The bracket on the perpendicular T-slot was not upright, causing the bracket hole to not be aligned with the base hole	Negative	Not Fixed	Future recommendation
11	Fool-proof DM-001 positioning	Negative	Fixed	Add letter D to DM-001
12	Skipped the step of laying the assembly down while connecting the wires	Negative	Fixed	Bolded the text to emphasize the action in assembly manual
13	Put some labels and circles to point out different plugs for the wires	Negative	Fixed	Added colored circles and corresponding color texts for each plugs in the assembly manual
14	The order of wires plug-ins were confusing	Negative	Fixed	Revised assemble manual
15	Really like the user-friendly design	Positive	No Action Required	
16	The assembly process was enjoyable	Positive	No Action Required	
17	Was not sure which direction to pull the PCB drawer	Negative	Fixed	Add an arrow on the guide. The side facing the acrylic plate
18	Assembly manual is aesthetically pleasing	Positive	No Action Required	
19	Clear acrylic plates looks great	Positive	No Action Required	