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Capstone Review: Filament Unit Multiplexing Engine

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by

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Introduction

The Electronic Prototyping Lab (EPL) is a lab within the Electrical and Computer Engineering department in Portland State University. The lab offers tools and resources for students from all majors with all levels of technical experience. As such, there are qualified student managers who work in the lab and are in charge of assisting with tools. Among other resources the lab offers, there is an Additive Manufacturing (AM) Print Farm, which includes at least six 3D printers.

Currently, the EPL is utilizing an OctoPrint server to manage and send printing jobs to the printers. The computer running the server is adjacent to the print farm. Underneath the printers, a filament spool holder is placed and hosts multiple filaments of different materials and colors. At this time, a staff member is needed to identify which printer is available and to ensure it is fed with the correct type of filament for the job. The staff member then receives an STL file from the student, prepares it, and sends it to the relevant printer.

Considering the need to have a staff member on-site, to reduce the downtime of the print farm, the EPL was looking for a way to automate the process above. The goal was to create a system that automatically identify a pair of filament and printer that are both available, prepare the file for printing, and send the prepared file to the printer, all without human intervention.

To solve this problem, the EPL offered to sponsor a Capstone project known as the Filament Unit Multiplexing Engine (FUME). In the mechanical engineering (ME) department, a capstone project is a group project that is conducted by students throughout their last year of the program, comprising of three academic terms. Students are required to work with an industry or faculty customer that is interested in solving a problem. The customer explains the problem, provides guidelines, a budget, and other project-specific requirements to the students. Additionally, each group is assigned an academic advisor that is expected to provide feedback, guidance, and academic resources to the students throughout the year.

Literature and Market Review

The Bambu labs AMS [1] and the Prusa MMU [2] are two examples of a system that allows for a printer to select between multiple filaments to allow for multicolor prints and for the ability to have back-to-back prints made with different materials and colors. However, those solutions are Multiple Input Single Output (MISO), focused on sending multiple filaments to a single printer. While they can assist in feeding a printer with different filaments automatically, they are not solving the problem in a space such as the EPL, where multiple users are sharing only a few filaments and printers.

Base Design, Scope Definition, and External Integration

Due to the complexity of the task at hand, it was required to define at early stages of the base design process the scope of the project. Over-committing to an excessive amount of scope would cause the project to fail due to student overload, while under-committing would fail to satisfy the ME Capstone requirements. The system can be divided into the following four categories: Filament handling, control, printer handling, and communication, as seen in Figure 1 below.

Figure 1: predicted scope diagram for the project.

First, the system must be able to handle spools of filament. Filament is usually supplied in 1kg or 2kg spools. While the size and shape of filament spools is not regulated, most suppliers generally provide filament spools in a similar shape, to allow for compatibility and profitability of their product. FUME would need to be adaptable to hold different types of filaments. The user would need to be able to easily load and unload spools to and from the system, without extensive technical knowledge. Additionally, the system is required to route the loaded filament into any of the printers in the print farm, while keeping the other printers and filaments operational. The team considered this part of the project central to the success of the project overall.

Second, the system is required to automatically control the flow of the filament to the printers, and ensure smooth operations over time and in variables conditions. This requires different types of sensors to identify the condition of different stages of the operation. One example for such a sensor is a filament sensor, whose goal is to identify whether or not a line of filament is present in a tube. The filament sensor will be discussed at greater length in the detailed design section below. Motors are required for moving components within the system. To utilize information from sensors and control the motors, the system will use a microcontroller, a board that is programmed and is able to use input/output pins to read or control electromechanical components, such as a sensor and a motor. The microcontroller is programmed using a code, or software, which describes the logic of operations that controls the system.

Another critical part of the system would be the printer integration. Once the filament reaches the output side of the system, it will need to be fed to a printer. At that moment, the line of filament is no longer pushed by the system's motors, rather it is being pulled by the printer's motor. A successful integration of this process requires coordination of the feeding rates and timing between FUME and the printer. Additionally, when the filament needs to be retracted from the printer and re-spooled, the opposite process would take place, which requires similar integration.

Lastly, since the system would serve multiple printers, which are individual and independent systems, FUME would require the ability to communicate with external systems. However, printers are not the only side of communication for FUME. The EPL was also interested in creating a quoting system, where students could send a file online, and the system would automatically communicate with FUME to pair the filament, printer, and STL file in order to start the print job.

The mechanical aspect of the project, that is the filament routing, printer feeding, sensors, motors, and control system, is extensively covered in the ME curriculum. Classes such as Dynamics, Strength of Materials, Analysis of Mechanical Component, Mechatronics, and Solid Modeling equip students with the ability to design and prototype such a system. While ME students are required to take some electrical engineering and programming classes, the scope of those classes is introductory and limited, meaning the team would require external assistance for this project to fully integrate with the user and printer side.

Initially, the team started as two ME students with a plan to receive several computer science (CS) students for additional support. After about two weeks of preliminary design work, the ME department decided to append two additional ME students, making the team a total of four ME students. Additionally, the customer informed the team that the CS students were not approved for the project, leading to some potential hardship on the ME team, as the project requires a substantial amount of software design – which is not covered in the ME curriculum.

While the ME capstone is a three-term long sequence, CS students spend their last two terms working on their capstone project. Halfway through the project, the ME team was informed that two CS capstone teams were approved to start working on two projects: FUME and PrusaSlicer Automated Routing & Quoting Engine (PARQE). The CS FUME team would work on integrating the ME FUME system with the printers and provide a software user interface, while the PARQE team creates a quoting system for the EPL's website, allowing students to upload print job requests that would be sent to FUME and the print farm. During the work on the project, the ME and CS teams met several times and discussed the integration of the two projects. While the goal was, and remains, that the two systems would power each other and integrate, it was agreed early in the process that each team would create an independent testing version that could demonstrate their project regardless to the other team's progress.

One of the classes required in the ME program is ME411: Engineering Measurements and Instrumentation. In this class, students are required to design and conduct an experiment from start to finish, with a focus on instrumentation and the design of measuring apparatuses to analyze the experiment's results and to draw conclusions. Since the team was enrolled in ME411 concurrently with the capstone project, this experiment was one that would contribute to the project. The primary objective of this experiment is to assess the requisite force necessary for the filament to be pushed or pulled through predetermined lengths of Polytetrafluoroethylene (PTFE) tubing, varying in diameter. The outcomes derived from this experiment will serve as guidelines to determine the strength of the motor required to feed filament the determined length of tubing that sets the parameters of the design. The data collected was cropped, filtered using a

Butterworth filter, and the calibration average steady state values were subtracted from each trial's average steady state value, as seen in Figure 2 below.

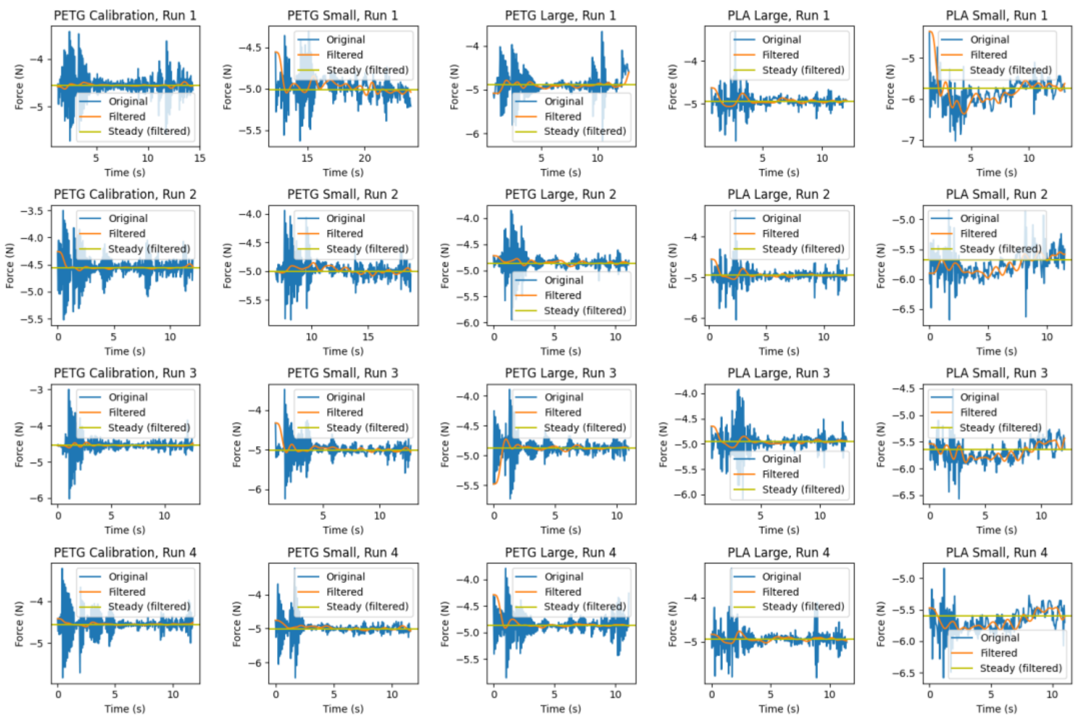


Figure 2: Force plots from the ME411 experiment. A reading from the sensor is processed and filtered in order to achieve an estimation of the force due to friction of different filaments in a smaller and a larger diameter tube.

The results of this experiment indicated that, as expected, using a PTFE tube with a larger diameter would result in less force due to friction between the walls of the tube and the filament. This insight is critical in applications where filament is required to travel over a long distance. Since FUME is supposed to be expandable, theoretically it may require pushing a line of filament from FUME to a printer located far from the system. In such a case, the experiment's results indicate that it would be beneficial to connect the two using a larger diameter tube, in order to reduce friction. However, while PTFE tubes are used in the project, since within the system the length of the tubes is relatively short, the team decided to use the smaller diameter tube in order to save space and money. This decision is due to this type of tubes being the industry standard and thus is more common.

Detailed Design Review

Throughout the first and second terms of the project, the design of FUME changed rapidly. One initial inspiration for the design was the telephone switchboard, as seen in Figure 3.

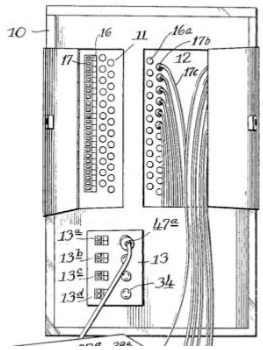


Figure 3: Drawing taken from a switchboard patent, filed on April 15, 1954. Signal wires are routed to different ports, depending on availability and need [3].

While there is no direct material running through the telephone lines in the switchboard, wires carrying electric current send and receive phone calls. The wires are being moved as needed by an operator. The switchboard design inspired the team in the early design process. The idea of routing a line into different ports is still used in the current design of FUME. However, due to possible entanglement, the team decided that each spool of filament would have its own track of ports, leading to the different printers.

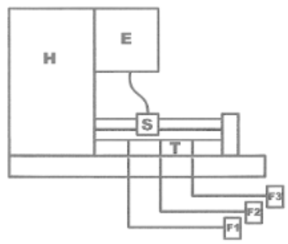
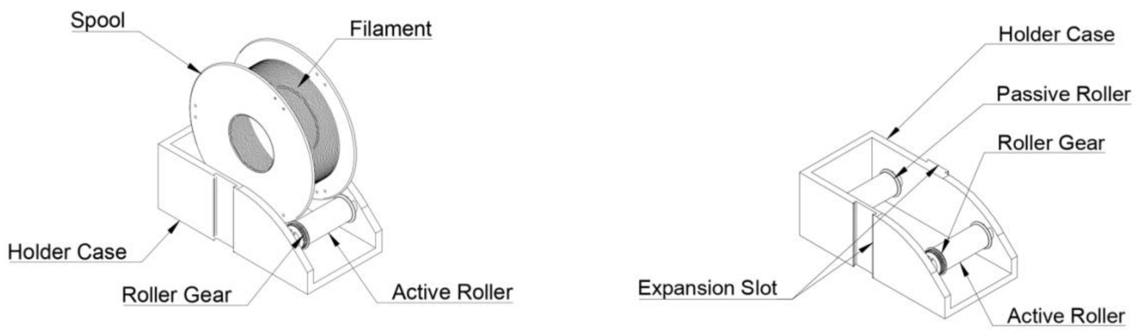


Figure 4: System diagram of FUME, where:
H = filament spool holder, E = Engine, S = shuttle, T = track, and F = funnel.

Figure 4 above describes the physical layout of the system. The spool holder (H) is connected to the engine (E). The engine is pulling filament from the holder, and is pushing it through the shuttle (S). The shuttle is a moving unit that travels along a track (T). On the track, PTFE tubes are connected, each leading to a different printer. At the end of the tube, right before the printer, a funnel collects all the tubes from the different holders that are routed to the printer. At every moment, each one holder can be sending a filament to any of the printers. However, while one pair of printer and holder is connected, FUME is able to freely route any of the other holders to any of the other printers if those are available.

Spool Holder

The first component in FUME is the spool holder. Filament is commonly packed in spools, as seen in Figure 5. The spool holder has an active and a passive roller, on which the filament spool is resting. The active roller is equipped with a gear which integrates with the engine. While the engine is driving filament to the printer, the active roller is free to rotate. However, when FUME retracts filament, the active roller is driven by the engine and wraps the filament around the spool.



(a)

(b)

Figure 5: FUME spool holder design. Fig. 5(a) shows the holder with a mounted spool. Fig. 5(b) shows an empty holder, where the passive roller and expansion slots are visible.

As seen in Figure 5(b), the holder is equipped with expansion slots on both sides. When assembled, multiple holders can be chained together to form a rack. An engine and a track are placed in front of each holder.

Engine

The main component of FUME is the engine. After filament exits the spool holder, it enters the engine, which purpose is to drive the filament through the shuttle and the track to the relevant printer. The engine is driven by a DC motor and utilizes a set of gears and a rotating axis which allow the engine, using only one motor, to perform two functions: filament retraction and filament driving.

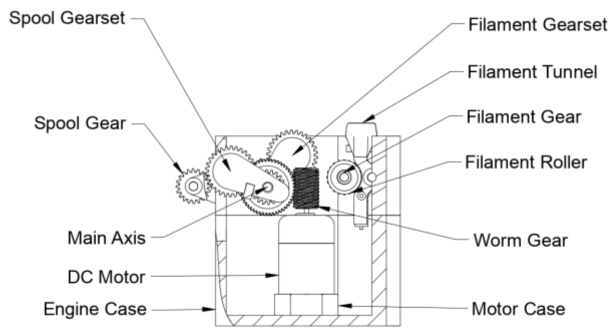


Figure 6: The FUME Engine. Cross-sectional cut is marked with diagonal lines, allowing to see the gears within the engine case.

As seen in Figure 6, the DC motor is hosted vertically in the engine case and is connected to a worm gear. The purpose of the worm gear is to take the fast rotation of the motor and generate a slower, yet powerful, movement in the gears. Depending on the motor's direction of rotation, the main axis will either rotate clockwise or counterclockwise, relatively to the orientation of Figure 6. If the rotation is clockwise, the filament gearset will engage with the filament gear and drive filament downwards, towards the shuttle. If the rotation is counterclockwise, the spool gearset will engage with the spool gear and drive the spool holder to retract filament from the system and back to the spool. In any of those modes, only one gearset is engaged, while the second gearset is stopped by the case and its gear rotates freely in space.

Track and Shuttle

After the filament exits the engine, it is directed to the shuttle and track.

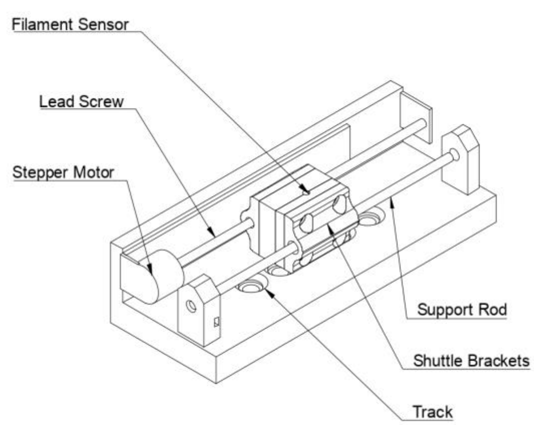


Figure 7: FUME's track and shuttle design.

Each track is equipped with a shuttle, made of a custom-designed filament sensor, brackets and a stepper motor. Figure 7 describes the shuttle's bracket, contains a nut that moves along the lead screw as the stepper turns, allowing it to move between different points on the track. As previously mentioned, an essential requirement for controlling the system is the ability to identify if a filament is present in a given point in the system. One such critical point is the shuttle. In order to successfully identify if the shuttle is cleared to move from one track point to another, the system needs to know if the filament passed the tube below. To achieve this, the team designed and built a filament sensor. The sensor utilizes a Hall effect sensor. This type of sensor utilizes the creation of voltage across a current-carrying conductor by a magnetic field. This effect is known as the Hall effect, discovered by Edwin Hall [4]. Simply put, the sensor is able to identify a change in voltage when a magnet is placed near it.

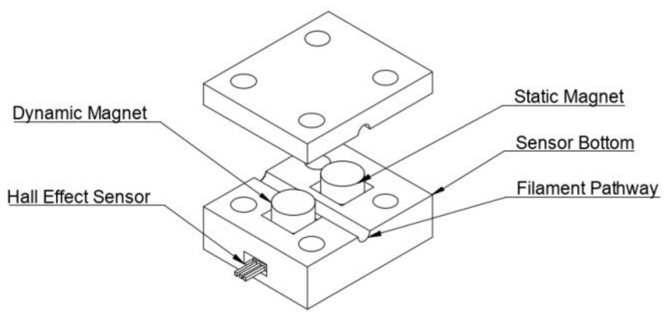


Figure 8: Custom designed filament sensor.

Figure 8 describes the filament sensor design. The filament sensor is designed such as that when filament is present in the filament pathway, the dynamic magnet is pushed to a position above the hall sensor, creating a change in voltage which is read by a microcontroller. The static magnet is constantly pulling the dynamic magnet to occupy the filament pathway. When the filament is retracted and is no longer in the filament pathway, the dynamic magnet moves further away from the sensor and removes the magnetic field, signaling to the system the filament is no longer present in the sensor. In designing this sensor, the team ensured the sensor could be incorporated in different components of the system, such as the shuttle as seen in Figure 7 above. The sensor takes about 10 minutes to print on a 3D printer and costs about $3, including materials, the Hall sensor, and magnets.

Funnel

The last stop of the filament is the funnel. Each printer is equipped with a funnel, which collects PTFE conduits from all spool holders and tracks into a single conduit leading to the printer. Perhaps the simplest component in the system, the funnel is printed such as that multiple inputs are joining into a single output, as seen in Figure 9.

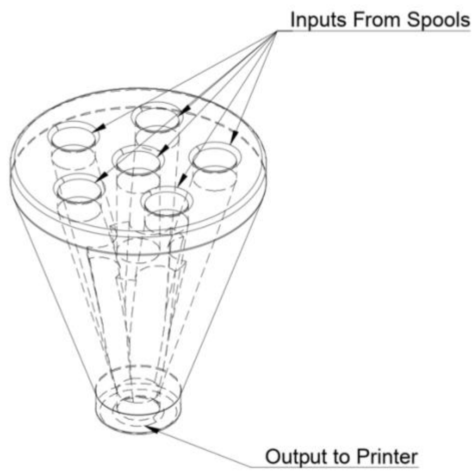


Figure 9: FUME's funnel design.

Difficulties and Limitations

Due to the changing structure of the team, new members needed to be informed of the design and task multiple times, both internally and externally, to the ME team. This required spending time both on technical reviews as well as team building. Additionally, since there are many ways to solve the task at hand, the team encountered conflicting ideas regarding the overall design of FUME.

In early stages of the project, the team decided to using the time to design the system as a whole, then designing each component on its own, in the following order: engine, holder, shuttle, track, and funnel. Since the engine is the main, most complex part of FUME, it would dictate the design of the holder on one side. Then, the shuttle would have to comply with the engine design, followed by the track and funnel.

As agreed, the team started by designing the engine. Initially, the engine was designed with a linear actuator separating the passive and active rollers, to allow opening of the channel when filament is being pulled and retraced by the holder. However, after modeling the engine, the rest of the components in the project, and starting the prototyping progress, the client updated the team that the linear actuator is not desired. This meant the team now had to redesign many of those parts, a process that lasted several weeks and deeply impeded the progress of the project. After multiple brainstorming sessions, the team agreed on using a similar design to the one used in the Bambu AMS, while redesigning each of the components to fit the needs of FUME.

In addition to the need to redesign those components, the team encountered several team dynamic struggles. With different team members enrolled in different classes, working part time jobs in addition to school, and caring for family members, it was especially challenging to find times where all team members could meet – especially in person. With one weekly standing meeting, several check-ins, and individual work, the team made progress on the design effort, but when the time came to prototype FUME, it became especially challenging to coordinate meetings. To solve this, the team decided to leverage each team member's strength and in addition to all-team meetings create tackle specific tasks in pairs or individuals, and report back to the team via chat and/or virtual calls.

Eventually, considering the time limitation of the project, the team decided to limit the deliverable scope of the project to a fully functional CAD model, and individual prototypes of the different components.

Conclusion

The Filament Unit Multiplexing Engine (FUME) project, sponsored by Portland State University's Electronics Prototyping Lab (EPL) aimed to automize the selection and routing of filament in the EPL 3D print farm to increase efficiency in the lab. The project's team was inspired by solutions such as the Prusa's MMU and the Bambu AMS. However, those solutions were limited in their capability to fulfill the needs of the lab. The team designed the different components of the system: the holder, engine, shuttle, track, and funnel, all intended to form FUME. Throughout the process, the team encountered restrictions, both technical and organizational, performed multiple design revisions, and applied theoretical knowledge gained in classes into practical solutions. Despite the challenges, the team produced a practical solution for the EPL while gaining valuable learning experience and creating potential benefit for the broader 3D printing community.

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