Enhancing Engineering Education: Integration of the Desktop Fiber Extrusion Device (FrED) for Hands-On Learning in Smart Manufacturing.

by

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Submitted to
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in partial fulfilment of the requirements for the degree of
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ABSTRACT

This thesis explores the integration of the Desktop Fiber Extrusion Device (FrED) into smart manufacturing education, emphasizing its transformative potential in engineering curricula. The research focuses on the development and application of educational and research-grade FrED models, designed to provide hands-on learning experiences remotely, which is increasingly pertinent in the evolving landscape of engineering education. Through iterative design and implementation of control systems, including Proportional-Integral-Derivative (PID) and Deep Reinforcement Learning (DRL), the study enhances the operational precision and educational utility of FrED. Furthermore, the introduction of an innovative, low-cost tension sensor in the fiber extrusion process represents a significant enhancement in monitoring and controlling the mechanical properties of extruded fibers, which is critical for understanding manufacturing dynamics.

The thesis also proposes a structured coursework framework titled "Remote Monitoring and Control in Smart Manufacturing" that utilizes FrED to teach key concepts of smart manufacturing. This coursework is designed to equip students with the skills to operate advanced manufacturing tools and analyze real-time data for process optimization.

The findings demonstrate that FrED not only supports the theoretical and practical education of engineering students but also serves as a bridge to high-tech industrial applications, making it a pivotal tool in the digital transformation of manufacturing education. This work lays the groundwork for future research on the scalability of such educational tools and their integration into different educational settings globally, potentially democratizing access to cutting-edge engineering education.

Thesis supervisor: Dr. Brian W. Anthony

Title: Principal Research Scientist

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Acknowledgments

First and foremost, I extend my deepest gratitude to god, my family—my mother, Jyoti Jaiswal and father, Sunil Jaiswal - Without them, I simply wouldn't be the person I am today.

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To the FrED 2023 team, Gary Sefah, Wenhao Xu and Somesh Jaiswal—yes, thanking myself because, why not? We've not only been teammates but great friends.

I am grateful for the collaboration with Tecnologico de Monterrey, especially Dr. Pedro Ponce Cruz, which has been instrumental in enhancing the educational impact of FrED.

A huge shoutout to my MEng cohort, they were great.

Lastly, if gratitude were a currency, I'd probably be causing inflation right now. But since it's not, let's just say I owe you all a big one—maybe in the form of a round of applause or, even better, a round of coffee when we next meet. Here's to more adventures, less fiber tangles, and the kind of learning that keeps us all awake—without caffeine!

Somesh Jaiswal

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Chapter 1: Introduction

The advent of professional online learning, accelerated by COVID-19 and the rise of Massive Open Online Courses (MOOCs) such as edX and OpenCourseWare, as well as specialized online courses from universities globally, has spurred extensive investments in developing these courses to emulate the traditional classroom learning environment [1] [2]. Yet, as the world further industrializes and undergoes digital transformation, the importance of laboratory education intensifies [3]. The pressing question remains: How can online engineering courses effectively deliver rigorous laboratory skills? The development of the Desktop Fiber Extrusion Device (FrED) is a strategic response to this challenge.

1.1 Background on Fiber Extrusion in Education

Optical fiber manufacturing, pivotal to internet communication technologies, utilizes a continuous process known as fiber extrusion. In this process, glass preform is melted in a furnace, precisely measured, and cooled [4]. Additional steps involving chemical coatings and curing processes are employed to enhance production speed and strengthen the fibers [4]. These manufacturing setups typically extend over multiple stories.

Several parameters, such as fiber diameter, melting temperature, and tension, are critical for achieving the desired fiber specifications. The MIT Mechanical Engineering Device Realization Laboratory initially selected this process for advanced process control studies.

Developments in Desktop Fiber Extrusion Kim et al. pioneered the first research-grade Desktop Fiber Extrusion Device (Desktop FrED), designed to allow users to manipulate various process parameters, explore different control strategies, and gather data for advanced analytics [5], [6], [7], [8]. Dr. Brian Anthony, an MIT faculty member, successfully utilized the research-grade FrED in a Smart Manufacturing course for managers and directors at manufacturing giant Arconic, garnering positive feedback on its effectiveness [5]. This success led to the creation of the online course "Smart Manufacturing: Moving from Static to Dynamic Manufacturing Processes" through MIT Professional Education, focusing on FrED, which now attracts 400 participants annually [5]. However, the course's virtual format highlighted the challenges of replicating hands-on learning experiences online, prompting the need for an affordable, educational-grade desktop FrED.

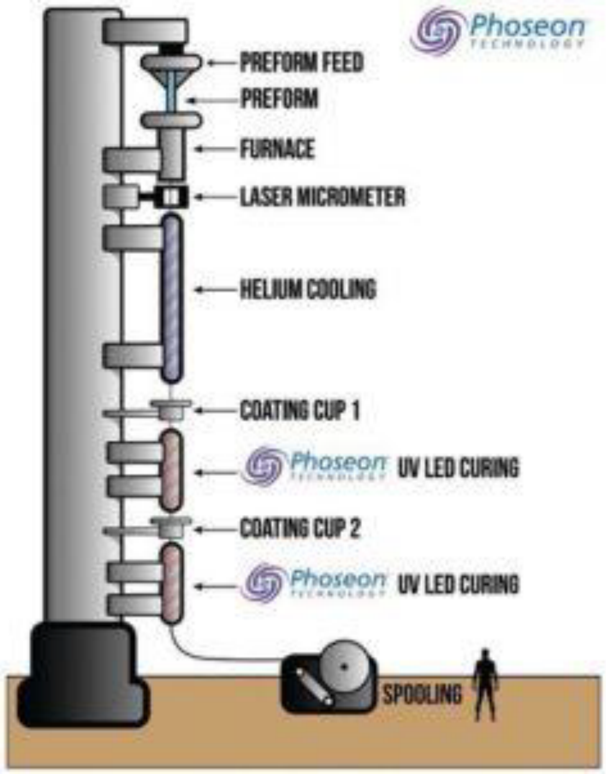

Figure 1.1 *Industrial process of optical fiber manufacturing, which may involve multi-story facilities [4]*

An assembly and teaching facility for FrED was established at MIT, serving dual purposes: manufacturing assembly and educational instruction for students in the

Master of Engineering in Advanced Manufacturing and Design program. Furthermore, a collaboration with Tec de Monterrey, a leading technical university in Mexico, was initiated to replicate and integrate similar courses based on FrED into their curriculum [5].

1.2 Aim of the Educational Grade Desktop Fiber Extrusion Device (FrED)

The educational grade Desktop FrED is designed to democratize access to sophisticated laboratory equipment by transforming it into an affordable, compact, and reliable desktop device. This device is intended to be distributed globally, enabling learners to engage in a variety of disciplines including computer vision, product design, controls, and data analytics. This hands-on, evidence-based approach not only reinforces theoretical knowledge acquired in online courses but also addresses common challenges in online education, such as reduced student motivation, variable teaching quality, and the difficulty of providing practical experience remotely [9]. Although some institutions have experimented with virtual laboratories to enhance the tangibility of engineering education, these solutions often fall short of replicating the indispensable real-life experience inherent to engineering practices [9].

Claudius et al. have developed a three-dimensional framework for online laboratories, which serves as the foundation for the Desktop FrED's framework, as illustrated in Figure 2 [3]. This framework enhances FrED's versatility, transforming it from a mere product into a comprehensive suite of services that can accommodate a wide range of applications beyond just fiber extrusion.

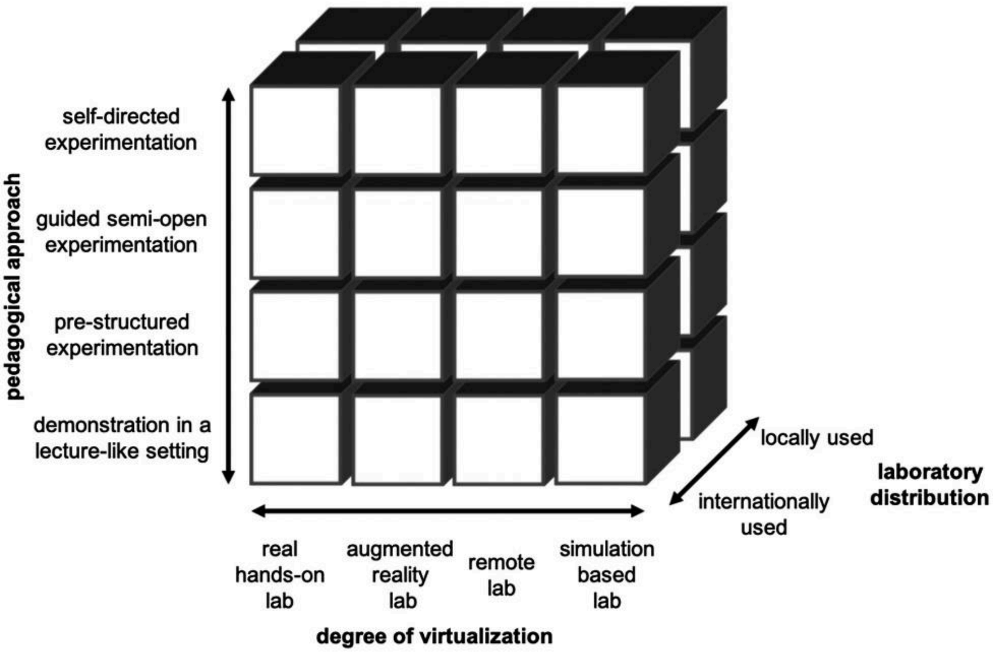

Figure 1.2 *Three-dimensional framework for online laboratories, adapted for Desktop FrED to meet diverse educational needs and learner requirements [3]*

Initially, the FrED is designed to offer structured, hands-on experimentation kits that can be shipped internationally. These kits come with detailed instructions tailored to specific learning outcomes. As the FrED's use expands, there is potential to evolve the instructional offerings from fixed to semi-open or even self-directed learning formats. This adaptation could make the technology accessible to learners with limited financial resources by integrating options such as remote or simulated laboratory environments. This could include a 'FrED farm' equipped with cameras and data transmitters, or digital twins of FrED that learners can interact with via their personal computers.

Moreover, the production facility for FrED, currently located in the basement of MIT’s Building, offers additional educational possibilities. This facility could serve as a real-world teaching lab for factory design, line configuration, data analytics, throughput analysis, and experimental design, further enriching the educational impact of the Desktop FrED.

1.3 **Research Grade FrED – Overview**

The research-grade Desktop Fiber Extrusion Device (FrED) was initially developed in 2017 by David Kim and Brian Anthony specifically for professional education purposes [10]. It was later utilized by Sangwoon et al. in 2020 to explore deep reinforcement learning controls [11], and by Cuiffi et al. in 2021 for manufacturing workforce training [12]. This version of FrED is engineered to downscale and economize the bulky and costly setups traditionally used in industrial optical fiber training. Notably, it simplifies the process by omitting the coating steps and replacing the glass preform with a hot glue stick, which is safer and easier to heat and extrude [5]. The device is equipped with various sensors to collect data essential for analytics and to facilitate diverse process control methods [5].

As depicted in Figure 4, the research-grade FrED comprises four main subsystems: the extruder, cooling unit, diameter measurement, and collection system [10] [12]. The extruder operates by heating the hot glue stick preform via heating elements embedded in a manufactured metal block. The softened preform is then pushed through a smaller exit hole using a stepper motor that regulates the extrusion speed [10] [12]. As the preform exits, it becomes less viscous and is drawn into the collection system, which includes a DC motor to rotate the collection spool and a stepper motor coupled with a lead screw to facilitate the reciprocating action needed to distribute the fiber evenly [10] [12]. The fiber's diameter is controlled by adjusting the pulling tension and solidified through cooling in a water tank. The diameter measurement system continuously monitors and records the fiber diameter, integrating this data into a process feedback control algorithm to achieve the desired specifications [10] [12].

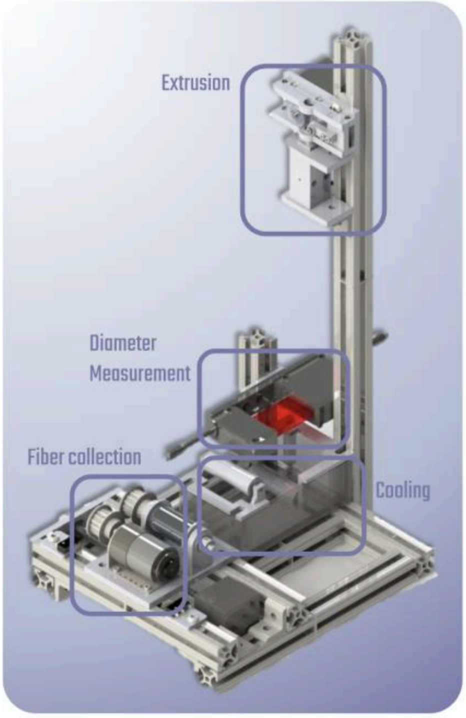

Figure 1.3 *CAD render of the research-grade FrED, illustrating the Extrusion, Diameter Measurement, Cooling, and Fiber Collection subsystems [5]*

Data collection is integral to the system's operation, involving three sensors: a Resistance Temperature Detector (RTD) to monitor and limit heating, a laser micrometer to precisely gauge fiber diameter for closed-loop feedback control, and a pair of limit switches to regulate the spool's translational motion [10] [12].

Initially, a basic mass conservation model was employed to control fiber diameter, given known extrusion and spooling speeds, although variations in temperature and mechanical timing led to inconsistencies [11]. To enhance precision, closed-loop controls were introduced, employing a Proportional Controller for the DC motor's spooling speed and a

Proportional-Integral Controller for managing diameter discrepancies [11]. This setup demonstrated effectiveness in maintaining consistent diameter measurements. Further improvements were achieved with the introduction of a deep reinforcement learning (DRL) control system, which enhanced the performance in tracking diameter errors [11]. It was also noted that pre-training the data could significantly reduce the online training time for this control method [11].

Despite its sophistication and utility, the cost of this advanced system stands at $54,281 [11], reflecting its development in a pre-COVID era when in-person classes were the norm.

1.4 **Desktop FrED 2022 - Overview**

Transitioning into the online learning environment necessitated a reevaluation of the research-grade Desktop Fiber Extrusion Device (FrED) due to its prohibitive cost and complexity for widespread deployment. To address these challenges, Bradly et al. undertook the task of redesigning FrED to make it more lightweight and cost-effective.

Utilizing rapid prototyping technologies such as acrylic laser cutting and Fused Filament Fabrication (FFF) 3D printing, along with integrating readily available commercial components, the team achieved a dramatic reduction in production costs. Originally priced at $5,428, the redesigned FrED 2022 was brought down to just $270.12—a 95% decrease in cost. The unit now weighs 5 pounds (2.4 kg) and consists of 152 parts, making it not only economical but also portable and accessible for broader educational use.

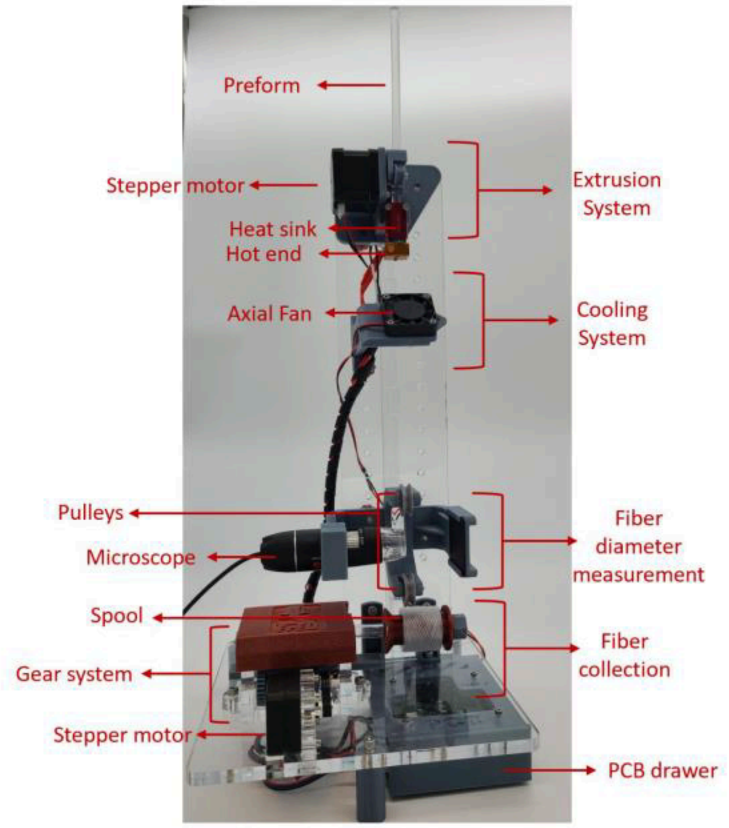

Figure 1.4 *Complete assembly of the Desktop FrED 2022, showcasing its 6 main subsystems.*

The revamped device is powered by Teensy, an Arduino-compatible development board. Users can program the device by uploading C++ code through a micro USB connector provided on the Teensy board. This flexibility allows for extensive customization and adaptability to various educational needs.

A significant innovation in the Desktop FrED 2022 is the introduction of a camera-based diameter measurement system. This system utilizes a microscopic camera with an adjustable zoom range of 40-1000x, effectively replacing the research-grade FrED’s most costly component—the laser micrometer, which typically costs upwards of $3,000. This adaptation not only reduces the expense but also maintains the precision needed for effective educational demonstrations.

In addition to the device itself, the team initiated the FrED Factory project by converting an old storage room on the MIT campus into a production facility. This new setup includes 3D printers and other essential machinery to support the development and planned annual production of up to 400 units. The facility was also organized to include proper tools and ample inventory space, ensuring efficient operations and scalability of the Desktop FrED 2022 production. This strategic move supports the goal of expanding hands-on engineering education globally by making advanced manufacturing tools more accessible and affordable.

1.5 **Desktop FrED used for this Project – Additional Overview**

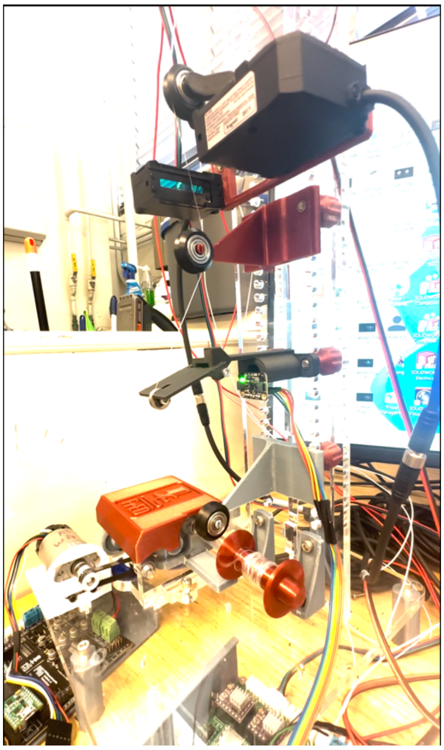

Figure 1.5 *Additional assembly to the Desktop FrED used for this project, showcasing tension sensor and a laser micrometer.*

In addition to the FrED in the earlier version, a diameter measuring device – laser micrometer was used. This was used to obtain accurate reading of diameter which would help in implementation of more accurate machine learning models to control diameter. A tension sensor was also developed - more details on the development will be included in the following chapters.

1.5 **Team and Contributions for FrED 2023**

The FrED 2023 project team consisted of Wenhao Xu, Gary Sefah, and Somesh Jaiswal (author), with responsibilities distinctly allocated to optimize the development and functionality of the Desktop Fiber Extrusion Device. The team was divided into two specialized groups: controls and product design.

1.5.1 Controls Team

Somesh Jaiswal, the sole member of the controls team, focused extensively on the enhancement of the device's operational capabilities. He was responsible for the implementation of sophisticated closed-loop Proportional Integral Derivative (PID) controls. His work extended into advanced control strategies surrounding motors, heating elements, and diameter control. Notably, he integrated a tension sensor into the FrED setup, significantly improving the precision and reliability of the extrusion process. These contributions are thoroughly documented in his upcoming thesis.

1.5.2 Product Design Team

The product design team, comprising Wenhao Xu and Gary Sefah, engaged in a collaborative effort to address and rectify various challenges identified in the previous model. Their collective work led to the identification and resolution of 27 distinct issues with the 2022 version of FrED, enhancing stability, cooling efficiency, and noise reduction. Key developments included transitioning from a microcontroller to a more powerful microprocessor and implementing sophisticated computer vision algorithms.

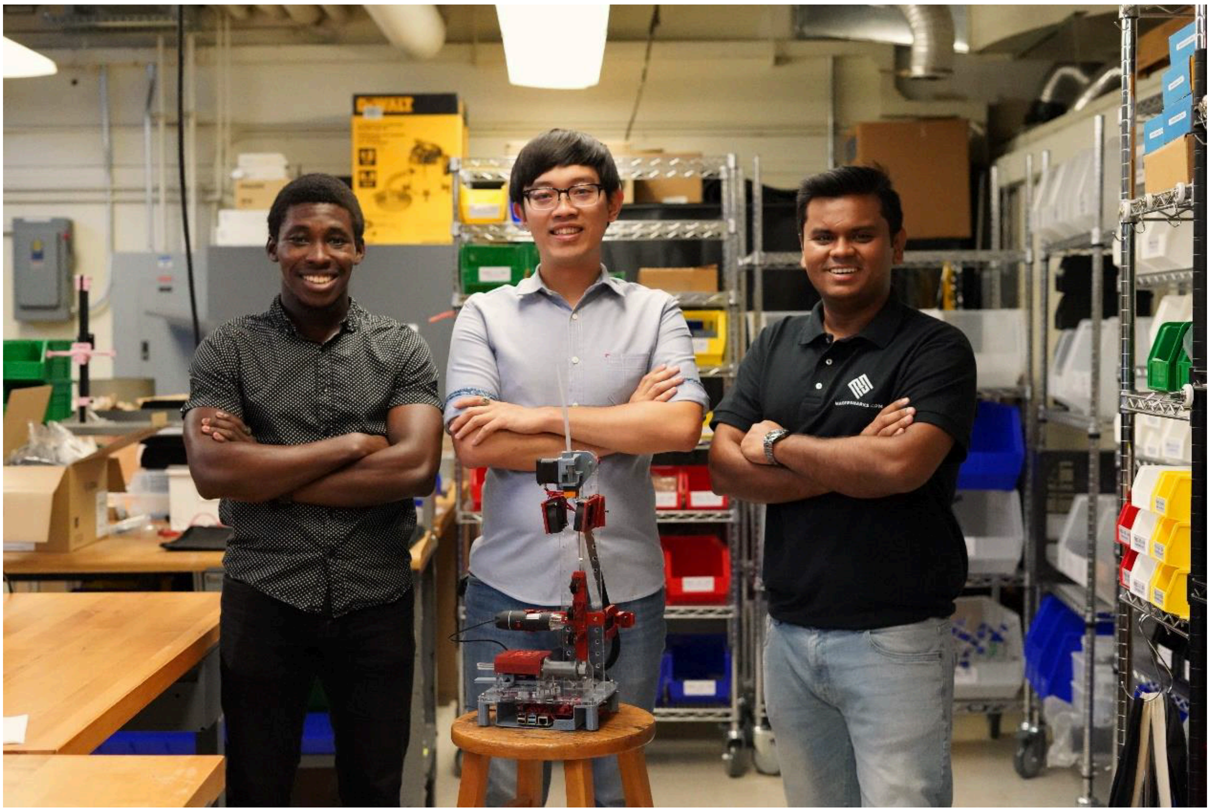

Figure 1.6 *FrED 2023 Team, consisting of Gary Sefah (left), Wenhao Xu (center), and Somesh Jaiswal (right)*

Gary Sefah played a pivotal role in the mechanical redesign aspects of the device. He was responsible for redesigning the extrusion system mount, integrating the Pi camera for enhanced visual feedback, and establishing the laser micrometer as a benchmark for precision. His efforts are detailed in his thesis, "Low-Cost Fiber Extrusion Device for Educational Purposes: Redesign, Manufacture, and Computer Vision Integration."

Wenhao Xu focused on various aspects of hardware optimization and user interaction. He led the design of the modular camera mount and the redesign of the Printed Circuit Board (PCB), which improved the device’s electronic integration and functionality. He also down-selected the diameter sensors to enhance measurement accuracy, reduced the part count and overall size of the frame for better manufacturability and portability, and contributed to defect detection and user experience enhancements.

This division of labor within the team ensured a comprehensive approach to the development of FrED 2023, combining advanced control techniques with thoughtful product design improvements to create a more efficient, user-friendly, and cost-effective educational tool.

Chapter 2: Previous Work on Learned Control System for FrED

Device Realization Laboratory collaborated with Sterlite Industries to develop control systems for optical fibre manufacturing. The control systems were deployed on the Desktop FrED. David Kim's foundational work in collaboration with Sterlite aimed at enhancing the accuracy and precision of optical fiber manufacturing processes began with his seminal paper on the design and fabrication of a desktop fiber manufacturing kit for educational purposes. This kit, referred to as FRED, effectively replicated the industrial process of optical fiber manufacturing on a smaller scale, serving multiple purposes: it provided a deeper insight into the fiber manufacturing process, facilitated rapid prototyping of new control strategies for fiber extrusion, and served as a practical educational tool for students learning about controls and smart manufacturing.

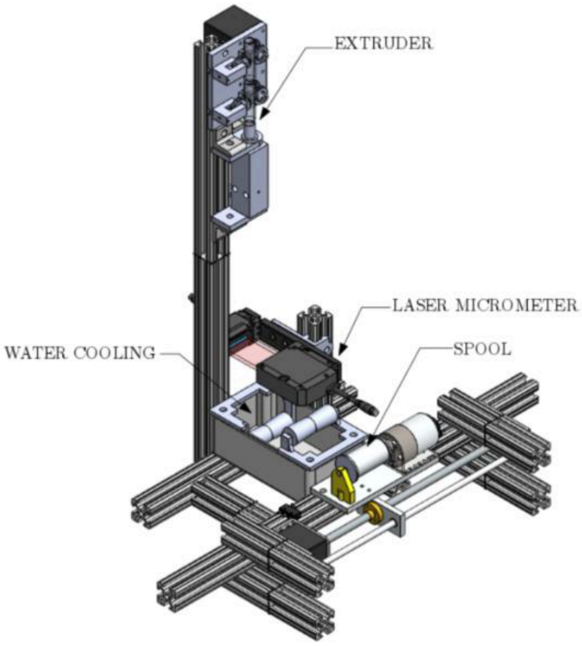

Figure 2.1:CAD model of the legacy FrED design. From D. D. Kim & Anthony, 2017

The FrED system comprised four main components: the extruder, the cooling system, the spool, and the sensors. The extruder's primary role was to heat and apply force to extrude the filament, while the cooling system was designed to quickly cool down the fiber to prevent any adhesion to surfaces. The spool system was responsible for collecting the extruded fiber at a controlled rotational velocity, crucial for managing the fiber's diameter. The sensors were strategically placed to monitor the temperature of the extruder and other critical parameters.

Kim's engineering approach included testing the device with a proportional gain feedback control system. He employed mass conservation equations to model the fiber manufacturing process, which informed the implementation of the proportional gain controller. A gain setting of 0.5 resulted in a steady state error of 0.01mm and a standard deviation of 0.061mm, establishing a benchmark for performance that would guide subsequent research and publications related to this project. This initial exploration laid the groundwork for future advancements in desktop fiber manufacturing technology, highlighting its potential in both educational and industrial applications.

A subsequent research paper authored by Sangwoon Kim expanded the scope of control mechanisms for the fiber extrusion device by incorporating a deep reinforcement learning (DRL) technique. This advanced approach enabled the controller to adaptively track a dynamically varying target diameter during the extrusion process, showcasing a significant leap in the control strategies for manufacturing systems.

In his innovative work, Sangwoon Kim deployed a sophisticated DRL framework utilizing four Long Short-Term Memory (LSTM) networks. These networks comprised two pairs of networks: the actor and the critic, along with their respective target networks—target actor and target critic. Each pair plays a crucial role in the learning and adaptation process. The actor network is responsible for proposing actions based on the current state inputs it receives, which directly influence the system's operational parameters. Conversely, the critic network evaluates the action suggested by the actor by estimating the 'Q-value', a metric that represents the expected future rewards for that action.

The operational mechanism of the system is divided into three key subprocesses: initialization, the control thread, and the training thread. During initialization, the LSTM networks are set up with initial weights, and baseline parameters are established.

In the control thread, real-time data is continuously gathered by the system's sensors, which monitor various aspects of the extrusion process such as temperature, tension, and diameter. This data represents the current state of the system, which the actor network uses to calculate the most suitable action to drive the extruder towards the target diameter. Once an action is executed, the system's response is assessed through updated sensor readings, and a reward is calculated based on the deviation from the target diameter and other operational efficiencies. These observations, actions, and the resulting rewards are then stored in a structured historical memory array, H, facilitating a rich dataset for training the network.

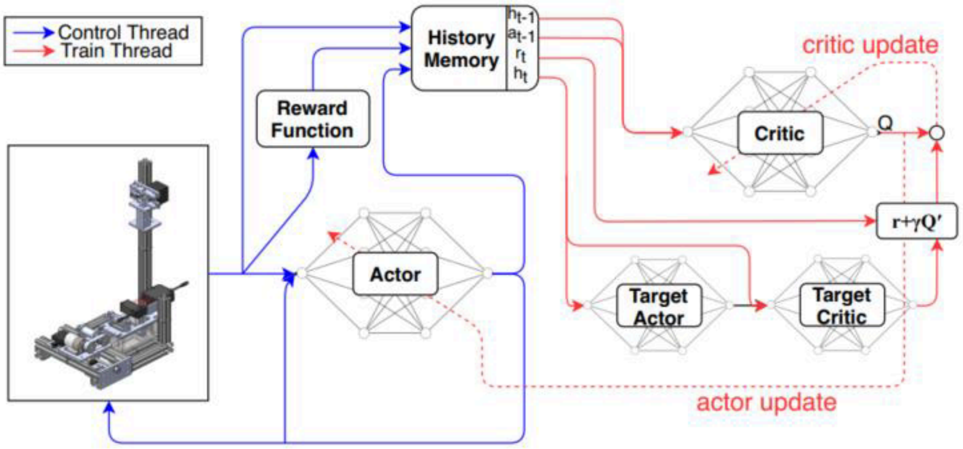

Figure 2.2: Learning Algorithm. From S. Kim, 2021

Meanwhile, in the training thread, the DRL system enhances its performance through continuous learning. A mini-batch of experiences is periodically sampled from the historical memory H. This batch is used by the critic network to compute the Q-values, which are estimates of the expected rewards from following a particular action in a given state. These computed Q-values are then compared against target values that are periodically updated from the target networks, which trail the primary networks slightly to provide stable targets during learning. The discrepancy between the computed Q-values and the target values is minimized through backpropagation, effectively refining the critic's accuracy in evaluation. Simultaneously, the actor network is adjusted to maximize the Q-value, aligning the proposed actions more closely with optimal control trajectories.

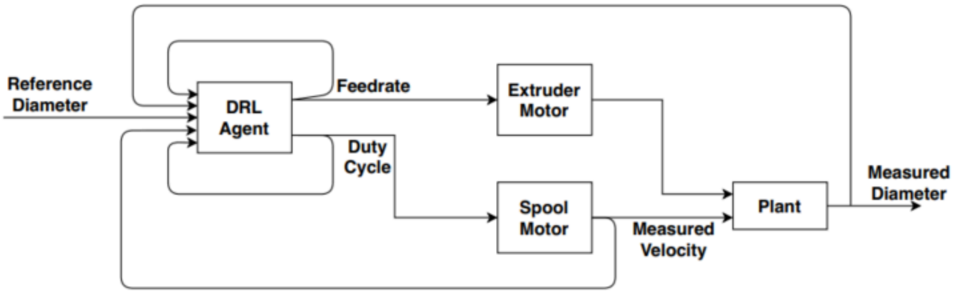

Figure 2.3: Block Diagram of the Deep Reinforcement Learning Control System. From S. Kim, 2021

Figure 2.3 visually encapsulates the overall architecture of Sangwoon Kim's learning algorithm, illustrating the interaction between the actor, critic, target actor, and target critic networks, along with their roles in the continuous adaptation cycle.

Figure 2.4 provides a detailed block diagram of the deep reinforcement learning control system, highlighting the operational flow from sensors input to action output, underpinned by the dynamic interaction between the control and training threads, which collectively enhance the precision and adaptability of the fiber extrusion process. This advanced control system not only demonstrates the application of DRL in industrial processes but also sets a new standard for smart manufacturing practices in fiber extrusion and potentially other manufacturing domains.

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Chapter 3: Design of Tension Sensor

To enhance control over the fiber diameter in the Desktop Fiber Extrusion Device (FrED), the integration of a tension sensor has become a pivotal improvement. Prior iterations of the FrED lacked this component, limiting the precision with which the system could regulate the extrusion process. Tension sensors play a critical role in monitoring the mechanical stress exerted on the fiber, providing essential feedback for adjusting process parameters to maintain the desired fiber characteristics.

Commercially available tension sensors, while effective, are often prohibitively expensive, typically costing around $1000 [16]. To address this issue and make the setup more accessible and cost-effective, a novel design was introduced using a combination of a torsional spring and a time of flight sensor VL530LX, with a total cost of just $7. This approach significantly reduces the financial barrier to incorporating advanced sensing technology in educational and small-scale industrial settings.

Mathew Reynolds of University of Pretoria, South Africa, who was a visiting student at MIT helped with putting together cad designs for the tension sensor.

3.1 Tension Sensor: Detailed Working Mechanism

The tension sensor replaces the traditional load cell with a torsional spring mechanism. The basic operation of this sensor involves several key steps:

1. Force Application: As the fiber passes over the pulley, it applies a force to an arm connected to the torsional spring. The amount of force exerted depends on the tension in the fiber.

2. Measurement of Displacement: The ToF sensor, positioned strategically, records how far the arm is displaced by the fiber. This displacement is a direct result of the tension exerted by the moving fiber.
3. Angular Displacement Calculation: Using the geometry of the system, the change in the angle of the arm, caused by the tension in the fiber, is determined. The torsional spring provides a restoring force that opposes this displacement.

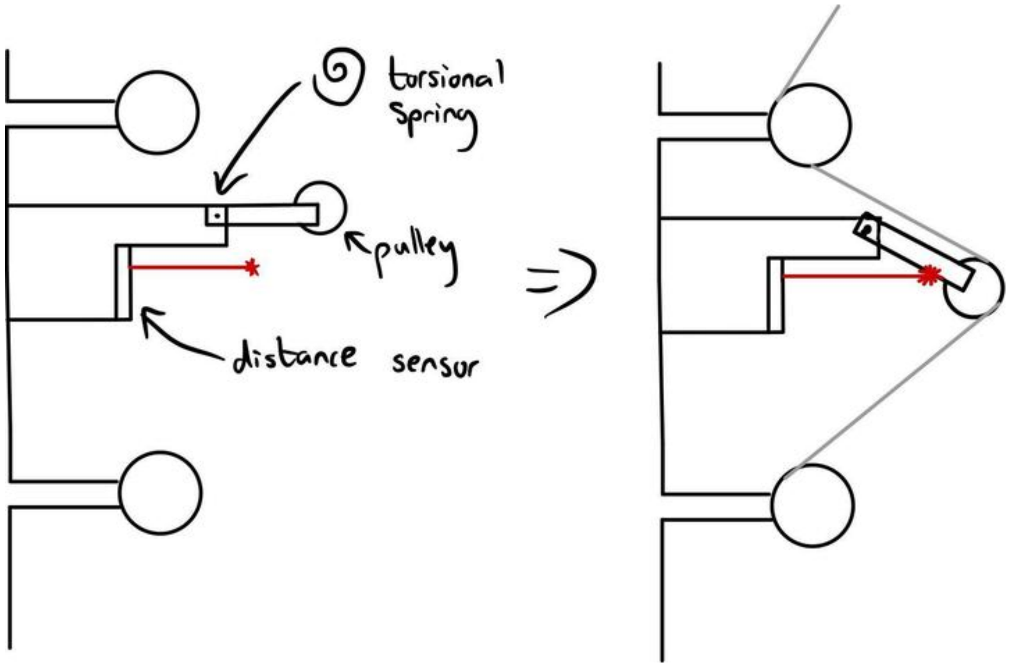

Figure 3.1 basic working of the tension sensor.

4. Force Calculation: The change in angle, as detected by the sensor, helps calculate the force exerted by the torsional spring against the fiber. This force is proportional to the displacement and the stiffness of the spring.
5. Tension Determination: From the calculated force exerted by the spring, the tension in the fiber itself is deduced. This measurement is critical as it influences the quality and properties of the extruded fiber.

6. Feedback for Process Optimization: The tension data is then fed back into the control system of the FrED. This feedback loop is crucial for adjusting parameters such as extrusion speed and cooling rate to optimize fiber quality.

The pulley holder is designed to support this enhanced functionality efficiently. It features a round holder through which a shoulder screw passes, acting both as a pivot point and as a secure fixture for the pulley. This arrangement allows the pulley to rotate freely, facilitating the smooth passage of the fiber. The supporting stem for the holder is crafted to be as thin as possible, maximizing space for the fiber's path while ensuring the pulley system's accessibility and operational efficacy.

By integrating these mechanical and electronic enhancements, the redesigned FrED system not only improves the precision of fiber diameter control but also exemplifies a cost-effective approach to integrating advanced sensor technology in manufacturing systems. This setup not only enhances the device's functionality but also promotes broader adoption in educational settings, where budget constraints often limit access to high-tech equipment.

3.2 Initial Setup and Challenges

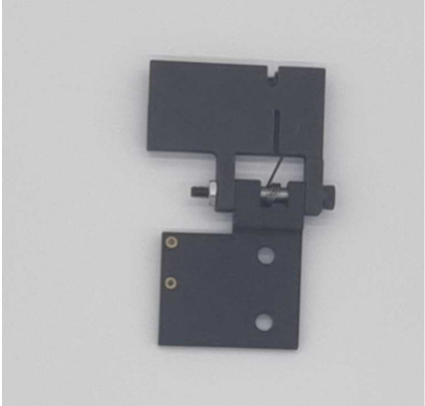

Figure 3.2 first tension sensor design

Initially, the tension sensor setup employed a flat base, as depicted in the referenced figure. This configuration was initially chosen for its simplicity and ease of assembly. However, it soon became apparent that this design posed significant challenges in terms of the accuracy and ease of performing geometric calculations critical for tension measurement. The flat base did not provide the necessary stability or the precise alignment required for the Time of Flight (ToF) sensor to function optimally.

To overcome these challenges, the design was revised to include an elongated base column. This modification aimed to enhance the structural stability and improve the sensor's alignment relative to the fiber path. The elongated base also facilitated more accurate angular measurements, which are essential for the ToF sensor to accurately calculate the displacement caused by the tension in the fiber.

The process of refining the base involved several iterations. Each iteration aimed to optimize the angle of incidence and the distance between the ToF sensor and the point where the fiber exerted force on the measuring arm. These parameters are critical as they directly affect the sensor's ability to measure the displacement accurately.

3.3 Key Design Considerations and Adjustments:

1. **Enhanced Stability**: The elongated base provided a more stable platform for the sensor setup, reducing vibrations and movement that could lead to errors in measurement.
2. **Improved Sensor Alignment**: By extending the base, the alignment of the ToF sensor with respect to the fiber’s path could be finely adjusted. Proper alignment is crucial for ensuring that the sensor accurately detects the displacement of the arm.
3. **Accurate Geometric Calculations**: The new base design allowed for easier and more accurate geometric calculations. The extended length of the base column facilitated a

better understanding of the angles formed by the fiber’s tension, crucial for translating the sensor data into meaningful tension values.

4. **Iterative Design Testing**: Each design iteration was rigorously tested to validate the geometric calculations and the functionality of the ToF sensor. This iterative process was essential for ensuring that each design adjustment contributed positively to the overall accuracy and reliability of the tension sensor.

Through these enhancements, the tension sensor's functionality was significantly improved, making it a more reliable and precise tool for measuring the fiber tension in the Desktop Fiber Extrusion Device (FrED). This development process underscores the importance of iterative design and testing in achieving a well-calibrated and efficient measurement system

3.4 Design Improvements and Optimization

The design of the tension sensor underwent multiple iterations, each aimed at refining the functionality and accuracy of the system before finalizing the optimal configuration. The primary focus of these design iterations was to ensure that the geometric parameters necessary for calculating the tension were precisely defined, enabling the acquisition of accurate and reliable tension data instantaneously.

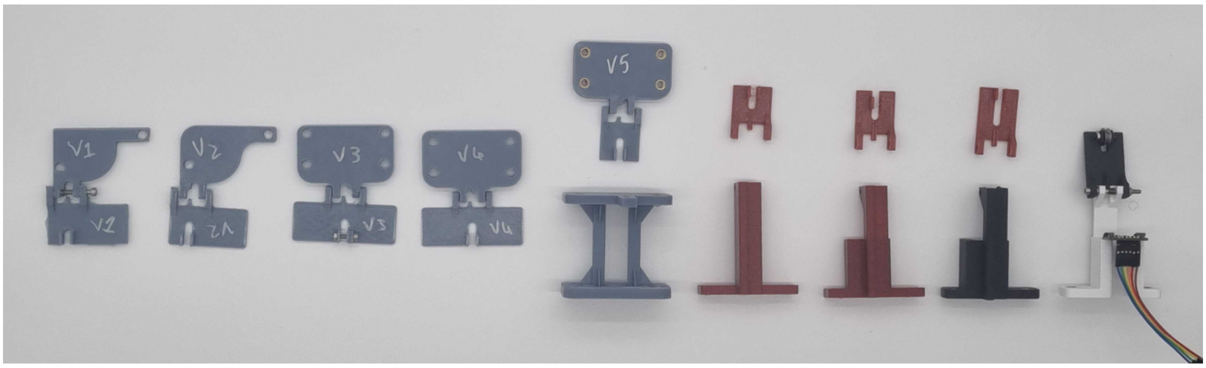

Figure 3.3 design improvements across versions

3.5 Key Technical Enhancements:

1. **Clarification of Geometric Angles**: The final design meticulously defined all angles involved in the geometric calculations. This clarity was crucial for ensuring that the tension measurements were not only accurate but consistently replicable. Properly defined angles helped in precisely calculating the force exerted by the torsional spring based on the displacement measured by the sensor, which directly influenced the accuracy of the tension readings.
2. **Resolution of Sensor Accuracy Issues**: Initially, the design encountered challenges with accurately reading distances using the proximity sensor. This issue was critical as inaccuracies in distance measurements could lead to significant errors in tension calculation. Through careful adjustment of the sensor placement and possibly enhancing the sensor interface, the design was optimized to provide more reliable and precise distance readings. This improvement was vital for ensuring that the tension measurements reflected true mechanical stresses on the fiber.
3. **Optimization for Manufacturability**: Alongside improving measurement accuracy, the design was also optimized for manufacturability. This meant simplifying the assembly process, reducing the number of components, and selecting materials that were easy to handle, durable, and cost-effective. Such optimization efforts reduced the overall manufacturing time, thereby enhancing the feasibility of producing the sensor at a larger scale. This approach not only made the device more accessible but also ensured that it could be replicated efficiently without compromising on quality.
4. **Data Collection Efficiency**: With the angles and distance measurements optimized, the system could collect tension data more efficiently. This efficiency was paramount for real-time processing and feedback in applications where adjustments to the

extrusion process needed to be made swiftly to correct or optimize the fiber characteristics.

The culmination of these design iterations resulted in a tension sensor that was not only accurate and reliable but also streamlined for efficient manufacturing and integration into the

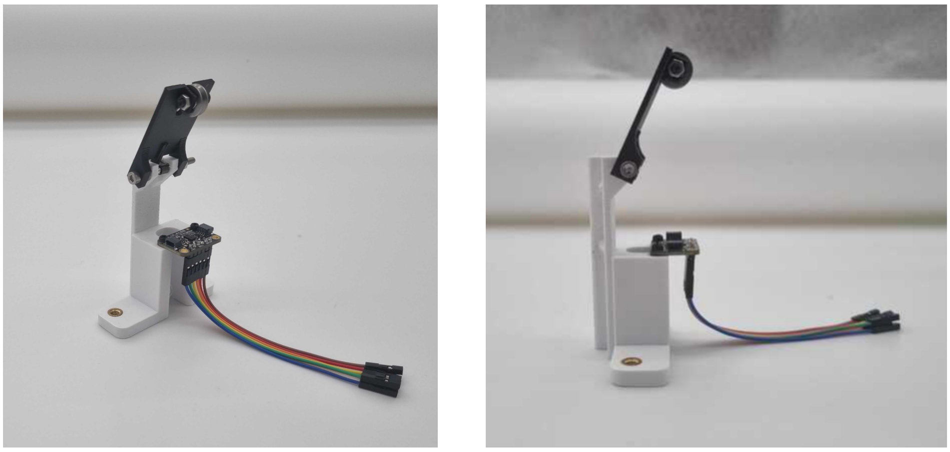

Figure 3.4 Final design of tension sensor

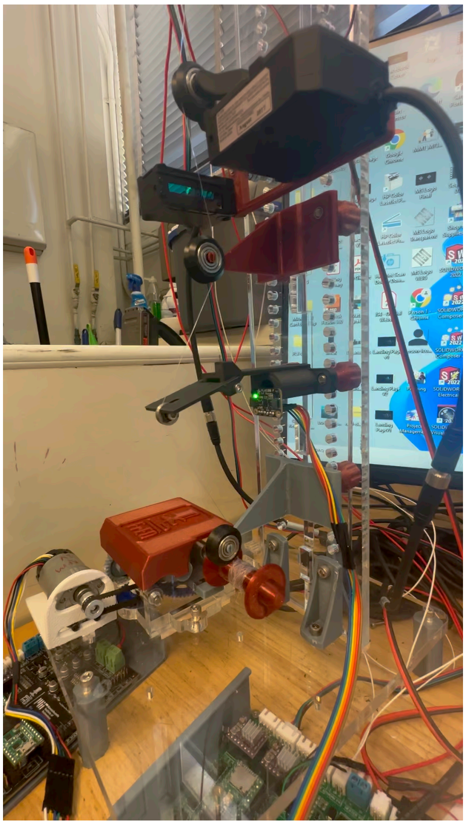

Figure 3.5 Picture indicating position of tension sensor on FrED

Desktop Fiber Extrusion Device (FrED). Each iteration brought improvements in the technical aspects of the device, from the physical design to the electronic integration, ultimately ensuring that the sensor could perform exceptionally well under the operational demands of fiber extrusion. This development process highlights the importance of iterative design and targeted improvements in achieving a high-performing and commercially viable product.

3.6 Enhanced Data Collection Using Tension Sensor

The use of the tension sensor in the Desktop Fiber Extrusion Device (FrED) enabled a comprehensive collection of data regarding the diameter, spooling speed, and tension across an extended period. This data collection facilitated a detailed analysis of the operational dynamics of the device, particularly how these variables interacted over time.

3.6.1 Detailed Observations and Control Strategy:

1. **Setpoint and PID Control**: The diameter of the fiber was maintained at a predefined setpoint. This setpoint was crucial as it dictated the adjustments in spooling speed via a Proportional-Integral-Derivative (PID) control system. The PID controller dynamically adjusted the spooling speed to maintain the diameter at its setpoint. This real-time adjustment ensured that the fiber dimensions were consistent, adhering to quality and specification requirements.

2. **Tension Monitoring**: Tension at various points was meticulously observed alongside the adjustments in spooling speed. This data was crucial for understanding how changes in spooling speed affected the mechanical stress on the fiber. Each datapoint of tension was recorded, providing a rich dataset for analysis.

3. **Data Visualization and Analysis**: To further investigate the relationship between spooling speed and tension, 100 datapoints representing these variables were plotted

against each other. This visual representation helped in identifying trends and anomalies in the relationship. Interestingly, the analysis revealed that decreases in spooling speed were correlated with increases in tension at specific positions along the spooling path. This observation was contrary to our initial hypothesis, which anticipated a direct proportional relationship between spooling speed and tension.

3.6.2 Figures and Results Presentation:

- The data and its implications are illustrated in several figures below. These figures provide a visual representation of the trends and anomalies noted during the experiments. By plotting the relationship between spooling speed and tension, we were able to visually confirm the unexpected behavior in the system's response to changes in operational parameters.

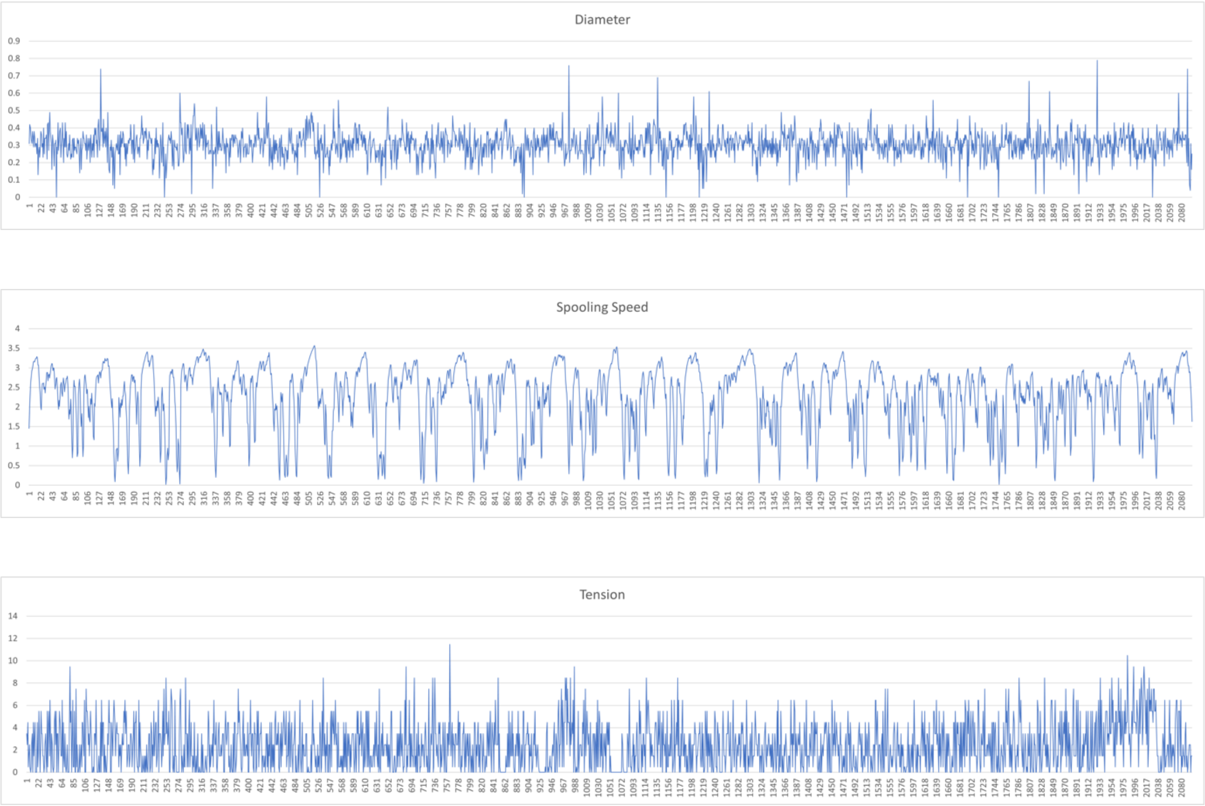

Figure 3.6 visual representation of the trends and anomalies noted during the experiments

- The results, documented comprehensively in the accompanying figures, highlight the intricate balance required in the spooling process and underscore the importance of precise control mechanisms to maintain optimal tension and speed. The findings challenge previous assumptions and contribute to a deeper understanding of the mechanical dynamics involved in fiber extrusion.

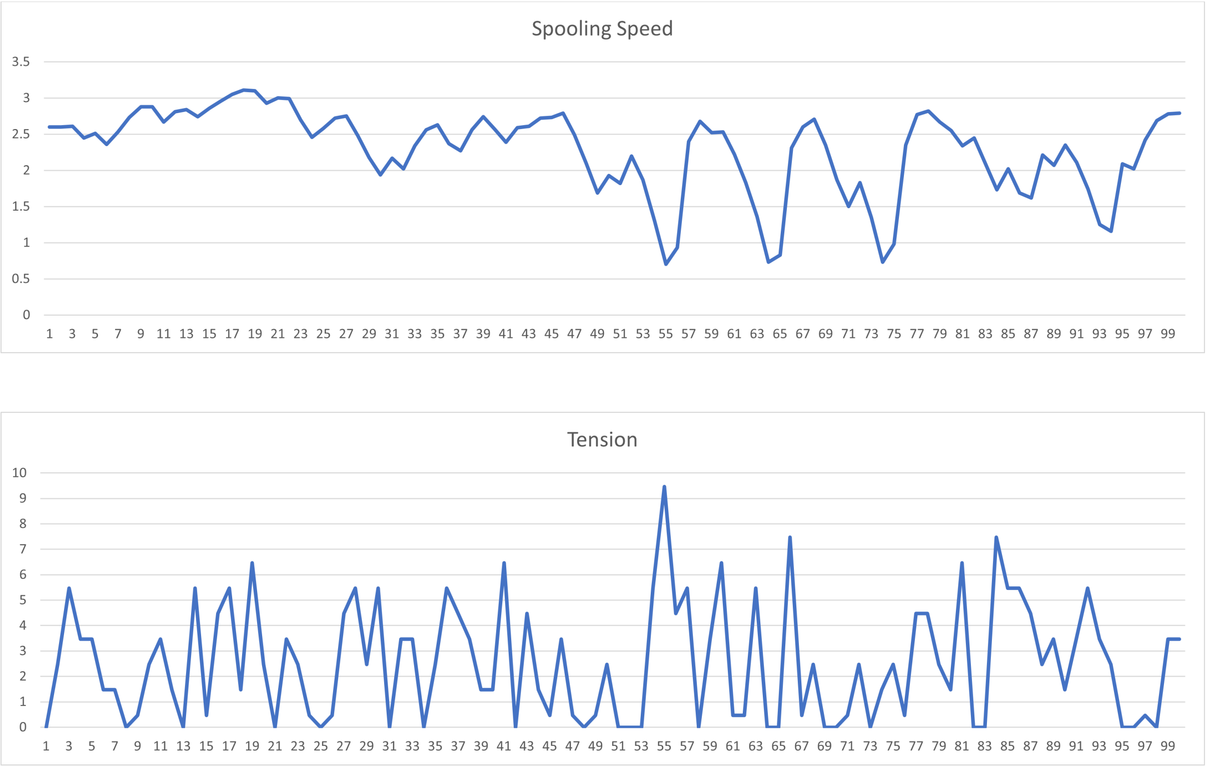

Figure 3.7 visual representation of the trends and anomalies noted during the experiments for 100 random data points

This detailed data collection and analysis not only provide insights into the fundamental operations of the FrED but also underscore the value of real-time monitoring and control in manufacturing processes. The observations made have significant implications for the development of more sophisticated control strategies and for improving the overall efficiency and quality of the fiber extrusion process.

Chapter 4: Implementation of PID Controls

4.1 Overview

In the iterative enhancement of the Desktop Fiber Extrusion Device (FrED), a significant advancement has been the incorporation of a sophisticated closed-loop feedback control system. This system is meticulously designed to regulate the diameter of the extruded fiber, ensuring adherence to specified geometric precision. The following describes the closed-loop control architecture as implemented in the FrED system:

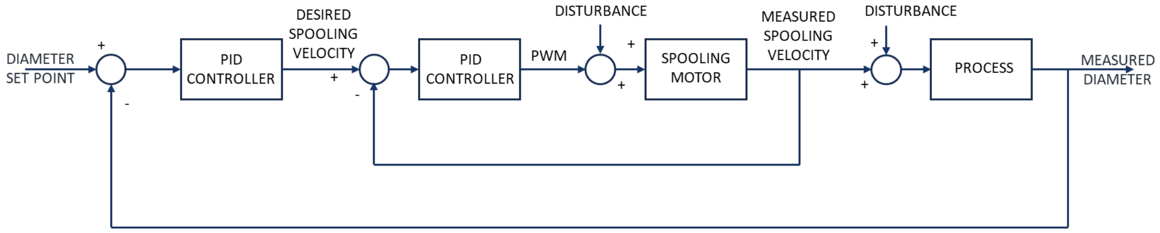

Figure 4.1 Feedback Control Diagram of Implemented PID Control for FrED

Diameter Set Point: At the outset of the control loop is the 'Diameter Set Point', which is defined by the desired fiber diameter specifications. This target metric is critical for ensuring that the fiber produced meets the strict standards necessary for its intended application.

Error Detection: Integral to the control process is an error detection mechanism, functioning as a comparator. It consistently measures the deviation between the 'Diameter Set Point' and the 'Measured Diameter', providing a quantitative assessment of discrepancy, known as the 'error signal'.

Control Algorithm: Upon receipt of the error signal, a control algorithm within the system's microcontroller engages. Utilizing proportional-integral-derivative (PID) control strategies, the algorithm computes the necessary corrective actions to mitigate the diameter deviation.

Actuation System: Subsequent to the control decision, the actuation system, which may include stepper motors, heating elements, or tension adjusters, operationalizes the corrective measures. These adjustments are finely tuned to influence the extrusion parameters, directly affecting the fiber's diameter.

Extrusion Process: Central to the system is the fiber extrusion process — the transformation of raw material into a fiber of designated diameter. It is at this juncture that the physical modifications enacted by the actuation system take effect, manipulating the extrusion dynamics to align the fiber diameter with the set point.

Sensory Feedback: Crucial to the feedback loop is the inclusion of a high-precision sensor. This sensor continuously monitors the diameter of the fiber post-extrusion and relays this data back to the error detection stage, thereby completing the feedback loop.

Feedback Loop: The real-time data obtained from the diameter measurement is funneled back into the control system, enabling an ongoing dynamic adjustment. This feedback mechanism is the linchpin of the system, promoting a self-corrective process that ensures the fiber diameter remains within the stipulated tolerance levels.

Incorporated into the FrED, this closed-loop feedback control system represents the pinnacle of process control engineering. It allows for real-time monitoring and adjustment of the extrusion parameters, thereby maintaining a consistent diameter of the fiber. This automated control is essential in a domain where dimensional fidelity translates directly to material performance and is indicative of the forward march of automation in manufacturing technology. The system not only optimizes the quality of the output but also underscores the shift towards intelligent manufacturing systems in academic and industrial settings alike.

4.2 Implementation and Results:

4.2.1 Analysis of Internal PID Loop on Spooling Speed

The implementation of an internal Proportional-Integral-Derivative (PID) control loop around the spooling speed of the Desktop Fiber Extrusion Device (FrED) aimed to enhance the precision and stability of the spooling process. Here we analyze the impact of the PID controller on the spooling speed, comparing it with the performance under a basic control setting using a constant Pulse Width Modulation (PWM) signal. This analysis is supported by detailed graphs illustrating the variations in speed under different control settings.

Control Settings and Observations:

1. **Without PID Control**:
    - **Control Strategy**: A constant PWM signal of 30/255.
    - **Observed Performance**: The mean spooling speed recorded was 2.06 Rotations Per Second (RPS) with a standard deviation of 0.06 RPS. This variance indicates a relatively higher fluctuation in speed, suggesting that the spooling process under this control method is less stable and predictable.

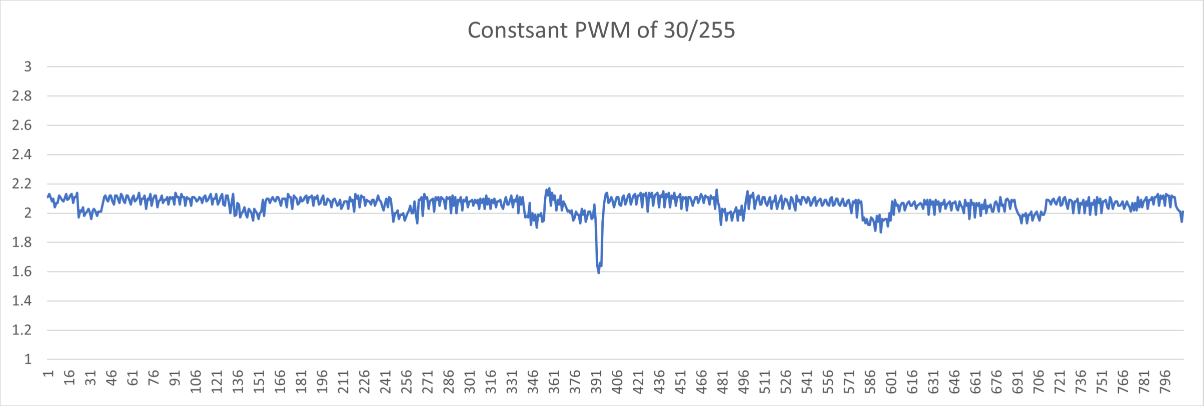

Figure 4.2 Speed at different timestamps at a constant PWM of 30

2. **With PID Control (Setpoint 2 RPS)**:

    - **Control Strategy**: The PID controller was tuned to maintain a setpoint of 2 RPS.

    - **Observed Performance**: Under PID control, the mean speed closely matched the setpoint at 1.99 RPS, and the standard deviation reduced significantly to 0.03 RPS. This improvement in the standard deviation highlights the increased stability and accuracy provided by the PID controller.

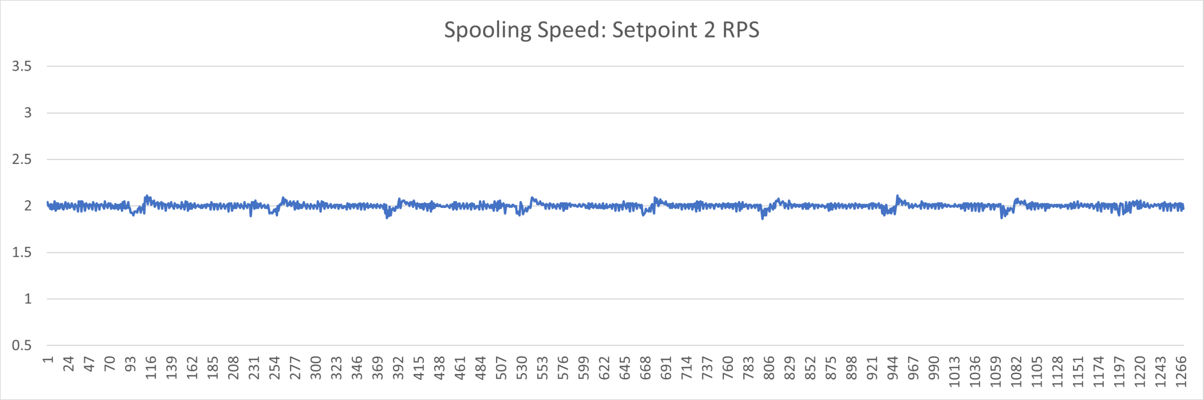

Figure 4.3 Speed at different timestamps at a setpoint of 2 RPS

3. **With PID Control (Setpoint 1.5 RPS)**:

    - **Control Strategy**: The PID controller was tuned to a lower setpoint of 1.5 RPS.

    - **Observed Performance**: The mean speed achieved was exactly 1.5 RPS with a standard deviation of 0.03 RPS, again demonstrating the controller's effectiveness in achieving and maintaining the desired setpoint with reduced variability.

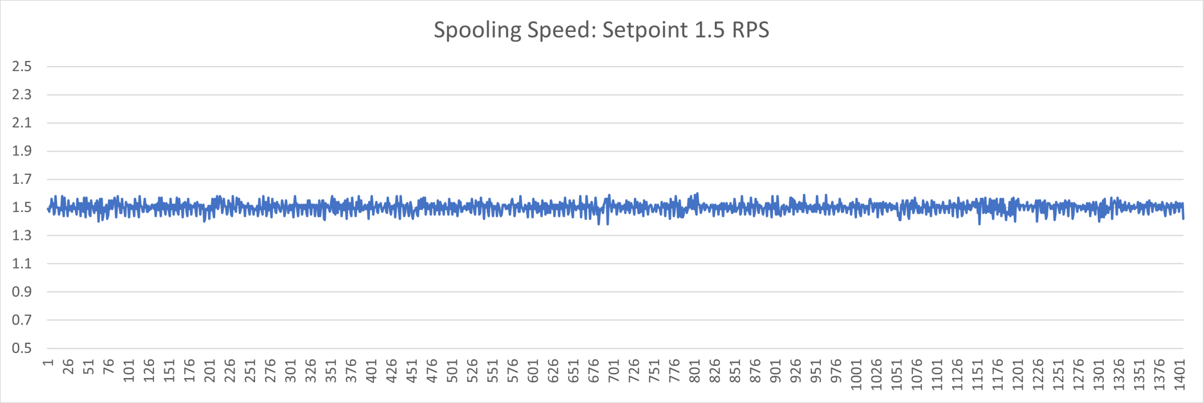

Figure 4.4 Speed at different timestamps at a setpoint of 1.5 RPS

4. **With PID Control (Setpoint 1 RPS)**:

- **Control Strategy**: The PID controller was tuned to a setpoint of 1 RPS.
- **Observed Performance**: The mean speed matched the setpoint at 1 RPS, with a slightly higher standard deviation of 0.04 RPS compared to the 1.5 and 2 RPS setpoints. Despite the slight increase in deviation, the results still signify a robust control performance at lower speeds.

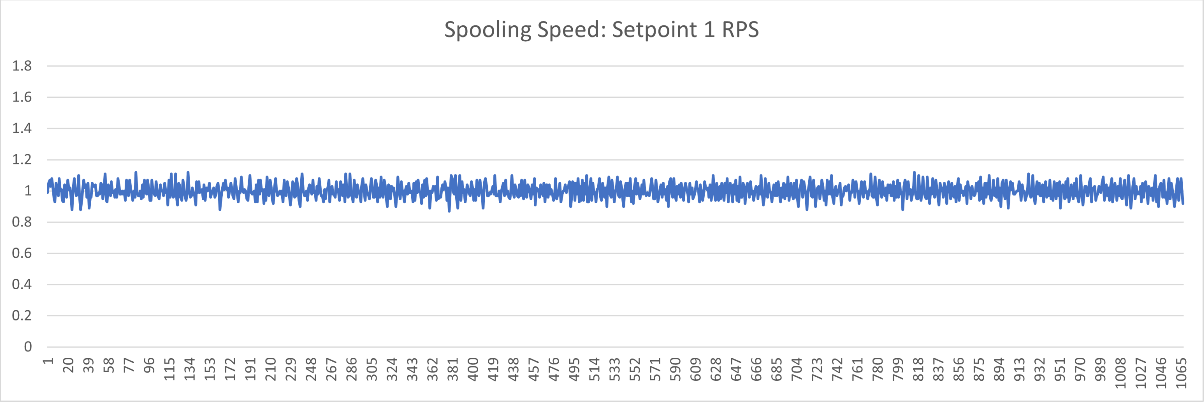

Figure 4.5 Speed at different timestamps at a setpoint of 1 RPS

Analysis and Conclusion:

The introduction of the PID control loop significantly improved the control over the spooling speed compared to the basic PWM control. The key improvements observed include:

- **Reduced Variability**: The lower standard deviations under PID control indicate reduced speed fluctuations, contributing to a more consistent and predictable spooling process.
- **Accurate Setpoint Tracking**: The mean speeds recorded under various setpoints demonstrate the PID controller's capability to accurately reach and maintain the set speeds, crucial for ensuring the quality and uniformity of the extruded fiber.
- **Enhanced Process Stability**: The enhanced stability across different setpoints under PID control suggests that the process can be reliably controlled across a range of operational conditions, enhancing the overall efficiency of the fiber extrusion process.

The graphs accompanying these results will visually represent the consistency and precision improvements afforded by the PID control, illustrating tighter clustering of data points around the setpoints and narrower speed variation ranges. Overall, the PID loop's implementation into the spooling speed control system of the FrED has proven to be highly effective, marking a significant advancement in the device's operational capabilities.

4.3 Analysis of External PID Loop on Diameter

The application of an external Proportional-Integral-Derivative (PID) control loop to manage the diameter of fibers produced by the Desktop Fiber Extrusion Device (FrED) represents a strategic enhancement aimed at increasing the precision and consistency of the extrusion process. This section details the impact of implementing the PID loop on diameter control, comparing its performance to a baseline scenario without PID control. The results are visualized through graphs that accompany this analysis, demonstrating the effects of the PID control on maintaining the desired fiber diameter.

4.3.1 Control Settings and Observations:

1. **Without PID Control**:

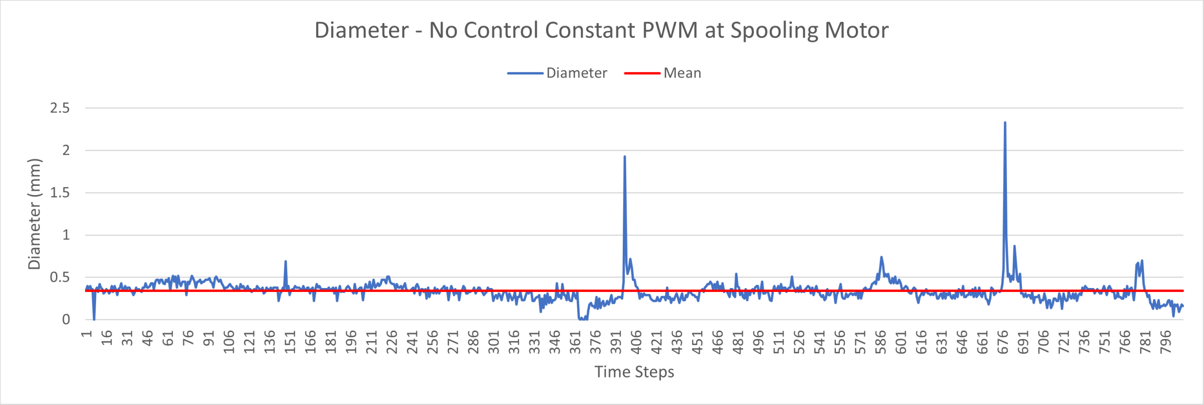

Figure 4.6 Diameter at different timestamps at a constant spooling speed

- **Control Strategy**: A constant spooling speed of 1.5 Rotations Per Second (RPS).
- **Observed Performance**: The mean diameter observed was 0.34 mm, with a high standard deviation of 0.14 mm. This considerable deviation indicates a lack of control and consistency in the diameter of the fibers, likely leading to variable and often unsatisfactory product quality.

2. **With PID Control (Setpoint 0.2 mm)**:

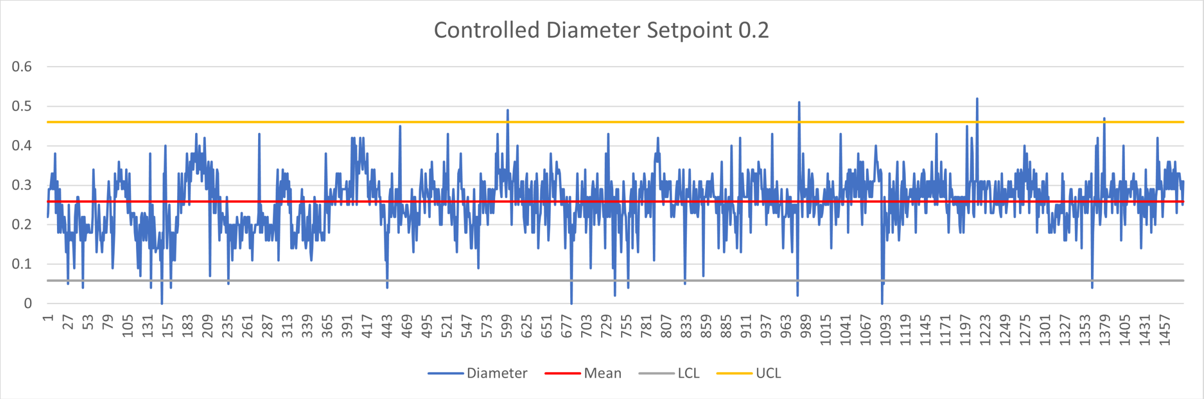

Figure 4.7 Diameter at different timestamps at a setpoint of 0.2 mm

- **Control Strategy**: The PID controller was finely tuned to achieve a diameter setpoint of 0.2 mm.
- **Observed Performance**: The mean diameter achieved was slightly above the setpoint at 0.25 mm, with a standard deviation reduced to 0.06 mm. Despite the mean diameter not precisely matching the setpoint, the significantly lower standard deviation demonstrates improved control stability and reduced variability.

3. **With PID Control (Setpoint 0.3 mm)**:

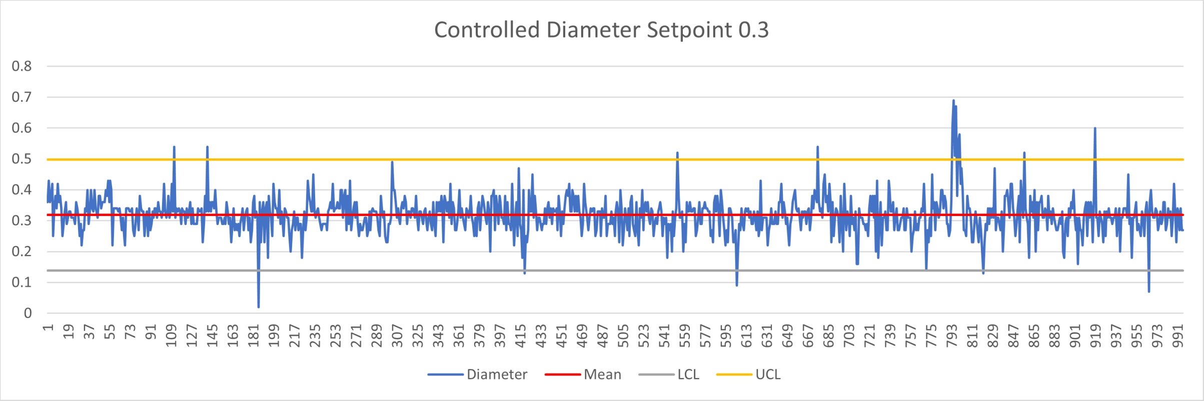

Figure 4.8 Diameter at different timestamps at a setpoint of 0.3 mm

- **Control Strategy**: The PID controller was adjusted to a setpoint of 0.3 mm.
- **Observed Performance**: The mean diameter recorded was 0.31 mm, with a standard deviation of 0.05 mm. Similar to the first PID scenario, while the mean diameter slightly deviates from the setpoint, the low standard deviation underscores a stable and consistent control over the diameter.

4. **With PID Control (Setpoint 0.4 mm)**:

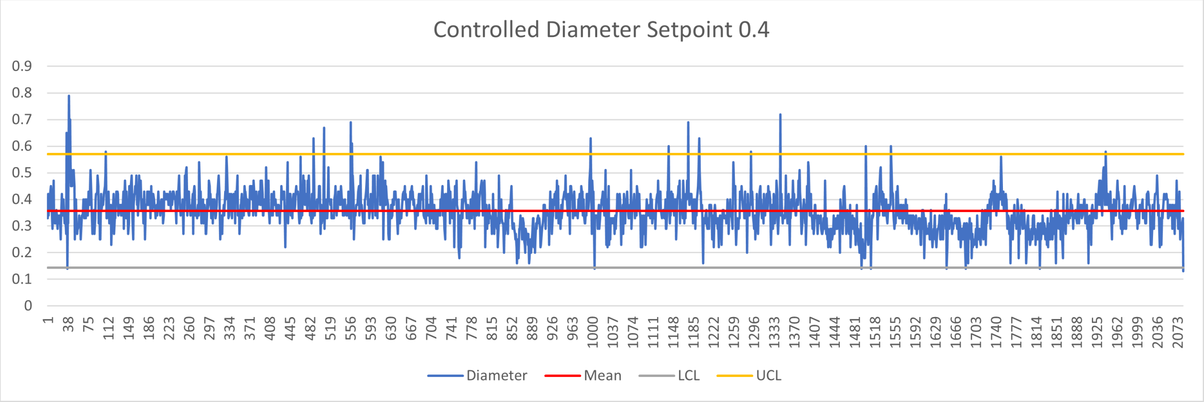

Figure 4.9 Diameter at different timestamps at a setpoint of 0.4 mm

- **Control Strategy**: The PID controller was adjusted to a setpoint of 0.4 mm.
- **Observed Performance**: The mean diameter recorded was 0.37 mm, with a standard deviation of 0.07 mm. Similar to the first PID scenario, while the mean diameter slightly deviates from the setpoint, the low standard deviation underscores a stable and consistent control over the diameter.

4.3.2 Analysis and Conclusions:

The implementation of the PID control loop significantly enhances the diameter control of the fibers compared to the non-PID scenario. Key improvements and observations include:

- **Reduced Variability**: The standard deviations under PID control are markedly lower than those observed without PID control, indicating a more stable process. This reduction in variability is crucial for maintaining consistent product quality and reducing waste.
- **Closer Adherence to Setpoints**: While the mean diameters under PID control did not perfectly match the setpoints, they were closer to the target compared to the non-PID scenario. This closer adherence illustrates the PID loop's effectiveness in dynamically adjusting process parameters to achieve desired outcomes.
- **Areas of Improvement**: The PID controller shows some limitations in achieving exact setpoints, particularly evident in the setpoint of 0.2 mm where the mean diameter was 0.25 mm. This suggests that while PID significantly improves control, further tuning or additional process adjustments might be necessary to perfect control accuracy.

In conclusion, the PID loop has improved the diameter control in the fiber extrusion process by reducing variability and enhancing the stability of the diameter measurements. However, achieving absolute precision remains a challenge, indicating an area for further refinement in the PID settings or perhaps an integration with other quality control systems to perfect the diameter control.

Chapter 5: Proposed Coursework for the Program with FrED

This chapter will cover a proposed coursework design to teach smart manufacturing using FrED.

Course Name: Remote Monitoring and Control in Smart Manufacturing

5.1 Course Description

This course introduces students to the principles of smart manufacturing with a focus on remote monitoring and control technologies. Using the Desktop Fiber Extrusion Device (FrED), students will learn to monitor critical process parameters and control the manufacturing process through a remote interface. The course combines theoretical learning with practical, remote laboratory sessions where students adjust process parameters and observe the outcomes on product quality and process efficiency.

5.2 Course Objectives

- Understand the key concepts and technologies in smart manufacturing.
- Learn to monitor and control manufacturing processes remotely.
- Develop skills in data interpretation and decision-making based on real-time data.
- Gain experience in using software tools for remote manufacturing operations.

5.3 Modules

Module 1: Introduction to Smart Manufacturing

Overview

This module introduces students to the concept of smart manufacturing, emphasizing its importance in the modern industrial landscape. It outlines the foundational technologies and processes that enable smart manufacturing, including automation, data analytics, and the integration of information and operational technologies. Students will explore how smart manufacturing transforms traditional factories into highly efficient and adaptive environments.

Learning Outcomes

By the end of this module, students should be able to:

1. Define smart manufacturing and discuss its relevance and benefits in today’s industrial sector.
2. Identify the key components and technologies that constitute a smart manufacturing setup.
3. Understand the role of IoT (Internet of Things), AI (Artificial Intelligence), and real-time data monitoring in manufacturing.
4. Analyze case studies to identify challenges and solutions in implementing smart manufacturing systems.

Topics Covered

1. **Introduction to Smart Manufacturing**
    - Definition and scope of smart manufacturing.
    - Historical evolution from traditional to smart manufacturing practices.
2. **Key Technologies in Smart Manufacturing**
    - Overview of IoT, AI, robotics, and cyber-physical systems.
    - The role of sensors and actuators in the automation of manufacturing processes.

3. **Benefits of Smart Manufacturing**
    - Enhanced productivity and efficiency.
    - Improved quality control and adaptability.
    - Reduction in operational costs and waste.
    - Increased safety and worker ergonomics.
4. **Challenges in Smart Manufacturing**
    - Integration of new technologies with existing systems.
    - Data security and privacy concerns.
    - Skilled workforce requirements and training challenges.
5. **Case Studies**
    - Discussion of successful smart manufacturing implementations across various industries such as automotive, aerospace, and consumer goods.
    - Analysis of the role of smart manufacturing in improving supply chain resilience and responsiveness.

Activities

- **Lecture Sessions**: Interactive presentations covering the theoretical aspects of smart manufacturing, supplemented with videos and animations to demonstrate modern manufacturing technologies in action.
- **Case Study Review**: Students will be divided into groups to analyze provided case studies of companies that have successfully implemented smart manufacturing

solutions. Each group will present their findings, focusing on the technologies used, benefits achieved, challenges overcome, and lessons learned.

- **Discussion Forums**: Online forums where students can discuss how smart manufacturing might impact different sectors of the economy. This activity encourages peer learning and the exchange of ideas.

Assessment

- **Case Study Analysis**: Each group will submit a detailed report on their assigned case study, which will be assessed based on depth of analysis, understanding of smart manufacturing principles, and clarity of presentation.
- **Quizzes**: Short quizzes at the end of the module to test students' understanding of smart manufacturing concepts and technologies.

Required Readings and Resources

- A list of articles, textbook chapters, and online resources that provide additional insights into smart manufacturing technologies and their applications.
- Access to multimedia resources that showcase real-world applications of smart manufacturing.

Support and Resources

- **Online Office Hours**: Scheduled times when students can discuss course materials and seek further explanation from instructors.
- **Discussion Board Moderation**: Regular instructor engagement on discussion boards to facilitate discussions and provide expert insights.

This module serves as the foundation for subsequent modules, where students will delve deeper into the specific technologies and techniques that enable remote monitoring and control in manufacturing environments.

Module 2: Fundamentals of Fiber Extrusion

Overview

This module focuses on the specific manufacturing process of fiber extrusion using the Desktop Fiber Extrusion Device (FrED). Students will learn about the materials, mechanical components, and operational parameters that influence the fiber extrusion process. The module provides a detailed introduction to the workings of the FrED, including its design, function, and the critical parameters that can be controlled and monitored remotely.

Learning Outcomes

By the end of this module, students should be able to:

1. Describe the components and functionality of the Desktop Fiber Extrusion Device (FrED).
2. Understand the materials used in the fiber extrusion process and their properties.
3. Identify the key operational parameters that affect the extrusion process, such as temperature, extrusion speed, and tension.
4. Explain the principles of material flow and temperature control in fiber extrusion.

Topics Covered

1. **Components of the Desktop Fiber Extrusion Device (FrED)**
    - Overview of FrED’s mechanical and electronic components.

    - Detailed description of the extruder, cooling system, diameter measurement, and collection subsystems.

2. **Materials Used in Fiber Extrusion**
    - Types of materials commonly extruded, focusing on those compatible with the FrED.
    - Properties of materials such as viscosity, melting point, and how these affect the extrusion process.
3. **Principles of Fiber Extrusion**
    - The mechanics of extruding fiber, including the role of heat, force, and die design.
    - Understanding the interactions between material properties and machine parameters.
4. **Controlling and Monitoring Extrusion Parameters**
    - Detailed discussion on controlling temperature, speed, and tension using FrED.
    - Importance of parameter control in achieving consistent fiber quality and diameter.
5. **Safety and Maintenance**
    - Best practices for safely operating the FrED.
    - Routine maintenance tasks to ensure optimal performance and longevity of the device.

Activities

- **Virtual Tour of FrED**: A video walkthrough of the FrED setup, demonstrating each component and its function.
- **Interactive Simulations**: Online simulations where students can manipulate extrusion parameters like temperature and speed, and observe theoretical outcomes.
- **Hands-on Remote Lab**: Students will remotely operate the FrED, applying their knowledge to control the extrusion process. This activity will be monitored in real-time via webcam and data logging.

Assessment

- **Practical Test**: Students will be tasked to remotely set up and run the FrED to produce fiber under specified conditions. The results will be assessed based on the quality of the fiber produced and the accuracy in following procedure and settings.
- **Written Assignment**: A detailed report on the relationship between material properties and extrusion parameters, and how these influence the fiber quality.

Required Readings and Resources

- Technical manuals and user guides for the Desktop Fiber Extrusion Device.
- Research articles and textbooks chapters on material science relevant to fiber extrusion.

Support and Resources

- **Interactive Q&A Sessions**: Regularly scheduled live Q&A sessions with the instructor to discuss any issues or questions related to the module content or FrED operation.

- **Tutorial Videos**: Step-by-step guides on operating the FrED and troubleshooting common issues.

This module is designed to provide students with both the theoretical knowledge and practical skills necessary to understand and manage a complex manufacturing process remotely. It lays the groundwork for more advanced topics in remote monitoring and control that will be covered in subsequent modules.

Module 3: Remote Monitoring Systems

Overview

This module dives into the specifics of remote monitoring systems, focusing on the integration of such systems with the Desktop Fiber Extrusion Device (FrED). Students will explore the various types of sensors and data acquisition methods used in remote monitoring, learning how to implement and utilize these systems to gather and analyze real-time data from the FrED.

Learning Outcomes

By the end of this module, students should be able to:

1. Understand the fundamentals of sensor technology and data acquisition systems used in manufacturing.
2. Identify the types of sensors integrated into the FrED and their roles in monitoring key process parameters.
3. Set up and configure remote monitoring tools and software for real-time data tracking.
4. Analyze sensor data to assess process stability and performance.

Topics Covered

1. **Introduction to Remote Monitoring**
   - Overview of remote monitoring technologies in manufacturing.
   - Benefits and challenges of remote monitoring.
2. **Sensors and Data Acquisition**
   - Types of sensors used in manufacturing processes, focusing on those relevant to the FrED (temperature, pressure, diameter, tension).
   - Principles of data acquisition, including sampling rates, resolution, and data logging.
3. **Integration of Sensors with FrED**
   - Detailed explanation of how each sensor is integrated into the FrED.
   - How sensors contribute to the control and monitoring of the fiber extrusion process.
4. **Remote Monitoring Software and Tools**
   - Software solutions for remote data monitoring and control.
   - Setting up a user interface for real-time monitoring and interaction with the FrED.
5. **Data Interpretation and Use**
   - Techniques for analyzing sensor data to make informed decisions about process adjustments.
   - Case studies illustrating how real-time data monitoring can enhance manufacturing outcomes.

Activities

- **Lab Exercise: Sensor Integration and Setup**
    - Students remotely access the FrED to configure and test various sensors.
    - Activities include calibrating sensors, setting up data acquisition parameters, and starting initial data collection runs.
- **Interactive Software Tutorials**
    - Step-by-step guides on using remote monitoring software to track and control the FrED.
    - Simulation exercises to demonstrate how adjustments in the software affect the FrED's operation.
- **Data Analysis Project**
    - Using data collected from the FrED, students will analyze the impact of varying process parameters on product quality.
    - Presentation of findings in a virtual class session, discussing the implications of their data analysis on process optimization.

Assessment

- **Practical Assignments**: Hands-on tasks involving sensor calibration, data setup, and initial monitoring setups.
- **Project Report**: Students submit a detailed analysis of the data collected from the FrED, including recommendations for process improvements based on their findings.

Required Readings and Resources

- Articles and textbook chapters on sensor technology and data acquisition.
- Manuals and documentation for the remote monitoring software used with the FrED.

Support and Resources

- **Discussion Forums**: Online platforms where students can discuss their experiences, share tips, and ask questions about remote monitoring.
- **Technical Support Sessions**: Scheduled support sessions to assist students with software or hardware issues encountered during remote monitoring setups.

This module aims to provide students with a thorough understanding of the technologies and methodologies required to effectively monitor manufacturing processes remotely. The skills developed here are crucial for advancing into more complex aspects of smart manufacturing and process control.

Module 4: Remote Control Techniques

Overview

This module introduces students to the principles and application of remote control techniques within the context of manufacturing, specifically through the operation of the Desktop Fiber Extrusion Device (FrED). Students will explore various control strategies, focusing on how they can remotely adjust and optimize the manufacturing process to achieve desired outcomes.

Learning Outcomes

By the end of this module, students should be able to:

1. Understand the basic and advanced control strategies used in manufacturing processes.

2. Implement these control strategies remotely using the FrED.
3. Analyze the effects of different control settings on the manufacturing process.
4. Utilize remote control techniques to optimize process parameters for improved product quality and efficiency.

Topics Covered

1. **Basics of Process Control**
    - Overview of control theory and its application in manufacturing.
    - Difference between open-loop and closed-loop control systems.
2. **PID (Proportional, Integral, Derivative) Control**
    - Introduction to PID control and its components.
    - Application of PID control in the fiber extrusion process using the FrED.
3. **Advanced Control Strategies**
    - Overview of advanced control techniques such as feedforward control, adaptive control, and predictive control.
    - Discussion on the suitability of each control technique for different types of manufacturing processes.
4. **Remote Implementation of Control Techniques**
    - Setting up remote access to control the FrED.
    - Step-by-step guidance on adjusting control parameters and monitoring the effects remotely.
5. **Optimization of Process Parameters**

    - Techniques for optimizing process parameters like temperature, speed, and tension to improve product quality.
    - Use of simulation tools to predict outcomes before applying changes to the actual process.

Activities

- **Interactive Lecture on PID Control**
    - An interactive session where the fundamental concepts of PID control are discussed with real-time examples from the FrED.
- **Remote Control Lab Exercises**
    - Practical exercises where students remotely tune PID settings on the FrED to control the extrusion process.
    - Tasks include adjusting temperature, extrusion speed, and tension, and observing the impact on fiber quality.
- **Simulation and Modeling**
    - Use of software to model the extrusion process and simulate different control strategies.
    - Comparisons of simulated outcomes with actual results from remote operations of the FrED.
- **Group Project**
    - Students work in teams to develop a control strategy for a given problem statement using the FrED.

    - Implementation and optimization of their strategy remotely, followed by a presentation of their results and analysis.

Assessment

- **Hands-on Control Assignments**: Practical tasks where students must apply control theories to manage the FrED's operation remotely.
- **Simulation Project Report**: A report documenting the simulation exercises, the rationale behind chosen control strategies, and the analysis of their effectiveness.
- **Group Project Presentation**: Evaluation based on the innovation, effectiveness, and clarity of the presentation on their control strategy implementation.

Required Readings and Resources

- Selected chapters from textbooks on control systems engineering.
- Research articles on advanced control techniques in manufacturing.
- User manuals and technical guides for control software and the FrED.

Support and Resources

- **Software Tutorials**: Video tutorials on using control and simulation software.
- **Q&A Sessions**: Regular sessions with instructors to discuss challenges and insights related to remote control techniques.
- **Technical Support**: Assistance with software or connectivity issues encountered during remote operations.

This module is crucial for understanding how theoretical control concepts are applied in real-world manufacturing scenarios. It prepares students not just to operate but also to innovate in the field of smart manufacturing through effective remote control strategies.

Module 5: Hands-on Remote Operation of FrED

Overview

This module provides a comprehensive hands-on experience with the Desktop Fiber Extrusion Device (FrED), enabling students to apply the theoretical knowledge and remote control techniques they have learned in previous modules. Students will conduct real-time experiments, optimize manufacturing parameters, and engage in troubleshooting and maintenance tasks, all through remote access.

Learning Outcomes

By the end of this module, students should be able to:

1. Operate the FrED remotely to carry out fiber extrusion tasks.
2. Apply different control strategies to optimize the extrusion process.
3. Analyze the impact of changes in manufacturing parameters on product quality.
4. Perform basic troubleshooting and maintenance of the FrED remotely.

Topics Covered

1. **Remote Operation Setup**
    - Procedures for safe remote operation of manufacturing equipment.
    - Setting up and verifying remote access functionalities.
2. **Conducting Remote Experiments**
    - Detailed instructions on how to start, monitor, and adjust the extrusion process using FrED.
    - Real-time data collection and monitoring via remote sensors.

3. **Optimization of Manufacturing Parameters**
    - Techniques for fine-tuning process parameters such as temperature, feed rates, and tension controls.
    - Case studies showcasing successful parameter optimizations.
4. **Troubleshooting and Maintenance**
    - Common issues encountered with the FrED and how to troubleshoot them remotely.
    - Scheduled maintenance practices to ensure the longevity and reliability of the equipment.
5. **Process Documentation and Reporting**
    - Importance of accurate record-keeping and documentation in manufacturing.
    - Preparing detailed reports on experiment outcomes, process adjustments, and troubleshooting actions taken.

Activities

- **Remote Control Practice Lab**
    - Hands-on activities where students remotely operate the FrED to produce fibers under varying conditions.
    - Tasks include setting initial parameters, starting the extrusion process, and making adjustments based on real-time feedback.
- **Parameter Optimization Project**

    - Students will use remote control to modify various parameters and attempt to achieve an optimal extrusion process.
    - Analysis of the fiber quality and process efficiency to determine the success of their optimization strategies.
- **Troubleshooting Simulation**
    - Interactive scenarios where students must diagnose and resolve issues with the FrED based on symptoms presented in a simulated environment.
    - Application of systematic troubleshooting techniques to ensure minimal downtime.
- **Group Collaboration**
    - Team-based projects that require coordination and collaboration to manage different aspects of the FrED operation.
    - Sharing of roles in monitoring, adjusting, and reporting on the extrusion process.

Assessment

- **Practical Tests**: Assessments based on the ability to operate the FrED effectively, implement control adjustments, and achieve desired outcomes.
- **Optimization Report**: A report documenting the optimization process, including rationale, methods used, results, and conclusions.
- **Troubleshooting Log**: Submission of a troubleshooting log detailing the issues encountered, steps taken to diagnose, and solutions implemented.

Required Readings and Resources

- Manuals and operational guides specific to the FrED.
- Articles on best practices for remote operation of industrial equipment.
- Access to simulation software for troubleshooting practice.

Support and Resources

- **Virtual Office Hours**: Scheduled times when instructors are available to provide guidance and answer questions in real-time.
- **Technical Support Team**: A dedicated team to assist with any technical issues related to remote access or equipment malfunction during the module.
- **Resource Library**: Online repository of instructional videos, troubleshooting guides, and optimization tips for quick reference.

This module serves as the culmination of the practical application of smart manufacturing principles using the FrED, offering students a deep and integrative learning experience that ties together theory, application, and critical thinking in a remote environment.

Module 6: Data Analysis and Reporting

Overview

In this final module, students will utilize the data collected from their remote operations of the Desktop Fiber Extrusion Device (FrED) to perform detailed data analysis. The focus will be on interpreting the data to understand the effects of various manufacturing parameters on the output and on reporting the findings in a professional manner. This module will enhance students' abilities to use data to make informed decisions and communicate results effectively.

Learning Outcomes

By the end of this module, students should be able to:

1. Analyze data collected from the FrED to identify trends, patterns, and correlations.
2. Use statistical tools and software for data analysis in manufacturing settings.
3. Develop and test hypotheses based on data from manufacturing processes.
4. Prepare comprehensive reports and presentations that effectively communicate findings and recommendations.

Topics Covered

1. **Introduction to Data Analysis in Manufacturing**
    - The importance of data analysis in improving manufacturing efficiency and product quality.
    - Overview of common data types and metrics collected in manufacturing processes.
2. **Statistical Tools for Data Analysis**
    - Introduction to statistical concepts and tools used for analyzing manufacturing data.
    - Practical training on software tools (e.g., Excel, Minitab, MATLAB) for performing statistical analysis.
3. **Analyzing FrED Data**
    - Techniques for cleaning and preprocessing data from FrED operations.
    - Methods for analyzing data to evaluate the impact of changes in process parameters.

4. **Hypothesis Testing and Experimental Design**
    - Formulating hypotheses based on observed data.
    - Designing experiments to test these hypotheses using the FrED.
5. **Reporting and Communication**
    - Best practices for creating reports and presentations in a professional environment.
    - Techniques for visualizing data and presenting findings in a clear and compelling way.

Activities

- **Data Analysis Workshops**
    - Interactive sessions where students learn to use statistical software to analyze data collected from their experiments with the FrED.
    - Exercises include data cleaning, statistical testing, and result interpretation.
- **Project Development**
    - Students will develop a project where they analyze a dataset from the FrED, formulate hypotheses, and validate these through further experimentation.
    - This project will be aimed at improving some aspect of the fiber extrusion process.
- **Presentation and Report Writing**
    - Students will prepare a final report and presentation of their project findings.
    - Peer reviews and feedback sessions to refine communication skills.

Assessment

- **Data Analysis Project**: Students will submit a detailed report on their data analysis project, including data analysis, hypotheses, experimental validation, and conclusions.
- **Final Presentation**: Students will present their findings to the class, demonstrating their ability to communicate technical information effectively.
- **Peer Review**: Participation in peer review sessions, providing and receiving constructive feedback.

Required Readings and Resources

- Selected readings on statistical analysis techniques and their applications in manufacturing.
- Tutorials and user guides for statistical analysis software used in the course.
- Access to a digital library of data visualization and report writing resources.

Support and Resources

- **Statistical Software Access**: Provision of licenses for statistical analysis software.
- **Data Analysis Tutoring**: Scheduled tutoring sessions to help students with complex analysis techniques.
- **Feedback Sessions**: Opportunities for students to receive feedback on their analysis and reporting from instructors and industry experts.

This module consolidates the skills learned throughout the course by applying them in a real-world context, enabling students to demonstrate their ability to use data-driven insights to improve manufacturing processes. It also emphasizes the importance of clear and effective communication, preparing students for professional roles in the industry.

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Chapter 6: Conclusion and Future Work

6.1 Conclusion

The development and integration of the Desktop Fiber Extrusion Device (FrED) within educational settings represent a significant advance in smart manufacturing education. Throughout the investigation and design processes detailed in this thesis, FrED has proven itself not only as a practical teaching tool but also as a catalyst for understanding complex manufacturing principles and controls. The device's ability to offer hands-on learning experiences remotely fills a crucial gap in current engineering education, which often struggles to provide practical experience in online settings.

By enabling direct manipulation of manufacturing parameters and real-time data monitoring, FrED facilitates a deeper comprehension of the underlying mechanics of fiber extrusion processes. This engagement is critical in fostering a generation of engineers who are not only theoretically proficient but also practically skilled in applying their knowledge to solve real-world problems. The educational impact of FrED extends beyond simple laboratory exercises; it introduces students to the challenges and innovations of modern manufacturing environments, preparing them for future roles in industry.

6.2 Future Work

Looking forward, the potential expansions and applications of the Desktop FrED are vast. One immediate area of exploration could be the diversification of materials used in the extrusion process. Investigating a broader range of materials could enhance the educational utility of FrED, allowing students to experiment with and understand the dynamics of different materials, which is crucial for roles in product development and materials science.

Further, the integration of more advanced control systems, such as adaptive and predictive controls, could elevate the sophistication of experiments students can conduct. This enhancement would not only improve the learning experience but also align educational practices more closely with cutting-edge industrial technologies.

Another promising direction involves expanding the accessibility of FrED to a wider array of educational institutions worldwide, including high schools and technical colleges, which may not currently have access to such advanced manufacturing tools. Developing a simplified version of FrED could democratize access to high-quality engineering education, thus inspiring more students to enter the field.

In conclusion, the ongoing development and implementation of the Desktop Fiber Extrusion Device in educational curricula have the potential to significantly influence the teaching of engineering and manufacturing principles. As this tool evolves, it will undoubtedly continue to bridge the gap between theoretical knowledge and practical application, preparing students for successful careers in the ever-evolving landscape of smart manufacturing.

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Appendix

Code for Controlling FrED and Data Collection

```
#include <Encoder.h>
#include <PID_v1.h>
#include <Wire.h>
#include "Adafruit_VL6180X.h"

//Define Pins for Heater
#define heaterPin 2
#define thermistorPin 41
//Constants and Variables for Heater
#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 90

//Define Pins for fan
#define fanPin 3
#define pwmPin 4
#define fanSpeed 50 //out of 255

//define pins for spooling stepper motor
#define motor1_stp 9
#define motor1_dir 10
#define stepsPerRevolutionMotor1 200 // update according to your motor
specification
float angularSpeedMotor1;

//define pins for spooling dc motor
const int spl_pwm = 4;
const int spl_enc_0 = 22;
const int spl_enc_1 = 23;
int period = 250; //Control loop at 4Hz
unsigned long time_now = 0;
double SetpointSpeedSpoolingDC, InputSpeedSpoolingDC, OutputPWMSpoolingDC;
double SpoolingKp=1.5, SpoolingKi=40, SpoolingKd=0; //PID Constants for running a
spooling dc motor

//define pins for extrusion motor
#define motor2_stp 11
#define motor2_dir 12
#define stepsPerRevolutionMotor2 200 // update according to your motor
specification
float angularSpeedMotor2;
```

```
//define pins for laser micrometer
#define laserPin1 14
#define laserPin2 15
float lp1, lp2, dia; //laser micrometer variables
double SetpointDia, InputDia, OutputSpeedSpoolingDC;
double DiaKp=80, DiaKi=50, DiaKd=0;

//Set up timing
unsigned long previousMotor1Time = millis();
unsigned long previousMotor2Time = millis();
unsigned long previousPlotterTime = millis();
unsigned long motor1Interval = 2; //spooling motor
unsigned long motor2Interval = 300; //extrusionn motor
unsigned long plotterInterval = 20;

// define a counter for each motor
static long stepsMotor1 = 0;
static long stepsMotor2 = 0;

//Encoder
Encoder myEnc(spl_enc_0,spl_enc_1);
long oldPosition = 0;


//Time of Flight Sensor
Adafruit_VL6180X vl = Adafruit_VL6180X();


//variables for tension calculation
double a, b, c, d, e, f, g, h, i, j, k, l, tempA, temprange, initialalpha, alpha,
alpha2, beta, gammaval, tension, springK;



//int given_pwm = 0;

//Create PID objects for speed and diameter
PID myPID1(&InputSpeedSpoolingDC, &OutputPWMSpoolingDC, &SetpointSpeedSpoolingDC,
SpoolingKp, SpoolingKi, SpoolingKd, DIRECT);
PID myPID2(&InputDia, &OutputSpeedSpoolingDC, &SetpointDia, DiaKp, DiaKi, DiaKd,
REVERSE);

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

  //variables value for tension calculation
   a=37;
   b=71.5;
   c=69.5;

  //Proximity Sensor Check
```

```
  Serial.println("Adafruit VL6180x test!");
if (! vl.begin()) {
  Serial.println("Failed to find sensor");
  delay(2000);
   while (1);
}
Serial.println("Sensor found!");


//initial alpha calculation
float lux = vl.readLux(VL6180X_ALS_GAIN_5);
uint8_t range;
int p = 0;
float q = 0;
for(p=0; p<40; p++){
  range = vl.readRange();
  q=q+range;
}
temprange = q/40;
tempA = sqrt(256 + sq(temprange-28.39));
initialalpha = asin(16/tempA);

// Heater
pinMode(heaterPin, OUTPUT);

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

// Spooling Stepper Motor
pinMode(motor1_stp, OUTPUT);
pinMode(motor1_dir, OUTPUT);
digitalWrite(motor1_dir, LOW);
digitalWrite(motor1_stp, LOW);

// Extrusion Stepper Motor
pinMode(motor2_stp, OUTPUT);
pinMode(motor2_dir, OUTPUT);
digitalWrite(motor2_dir, HIGH);
digitalWrite(motor2_stp, LOW);

//laser micrometer
pinMode(laserPin1, INPUT);
pinMode(laserPin2, INPUT);

//spooling dc motor
pinMode(spl_pwm, OUTPUT);

SetpointDia = 0.4; //setpoint value for diameter
```

```
  // Set up the PID controller for Spooling Speed
  myPID1.SetMode(AUTOMATIC);
  myPID1.SetOutputLimits(8, 80);

  // Set up the second PID controller
  myPID2.SetMode(AUTOMATIC);
  myPID2.SetOutputLimits(0.5, 3.8);

}

void loop() {

  //spooling DC motor

  while(millis() < time_now + period){
        //wait
  }


  //Read spooling dc motor velocity
  long newPosition = myEnc.read();
  float ds = newPosition-oldPosition;
  float dt = millis() - time_now;
  float vel = (ds*1000*1.12)/(dt*3200);//rotation per second

  //Set values
  time_now = millis();
  oldPosition = newPosition;

  static unsigned long lastSpeedCalculationTime = 0;
  unsigned long currentMotor1Time = millis();
  unsigned long currentMotor2Time = millis();
  unsigned long currentPlotterTime = millis();

  digitalWrite(motor1_stp, LOW);
  digitalWrite(motor2_stp, LOW);

  if(currentMotor1Time - previousMotor1Time > motor1Interval){
    digitalWrite(motor1_stp, HIGH);
    previousMotor1Time = currentMotor1Time;
    stepsMotor1++; // increment the steps counter for Motor1
  }

  if(currentMotor2Time - previousMotor2Time > motor2Interval){
    digitalWrite(motor2_stp, HIGH);
    previousMotor2Time = currentMotor2Time;
    stepsMotor2++; // increment the steps counter for Motor2
  }

  //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;

//laser micrometer reading
/*
lp1= analogRead(14);
lp2= analogRead(15);
dia=max(((lp1-lp2)*28*3.3/(5*1023)),0);
*/

if(currentPlotterTime - previousPlotterTime > plotterInterval){
  previousPlotterTime = currentPlotterTime;

  //calculating angular of both the motors at the same frequency as the plotter
  angularSpeedMotor1 = (stepsMotor1) / stepsPerRevolutionMotor1; // rotation/sec
  angularSpeedMotor2 = (stepsMotor2) / stepsPerRevolutionMotor2; // rotation/sec

  //laser micrometer reading
  lp1= analogRead(14);
  lp2= analogRead(15);
  dia=max(((lp1-lp2)*28*3.3/(5*1023)),0);

  //Compute the PID for diameter to give out speed
  InputDia = dia;
  myPID2.Compute();

  //Use the output of speed from PID2 as the setpoint of PID1
  SetpointSpeedSpoolingDC = OutputSpeedSpoolingDC;


  InputSpeedSpoolingDC = vel;
  myPID1.Compute();


  float lux = vl.readLux(VL6180X_ALS_GAIN_5);
  uint8_t range = vl.readRange();

  //Tension Calculation
  tempA = sqrt(256 + sq(range-28.39));
  alpha2 = asin(16/tempA);
  alpha = alpha2 - initialalpha;
  d = a*sin(alpha2);
  e = c + a*cos(alpha2);
  f = 101 - a*sin(alpha2);
  h = sqrt(sq(e) +sq(f));
  l = ((b*e)/(b+d))-c;
  g = sqrt(sq((l+c))+sq(b));
  k = (d*g)/b;
```

```
beta = asin((sq(k) + sq(a)- sq(l))/(2*k*a));
i = (e/tan(alpha2))-f;
gammaval = asin((i*sin(alpha2)/h));
tension = (0.0905*alpha)/(cos(gammaval)-cos(beta));


/*Serial.print(l);
Serial.print(",");
Serial.print(sq((l+c))+sq(b));
Serial.print(",");
Serial.print(tempA);
Serial.print(",");
Serial.print(initialalpha);
Serial.print(",");
Serial.print(alpha2);
Serial.print(",");
Serial.print(alpha);
Serial.print(",");
Serial.print(e);
Serial.print(",");
Serial.print(f);
Serial.print(",");
Serial.print(g);
Serial.print(",");
Serial.print(h);
Serial.print(",");
Serial.print(i);
Serial.print(",");
Serial.print(k);
Serial.print(",");
Serial.print(beta);
Serial.print(",");
Serial.print((sq(k) + sq(a)- sq(l))/(2*k*a));
Serial.print(",");

Serial.print(h/(i*sin(alpha)));
Serial.print(",");
Serial.print(gammaval);
Serial.print(",");*/

Serial.print(range);
Serial.print(",");
Serial.print(tension*100);
Serial.print(",");
Serial.print(SetpointSpeedSpoolingDC);
Serial.print(",");
Serial.print(TX);
Serial.print(",");
Serial.print(fanSpeed);
//Serial.print(",");
//Serial.print(angularSpeedMotor2);
```

```
    Serial.print(",");
    Serial.print(vel);
    Serial.print(",");
    //Serial.print(lp1);
    //Serial.print(",");
    //Serial.print(lp2);
    //Serial.print(",");
    Serial.print(dia);
    Serial.println();


   /*
    Code for Motor Characteristics
    Serial.print(given_pwm);
    Serial.print(",");
    Serial.print(vel);
    Serial.println();
    given_pwm = given_pwm+1;
   */

    stepsMotor1 = 0; // reset the steps counter for Motor1
    stepsMotor2 = 0; // reset the steps counter for Motor2
  }
analogWrite(spl_pwm, OutputPWMSpoolingDC);
  //Temperature Control
  if (TX < targetTemp) {
    analogWrite(heaterPin, 200);
  } else {
    analogWrite(heaterPin, 0);
  }
}
```