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Abstract

The Fiber Extrusion Device (FrED) serves as an effective solution for engineering education, providing an affordable and versatile desktop tool for teaching various engineering concepts. This paper examines FrED's implementation as a teaching tool at Tecnológico de Monterrey with their version, analyzing its impact on mechatronics education and research capabilities. Through multiple iterations and continuous development, FrED has evolved from a classroom project to a comprehensive educational platform that bridges theoretical knowledge with practical experience.

Keywords: Fiber extrusion, Control, Educational device, Mechatronics

1 Introduction

Engineering education consistently faces the challenge of bridging theoretical knowledge with practical experience while ensuring cost-effectiveness and accessibility. The Fiber Extrusion Device (FrED), developed through collaboration between MIT and

Tecnológico de Monterrey, offers an innovative solution to these challenges by providing both educational value and research capabilities. This paper examines the implementation of Al_FrED_0 (the Mexican iteration of FrED) as a teaching tool, its evolution through several iterations, and its impact on engineering education at Tecnológico de Monterrey. By integrating various technologies such as computer vision, control systems, and the Internet of Things (IoT), Al_FrED_0 serves not only as a practical learning platform for mechatronic components and manufacturing concepts but also facilitates advanced research. Additionally, the device's modular design and affordability make it particularly valuable for educational institutions aiming to enhance their engineering curriculum with hands-on experience.

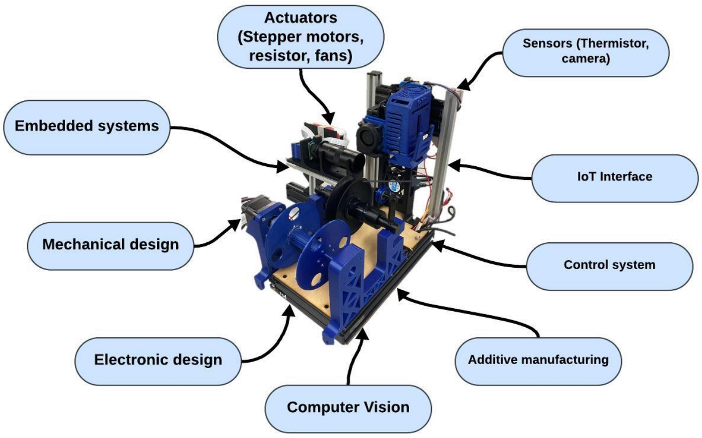

Fig. 1: Education topics of Al_FrED_0

2 Al_FrED_0 as teaching tool Case Study

Al_FrED_0 has been used as a teaching tool since its early development for the Tecnológico de Monterrey (Tec) version. The first version was designed in the mechatronic design class (year), used as a project to learn subjects such as different mechatronic components, design methodologies, and the use of standard norms for designs. Later, this version of Al_FrED_0 was implemented in Automation of Manufacturing Systems (year).

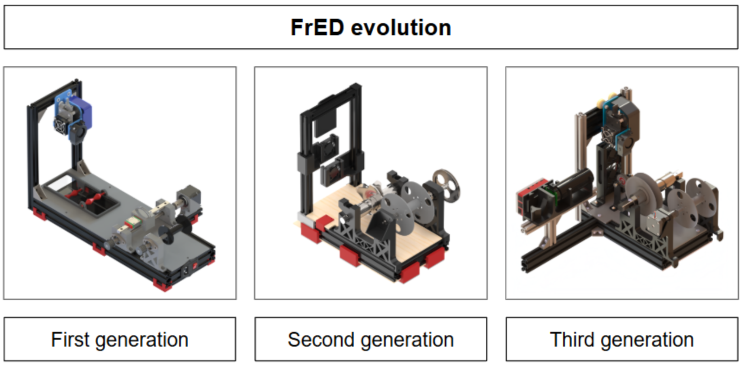

Fig. 2: Evolution of Al_FrED_0

In this class, the device is used to learn topics such as automation implementation, manufacturing concepts, production simulations, and the use of various manufacturing processes. (mencionar cuántos alumnos aproximados han sido impactados por FRED 307). The device has also been used for on-campus internships, which students of all mechatronics semesters can apply for.


Fig. 3: FrED factory in Tecnológico de Monterrey

3 Mechatronics education

Education in engineering often faces the challenge of providing practical activities that offer a closer experience to the topic. Many rely on laboratories that come with high costs. One of the best alternatives is devices that focus on specific engineering topics, however, their lack of versatility and high costs often limit their widespread adoption. Al_FrED_0, on the other hand, stands out as an innovative and practical solution capable of addressing these challenges.

As Table 1 shows, devices like MONA and DaNI 2.1 focus heavily on modularity and high-end design, excelling in their respective niches, such as electrical circuit design and robotics. While these devices are ideal for advanced robotics applications, they can be less practical for broader educational uses. Additionally, their dependence on specialized components may make them less accessible to beginners or institutions with limited budgets.

Al_FrED_0 breaks these barriers by offering a more adaptable and cost-effective solution. Its modular design allows educators to customize the device for various topics, including mechanical design, electrical design, programming concepts, computer vision, and data analytics. This flexibility makes Al_FrED_0 a valuable tool for interdisciplinary education.

The affordability and educational flexibility of Al_FrED_0 ensure that it can be implemented in diverse educational environments, from high schools to research facilities. It enables institutes to teach a wide range of engineering topics, making it not just a device for learning, but a platform for innovation and exploration in engineering education.

Project	**Distinctive feature**	**Electrical design**	**Mechanical design**	**Micro-Controllers**	**Software**
MONA	Programming option with hive-mind capability to control multiple MONA devices, including integration of adaptable modules to enhance the device with new capabilities (utilizing LDR lights and ROS).	High level of electrical design, custom PCB design, modified microcontroller.	Simple mechanical design with commercial parts and custom components.	ATmega 328, Extension-Raspberry Pi Zero.	ROS, Arduino, Ardublock, Mblock
WebLabs	Laboratory with four control teaching devices for DC Motor, Mobile Robot, Temperature and Level Control with remote access.	Commercial components and custom design for Temperature Control.	Few custom designs, mostly commercial.	NI ELVIS and Arduino UNO.	LabVIEW, Arduino, Matlab
Experiments to Teach Control Theory	Two simple devices (See-Saw and turbine) easily manufactured, with student feedback.	Commercial boards and custom connections.	Custom-made with simple materials.	Arduino UNO.	Arduino, LabVIEW, Matlab
DaNI 2.1	High design complexity with various control platforms. Students create obstacles and set difficulty levels.	Modified for robot's needs using commercial microcontrollers.	Modified commercial kit.	Custom Arduino controller, Xilinx Zynq-7000.	LabVIEW

Table 1: Comparison of Control Engineering Educational Projects

4 Research Capabilities

The Al_FrED_0 project has the ability to create numerous pathways and scenarios as a research tool. As an educational device and product, this project branches into two main components are the main branches that come from this project.

Both students and teachers can modify their Al_FrED_0 systems, enabling them to upgrade various components or develop new modules for different experiments. This feature highlights Al_FrED_0's first main branch as a research device. It encompasses multiple research areas, including control systems, the Internet of Things (IoT), computer vision, mechatronics design, materials science, data analytics, and education.

The second main branch uses the device as a product in a learning factory to conduct different investigations on areas such as manufacturing, automation, quality control, supply chain management, systems integration in production, and education.

In Table 1, we summarize a list of different educational and research devices for engineering, highlighting the most impactful devices from the last decade. This demonstrates the significant potential of Al_FrED_0 in all these areas.

5 Al_FrED_0 hardware specification

The design of Al_FrED_0 was primarily based on the initial design developed at MIT [31]. The goal is to create a low-cost design for accessibility and to generate data in various ways. The Mexican version has undergone three different iterations, reaching the current functional prototype, which is continuously being improved.

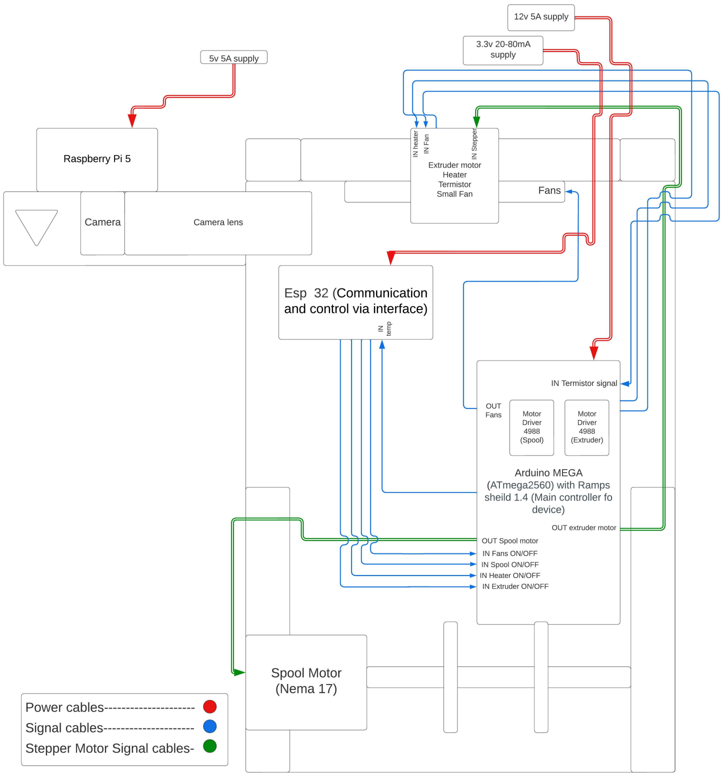

Fig. 4: Mechatronic schematic of AI_FrED_0

5.1 Main controller

The device is composed of various microcontrollers fulfilling each one with a different purpose. The computer vision aspect of the device was done using a Raspberry Pi 5, and then the main control of the actuators and sensor was done by an Arduino Mega 2560 Rev3 using a ramps 1.4 shield and two A4988. The use of this microcontroller is because of the open-source and resemblance with 3d printer hardware and open-source code access. For data communication and interface functions, the device employs the ESP32-D0WD-V3, which features a Wi-Fi and Bluetooth combo. This controller allows the device to be controlled via Wi-Fi using computers and smartphones. Additionally, it streams real-time temperature data from the nozzle of the extruder.

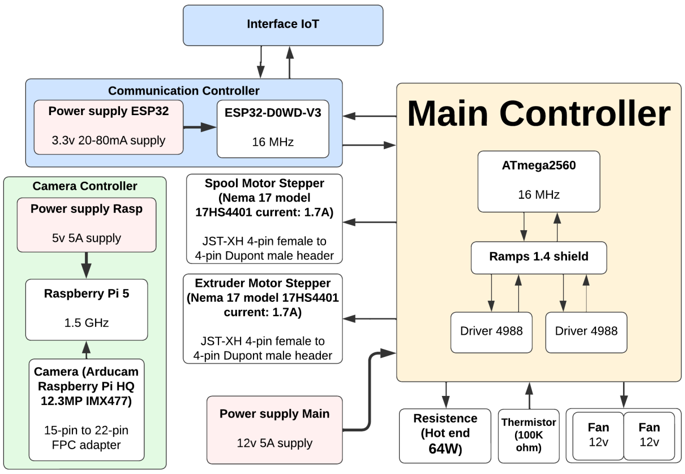

Fig. 5: Distribution of the hardware and communication in Al_FrED_0

5.2 Sensor system

Al_FrED_0 features two primary feedback systems that enhance control over the actuators. One of its main objectives is to provide data for various data analysis applications. The entire extruder mechanism is adapted from the Artillery Sidewinder X1, and the first sensor used is an NTC 3950 thermistor with a resistance of 100K ohms (Found reliable source). The thermistor calculates temperature using the Steinhart-Hart equation.

- R_t is the current resistance of the thermistor.
- R_0 is 100K (resistance at reference temperature).
- B is 3950 (beta coefficient).
- T is the temperature in Kelvin.
- T_0 is the reference temperature (298.15K = 25°C).

$$R_t = R_0 \cdot e^{B(\frac{1}{T} - \frac{1}{T_0})}$$

$$T(C) = \left(\frac{1}{\left(\frac{1}{B}\ln\left(\frac{R_t}{R_0}\right) + \frac{1}{T_0}\right)}\right) - 273.15$$

Additionally, the device features an Arducam Raspberry Pi HQ 12.3MP camera, identified as IMX477, paired with an EBTOOLS Microscope Lens CCD Mount that offers magnification from 8X to 100X. This camera is mounted on a mechanism that allows for adjustable distance between the camera and the filament diameter. Initially, edge detection calculations were performed (pending documentation from the camera team or Professor Alexandro), but later, the system was upgraded to use YOLO for improved performance.

Table 2: Actuators basic data

Sensor name	Voltaje	Amperage
NTC Thermistor 100K 3950	12V-24V	< 0.7 mA
Arducam Raspberry Pi HQ 12.3MP IMX477	3.3V	250mA A[1]

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5.3 Actuators

The device operates with three actuators. A NEMA 17 motor, referred to as A4988, is used for the spooling of the fiber. Precise configuration is required for both the spool and extruder motor, based on their technical specifications and those of the corresponding driver. The NEMA 17 model 17HS4401 typically operates at 12V with a step angle of 1.8 degrees, resulting in 200 steps per revolution. The driver, A4988, allows for microstepping up to 1/16, equating to 3200 steps per revolution, and can handle up to 2A per coil at peak current. For safe and efficient operation, it is recommended to limit the current to 70% of the motor's rated capacity. This results in a Vref of approximately 0.648V, which can be calculated using the relevant formula.

$$V_{ref} = I_{limit} \times 8 \times R_{cs}$$

- V_{ref} is the reference voltage
- I_{limit} is the current limit (70% of the rated current)
- R_{cs} is the sensing resistor ($0.068\,\Omega$)

The heating cartridge operates with a 12-24V power supply and has a power rating of 64W. It employs a PID control system to accurately regulate the temperature, reaching a a set point of 200°C. The extruder features an aluminum heating block that measures 20 x 20 x 12 mm, allowing it to achieve the maximum temperature in under 3 minutes while heating a 1.3mm nozzle. The control system, which utilizes PWM and a thermistor, ensures exceptional thermal stability.

Table 3: Actuators basic data

Actuator Name	Voltaje	Amperage
Motor Stepper Nema 17 model 17HS4401	12V-24V	1.7A
Heating Cartridge for Artillery X1	12V-24V	2.67-5.33 A[1]
Evercool 60mm X 15mm Dual-Ball PWM Fan	12V	0.06-0.21 A

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5.4 Communication

In the initial functional version of the Al_FrED_0 system for Mexico, communication was established using an ESP32-D0WD-V over Wi-Fi, connecting to an interface depicted in Figure 5. The Arduino Mega 2560 Rev3 communicated using digital signals, enabling control through buttons and providing an indicator for when the temperature reached the setpoint. These signals were transmitted via Wi-Fi to the Blynk interface (Fig 6).

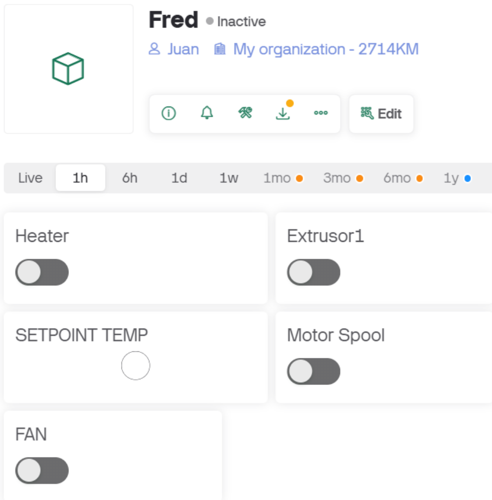


Fig. 6: First interface

The interface was switched to Thinger.io due to the of detailed documentation online (Fig 7). The ESP32 microcontroller was removed, and data communication shifted to a serial connection from the Arduino Mega 2560 Rev3 to the Raspberry Pi 5. With this new interface, the device can be controlled remotely, receive data from the thermistor, graph it in real-time, stream video from the camera, and record the diameters measured.

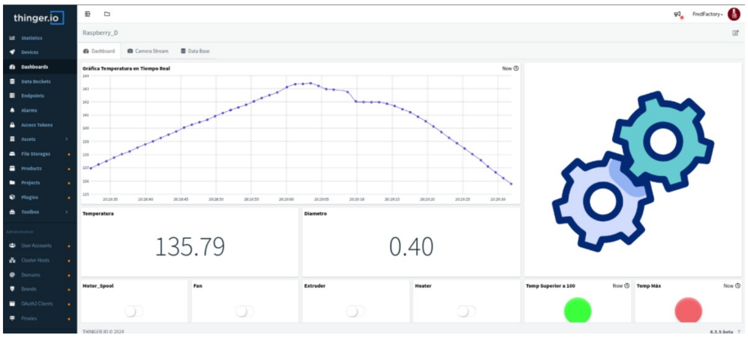


Fig. 7: Second interface

5.5 Electronics

The device is organized into three main circuits: the main controller, communication, and camera. This configuration was chosen to optimize parallel workflows and utilize the available resources effectively (Fig 4).

The main controller features an ATmega2560 microcontroller, as illustrated in the mechatronics schematic and the microcontroller communication flow diagrams. This microcontroller utilizes a Ramps 1.4 shield as an attachment and employs two A4988 driver chips to control two stepper motors. The Ramps 1.4 shield is commonly used in 3D printers, and since Al_FrED_0 operates very similarly, this arrangement simplifies the layout of the electronics. The thermistor is connected to pin A15, which receives the analog signal. The heating cartridge is controlled via digital output pin D10, while the fans are connected to digital output pin D9. One stepper motor operates the extrusion process and is connected to the E0 pins on Ramps 1.4, while the second stepper motor, responsible for the spooling action, is connected to the X-axis on Ramps 1.4. This system is powered by a 12V supply with a current rating of 5A.

For communication, the system employs an ESP32-D0WD-V3 microcontroller. This microcontroller uses digital connections to facilitate simple interface control actions, as described in the software section. It has four output pins and one input pin, and it is powered by a 3.3V supply that draws between 20-80mA.

The final microcontroller used in the device is a Raspberry Pi 5, which is dedicated to camera functionality. The power supply for this system is 5V with a current rating of 5A.

6 Software

The development of educational engineering devices in the last four years has involved the use of various software tools. A review of the most commonly used software among students reveals that Arduino and Python programming are the most used, as seen in the figure(num). This insight allows us to leverage these programs to meet the educational programming needs of engineering.

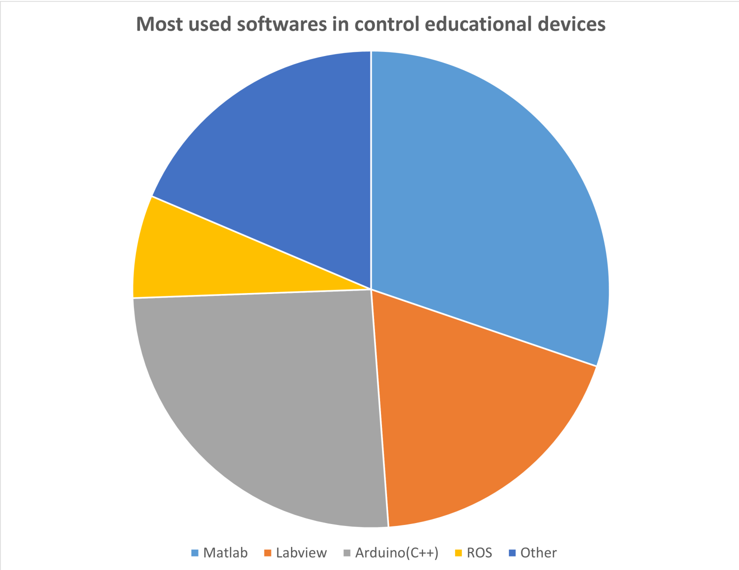


Fig. 8: Graph of most commonly used programs in engineering control education projects (Full graph attached in excel file: page 1)

In the initial iteration, the main control and communication were handled using Arduino software (C++). The main thread employs a state machine architecture to gain basic control over different variables. The code receives control signals from an ESP32 connected to an IoT interface provided by Blynk. The microcontroller sends digital signals that turn certain controls on and off, thus setting their states in the Arduino Mega. Additionally, Python code was used for computer vision on the Raspberry Pi 5 to provide a live video feed of the filament and measure its diameter.

In the latest iteration of the device, communication now occurs through serial communication between the Arduino Mega and Raspberry Pi. The interface code also runs on the Raspberry Pi, which lowers costs and improves communication efficiency by eliminating the ESP 32. This setup allows us to graph the temperature of the thermistor using a new IoT interface hosted on Thinger.io.

7 Control temperature

The first functional version of Al_FrED_0 for temperature control was developed as an open-source model for the Artillery Sidewinder X1 extruder and was manually tuned. The latest version, utilizing tools like MATLAB, is based on an open-loop data model derived from various iterations at a desired set point, with the aim of achieving the most accurate representation possible.

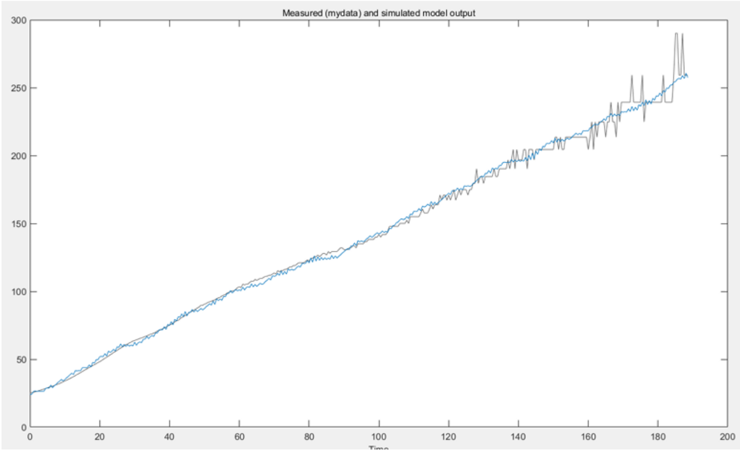


Fig. 9: Open loop model

Using this new model, MATLAB was employed to determine the optimal values for a PID controller. With the new temperature controller, the error was reduced to less than 1 ° C variability and the response time improved by 30%.

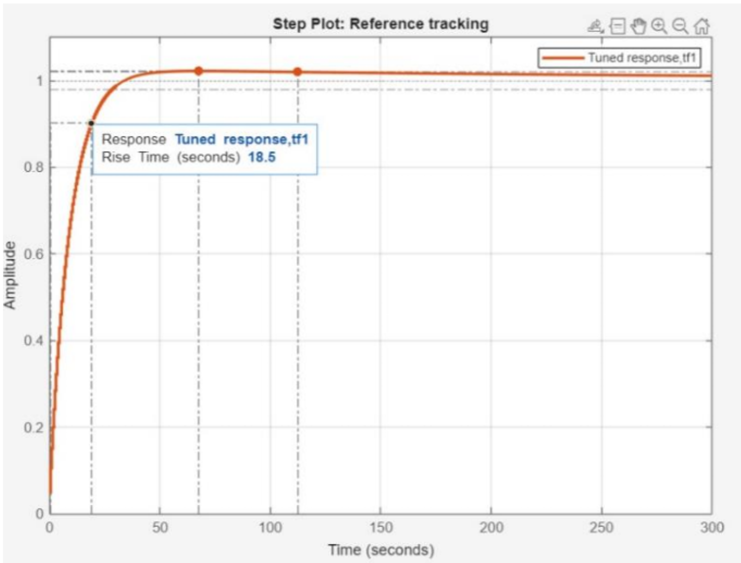


Fig. 10: Close loop PID model

8 Results

The implementation of FrED in Tecnológico de Monterrey has produced significant results in various areas. The optimized PID control system has achieved remarkable precision, maintaining temperature variations below 1 ° C and improving response times by 30%. This advancement enables for more consistent and controlled filament quality.

Additionally, the integration of computer vision, using an Arducam Raspberry Pi HQ 12.3MP camera with an EBTOOLS microscopic lens, has allowed for precise measurements of filament diameter. The upgrade to the YOLO framework for image processing has significantly enhanced edge detection accuracy and real-time measurement capabilities.

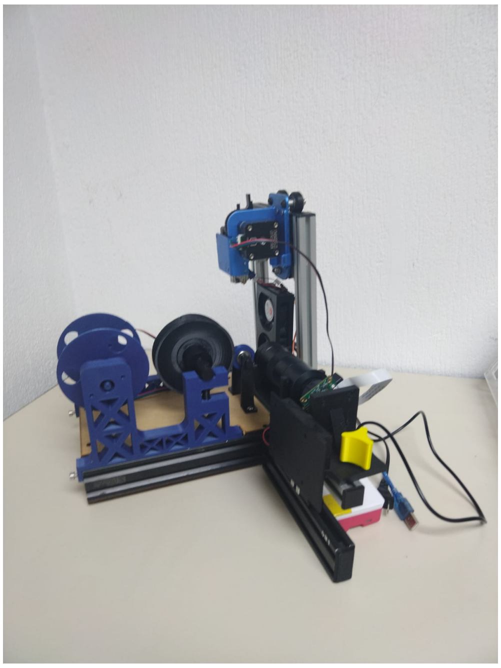
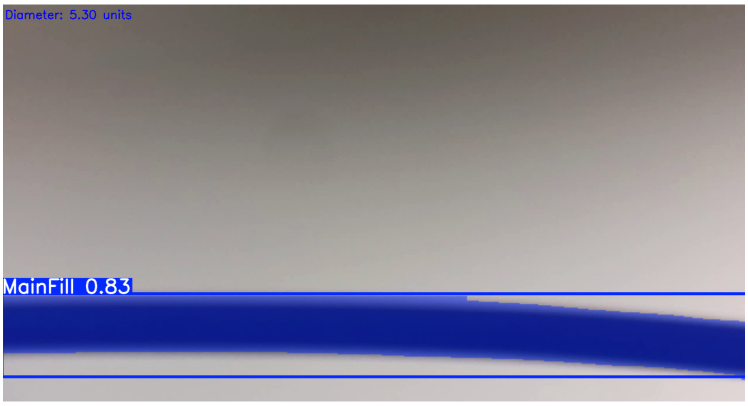


Fig. 11: Isometric view Al_FrED_0

Migration to Thinger.io has resulted in a robust interface that provides real-time temperature monitoring, video streaming of the extrusion process, filament diameter data logging, and remote parameter control.

The system has demonstrated its ability to maintain stable temperatures of up to 200 ° C while producing filaments with consistent diameters, validating its functionality in diverse educational environments.

The successful implementation of Al_FrED_0 has significantly improved the practical teaching of mechatronics, control, automation, and manufacturing concepts. It has established itself as a versatile platform for experimentation and hands-on learning in engineering. This educational impact is particularly noteworthy, as it has benefited (number of students through the years impacted by FrED at Tec) students at TEC. AI_FrED_0 has helped these students learn new engineering concepts and conduct their own research on topics that interest them.



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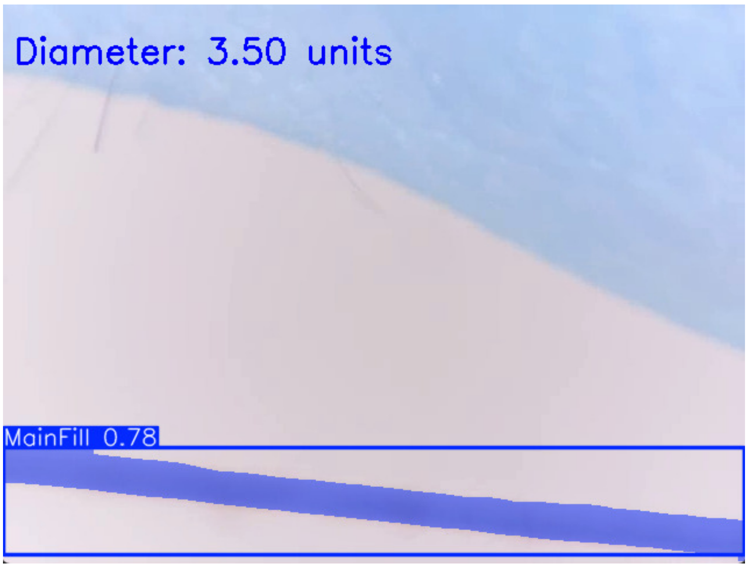

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9 Conclusion

The significant advancements achieved in the Mexican version of FrED demonstrate its successful evolution toward matching MIT's original capabilities while maintaining its educational value. The implementation of precise temperature control systems, coupled with accurate diameter measurement capabilities, represents a major milestone in the device's development. The streamlining of electronic components and microcontroller architecture has resulted in a more efficient and reliable system. The development of a comprehensive user interface that enables real-time temperature visualization and diameter data logging has enhanced the device's functionality for both educational and research purposes. Most notably, Al_FrED_0's capability to produce functional filament spools validates its practical applications in manufacturing processes. These improvements not only showcase the device's technical maturity but also reinforce its position as a versatile educational platform where students can engage in hands-on learning and conduct research across various engineering disciplines according to their interests. The continuous refinement of Al_FrED_0's capabilities while maintaining its core educational purpose exemplifies the successful balance between technological advancement and pedagogical effectiveness.

Appendix A Section title of first appendix

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