



ING. MECATRÓNICA

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Sistema de Medición de Profundidad de Banda de Rodadura de Neumáticos mediante Triangulación Láser
Mechatronic Tire Tread Depth Measurement System using Laser Triangulation

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Aprobación del Tutor del Trabajo de Integración Curricular

Yo Guillermo Alfredo Mosquera Canchingre, en calidad de tutor del Trabajo de Integración Curricular denominado: *Sistema de Medición de Profundidad de Banda de Rodadura de Neumáticos mediante Triangulación Láser*, realizado por Adrian Paúl Ochoa Daza, ha sido orientado y revisado en todas sus partes y considero que cumple los requisitos establecidos por la institución. En virtud de ello doy mi aprobación a fin de continuar con el proceso académico correspondiente.



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Dedicatoria

Este logro va dedicado a mi familia, mi pilar fundamental en mi vida. A mis padres, que me han cuidado desde el día 1, y siguen brindándome su apoyo incondicional. Su amor eterno siempre va a estar presente en mis corazones. A mi hermana, mi pequeña compañera de vida, con la que he compartido millones de experiencias. A mis abuelos, que vean desde el cielo a su nieto convertido en ingeniero, que logró cumplir su promesa de graduarse, y a mis amigos de toda la vida, a quien considero familia, por acogerme en un país nuevo y hacerme sentir en casa. Les agradezco de todo corazón.

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Resumen

La condición de la banda de rodadura de los neumáticos de un vehículo es un factor crítico en la seguridad automotriz. Las inspecciones tradicionales en los talleres dependen en gran medida de medidores mecánicos manuales, los cuales son subjetivos, carecen de trazabilidad digital y frecuentemente fallan en identificar un desgaste peligroso de los neumáticos. Para abordar esta deficiencia, esta investigación detalla el diseño, desarrollo y validación de un prototipo mecatrónico no intrusivo y de bajo costo, capaz de realizar perfilometría óptica automatizada. El objetivo principal es reemplazar las evaluaciones manuales humanas con mediciones de profundidad submétricas, matemáticamente verificables, que cumplan con los umbrales de seguridad de 1.6 mm establecidos por las normativas NTE INEN 2204:2013 y UNECE R30.

La arquitectura física consiste en un pórtico lineal rígido posicionado sobre el paso de rueda superior de un vehículo estacionario. Impulsado por un motor paso a paso NEMA 17 y un husillo T8, el carro acciona un módulo láser de línea y un sensor de visión Logitech C920 HD Pro. Todo el sistema electromecánico es controlado localmente por una Raspberry Pi 5, utilizando su procesamiento local en lugar de depender de procesamiento externo en la nube.

Para extraer la profundidad física precisa de la banda de rodadura, se desarrolló una tubería de visión artificial personalizada en Python utilizando OpenCV. El algoritmo aísla la línea láser proyectada mediante segmentación de color HSV y filtrado morfológico, seguido de un cálculo de centroide subpíxel para convertir los desplazamientos de los píxeles en profundidades métricas. La interacción con el sistema se gestiona a través de una Interfaz Gráfica de Usuario basada en web, que permite a los operadores activar barridos de escaneo automatizados de 100 mm, y acceder a registros de datos históricos.

Las pruebas validaron la precisión del prototipo en repetidas sesiones de medición, demostrando una desviación estándar media de ± 0.045 mm. Al compararse con las mediciones manuales de referencia tomadas con un calibrador de profundidad, la tubería óptica automatizada logró una tasa de error promedio del 2.16%, con una desviación absoluta máxima de 0.152 mm, cayendo completamente dentro del margen estándar de error visual humano. Además, las pruebas de control en superficies de referencia planas activaron con éxito estados de fallo automatizados.

Palabras clave: Perfilometría Óptica, Visión Artificial, Triangulación Láser

Abstract

The condition of a vehicle's tire tread is a critical factor in automotive safety. Traditional workshop inspections rely heavily on manual mechanical gauges, which are subjective, lack digital traceability, and frequently fail to identify dangerous tire wear. To address this deficiency, this research details the design, development, and validation of a low-cost, non-intrusive mechatronic prototype capable of automated optical profilometry. The primary objective is to replace manual human assessments with mathematically verifiable, sub-millimeter depth measurements that comply with the 1.6 mm safety thresholds established by NTE INEN 2204:2013 and UNECE R30 standards.

The physical architecture consists of a rigid linear gantry positioned over the upper wheel well of a stationary vehicle. Driven by a NEMA 17 stepper motor and a T8 lead screw, the carriage actuates a line laser module and a Logitech C920 HD Pro vision sensor. The entire electromechanical system is controlled locally by a Raspberry Pi 5, using its local processing instead of external cloud processing.

To extract the precise physical depth of the tire tread, a custom machine vision pipeline was developed in Python utilizing OpenCV. The algorithm isolates the projected laser line using HSV color segmentation and morphological filtering, followed by a sub-pixel centroid calculation to convert pixel displacements into absolute metric depths. System interaction is managed through a, web-based Graphical User Interface, allowing operators to trigger automated 100 mm scanning sweeps, view real-time safety classifications, and access historical data logs.

Empirical testing validated the prototype's accuracy across repeated measurement sessions, demonstrating a mean standard deviation of ± 0.045 mm. When compared against manual ground-truth caliper measurements, the automated optical pipeline achieved an average error rate of 2.16%, with a maximum absolute deviation of 0.152 mm, falling entirely within the standard margin of human viewing error. Furthermore, control tests on flat reference surfaces successfully triggered automated failure states. Ultimately, this thesis proves that high-precision, automated optical tire inspection can be achieved using accessible hardware, successfully eliminating the inconsistencies of traditional workshop measurements.

Keywords: Optical Profilometry, Machine Vision, Laser Triangulation

ABET Criteria/ Final Report Cross Reference Table

TABLE 1
ABET Criterion Outcomes and Target Mastery Levels

ABET Criterion Outcome	Target Level of Mastery	Best Examples with Section Numbers
1. An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.	Advanced	Section 3: Centroid extraction, machine vision, and optical data acquisition
2. An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.	Advanced	Section 1: Reduce fatal car accidents with better monitoring of car tire treads
3. An ability to communicate effectively with a range of audiences.	Intermediate	Section 3: Design of graphical interface for users to understand data efficiently and easily
4. An ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts.	Intermediate	Section 1: Recognizes the impact of mechanical failures on road safety
5. An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.	Intermediate	Section 1: Establishes clear objectives and schedule with a Gannt chart
6. An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.	Advanced	Section 5: Gives comparisons, accuracy and results in an effective way

Chapter 1

Introduction

The condition of a vehicle's tire tread is a very important factor in road safety, as it gives traction, improves braking efficiency and resistance to sliding or hydroplaning. Traditionally, people that want to measure a tire's tread depth have relied on manual measurements, visual assessments or mechanical depth gauges to conclude if a tire is road legal or not. These methods usually generate inconsistent data, lack traceable data, and cannot accurately identify tires very near the tire tread legal limit of 1.6 mm established by international standards such as UNECE R30 [1] and national standards like NTE INEN 2204:2013 [2].

Having a tire below the legal limit can have severe consequences when left unattended. It increases the risk of skidding and fatal collisions by up to 40 % [3,4]. According to the WHO, over 25 % of currently operating vehicles are operating with tires below the legal limit [5].

Existing operational reading failures can be traced back to human error and lack of standardized, automated technology. This means there is a necessity for low-cost prototypes capable of providing precise and repeatable data that can align with modern safety standards [6, 7].

The scope of this project only entails the development of a functional laboratory prototype that measures tire tread depth using laser triangulation. The project includes the integration of the physical prototype, the electronic development, data processing software, and development of a graphical user interface to visualize data.

The scope of this project focuses strictly on the development of a functional laboratory-scale prototype that measures tire tread depth using non-contact optical sensing methods. The project encompasses the complete integration of the physical hardware, the embedded data processing software, and the development of a user interface. Implementation using industrial components, utilizing mechanical centers' machinery or doing dynamic measurements all fall outside of the scope of this research.

The automatic measurement of tire tread depth has slowly changed from manual mechanical gauges to highly advanced optical techniques. Early research on computer vision to measure profilometry demonstrated the possibility of using techniques like laser triangulation to quantify physical distances without contact [6, 8]. These early iterations have evolved into

more complex vision machines that can tackle the challenging geometry of tires, and the low reflectivity of tire rubber. [9]

Recent articles have indicated the growing use of laser triangulation, image processing and 3D surface profiling in the profilometry industry, leading to new ways to Implement these concepts into various contexts in the automotive world. As the performance of an optical setup are dependent on light conditions, material surfaces and edges, setups have to be calibrated for rubber surfaces, using low cost scanning systems [10, 11].

New studies have utilized image filtration techniques developed mainly in Python via the OpenCV library [12]. These research articles have also explored the identification not only of tread depth measurements, but also development of structural anomaly identification and surface damage verification of the tire [7, 13].

Studies have also been done on dynamic measurements, with special focus on advanced optical preprocessing for tire sidewall extraction and analysis [14], as well as the integration of loop imaging for measuring tire deformation during rolling [15].

As the resurgence of AI continues to change various fields of research, some articles have focused on the integration of deep learning with computer vision setups. Concepts like multispectral vision, edge computing and pattern recognition have pushed the boundary of optical setups by proposing real-time visual tire wear classification and deformation measurement. [16] [17]

Laser triangulation is based on the geometric relationship between a laser plane, a camera, and the surface under measurement, utilizing principles of optical trigonometry [18]. A line-generating laser module projects a planar sheet of light onto the surface at an oblique angle θ . A camera positioned perpendicular to the surface images the illuminated line. For a flat reference surface, the line appears at a fixed image row r_0 across all columns. When the surface deviates in height by Δz , the line displaces vertically in the image by Δr pixels, related by:

$$\Delta z = \frac{\Delta r}{k \cdot \tan \theta} \quad (1.1)$$

where k is the camera's pixel-to-metric scale factor (pixels per millimetre at the measurement plane). Because the entire relationship reduces to measuring a row displacement per image column, the problem of profilometry becomes the problem of accurately locating the laser line

centre row at every column in the image [6, 9].

The Hue-Saturation-Value (HSV) colour model decouples the colour (hue, H) from the luminance (value, V) and purity (saturation, S) of a pixel. This is advantageous over the RGB model for colour-based segmentation because changes in illumination intensity primarily affect V and S, leaving H relatively stable. In OpenCV's HSV encoding, hue is represented in the range $[0, 179]$ [12]. Red occupies two discontinuous hue ranges: $H \in [0, 10]$ and $H \in [160, 179]$, because red straddles the $0^\circ/360^\circ$ boundary. Both ranges must be thresholded and combined with a logical OR operation to establish a robust initial mask for 2D-to-3D profile conversion [14, 19].

Mathematical morphology operates on binary images using a *structuring element* (kernel) of defined shape and size to filter image artifacts [12, 13].

Erosion Removes pixels that are not completely surrounded by foreground pixels within the kernel footprint. Shrinks bright regions.

Dilation Adds pixels wherever the kernel overlaps any foreground pixel. Expands bright regions.

Opening Erosion followed by dilation. Removes small foreground objects (noise) smaller than the kernel, without significantly altering larger objects.

Closing Dilation followed by erosion. Fills small holes and gaps within foreground regions.

A key insight noted in this work is that the kernel shape entails geometric prior knowledge. A tall, narrow kernel (e.g. 9×1 pixels) applied in an opening operation erases objects that are taller than wide — such as diffuse glow blobs — while preserving objects that are wider than tall — such as a horizontal laser line. Conversely, a short, wide kernel (e.g. 3×150 pixels) in a closing operation bridges horizontal gaps in the laser line (caused by wire occlusions or low-brightness patches) without expanding the mask vertically.

The laser line spans several pixel rows in each image column due to the finite beam width and diffraction effects. Detecting only the single brightest row would count the height measurement to whole pixels, limiting accuracy. Sub-pixel accuracy is achieved by computing the intensity-weighted centroid of the vertical intensity profile within each column [15]:

$$r_{\text{centroid}}[c] = \frac{\sum_{r=0}^{H-1} r \cdot I(r, c) \cdot m(r, c)}{\sum_{r=0}^{H-1} I(r, c) \cdot m(r, c)} \quad (1.2)$$

where $I(r, c)$ is the red-channel intensity at row r , column c ; $m(r, c) \in \{0, 1\}$ is the binary mask value; and H is the image height. A Gaussian blur is applied to I prior to centroid computation to smooth high-frequency sensor noise that would otherwise corrupt the weighted mean [12].

In order to develop the idea, the following general objective was defined: Implement a mechatronic prototype capable of measuring tire tread depth for tires R15,R16,R17 & R18 tires, providing decision criteria according to applicable regulatory safety thresholds.

To fulfill the general objective, the following specific technical milestones must be achieved:

- Develop and physically manufacture a rigid, automated mechatronic prototype utilized for the controlled acquisition of tire surface data.
- Select and integrate optical sensors suitable for accurate, sub-millimeter tread depth measurement.
- Implement computer vision algorithms for data processing to calculate the geometric tread depth and wear distribution.
- Design a graphical user interface (GUI) to display the measurement results, normative decision indicators, and past results for the end-user.

Chapter 2

Methodology & Design

This project follows the Systems Engineering V-Model, providing a sequential approach in developing a project, making sure that every design choice is linked to a physical output.

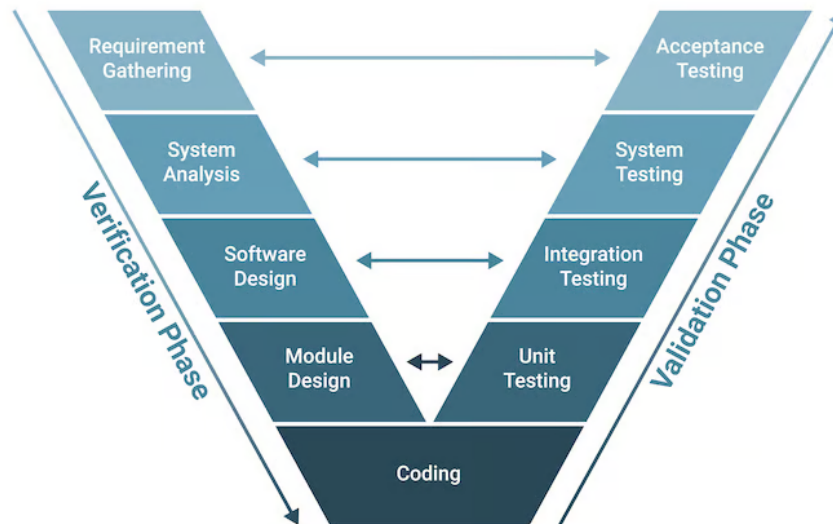


Fig. 1. V-Model Methodology Diagram

Source: [20]

2.1 Requirements Definition

The first step of the V-Model established the definition of the requirements, objectives, and constraints of the project. The system needed a light frame in order to prevent the motor from carrying too much load, and adhering to a strict budget, utilizing already available materials, as well as off-the-shelf components.

To start the engineering design process, the system characteristics were divided into functional, non-functional requirements, and constraints of the project.

2.1.1 Functional Requirements

- The system must do an automated sweep across the top side of the tire using a moving cart
- The system must be able to capture data using an optical setup, consisting of a laser module and a camera.
- The system must utilize image processing algorithms to process data from digital inputs

to physical units.

- The system must give results that compare results to current road safety standards.
- The system must manage thermal outputs by toggling both the motor and the laser module.

2.1.2 Non-Functional Requirements

- The system must process all data internally, without using any external cloud processing.
- The system must move the optical cart without any stutters or mechanical bindings, so that the images taken can stay sharp and unobstructed.
- The system must include a clamping mechanism that allows the user to easily latch the system onto a tire.

2.1.3 System Constraints

- The prototype must be able to measure R15, R16, R17, and R18 tires to determine their tire tread depths.
- The prototype is set for a laboratory scale, meaning any rolling measurements or environmental protection is not included in this study.

2.2 Conceptual Design

Having established the system requirements, the initial concept design of the prototype was done, establishing the measurement system to be an optical laser setup using laser triangulation in order to capture test images of the laser, and then process them using image extraction algorithms.

Some conceptual hurdles and decisions, listed below, has to be considered before landing on a final prototype:

2.2.1 Kinematic Strategy

The first conceptual debate was in the motion sweep to be performed when scanning the tire. 2 options were looked at, with the first one being sweeping the tire while the optical setup remained still on one place, or the second one, being keeping the tire stable while moving the optical cart itself. The second one was chosen because moving a lightweight optical carriage requires far less energy and simpler actuation than moving an heavy vehicle wheel.

2.2.2 Trajectory Architecture

Once the carriage method was selected, the sweep motion was evaluated. The first option included the manufacture of a curved rail that would follow the tire's natural curvature , or designing a linear motion system and fixing the angle discrepancy through software means.

The linear option was selected, as manufacturing a custom-made curved rail with the tolerances needed for optical measurements would mean unnecessarily high costs and extreme mechanical difficulty, as opposed to a linear system, easily achievable with standard components, leaving the software correction to a specialized program.

2.2.3 Mounting Orientation

Some mounting placements were analyzed, comparing a top mount and a side mount to grip the prototype to. The top mount was chosen primarily because the prototype does not have to fight gravity, which improves its mechanical stability, reducing the clamping force needed to tighten the prototype onto the tire.

2.2.4 Frame and Guide Mechanism

The system was done as a one-sided driven tire mounted measuring system. This was done because the center of the prototype needs to be clear, so that there are no interferences with the optical setup. This introduced another problem, mechanical racking. To fix this issue, V-slot wheel carts were installed on both sides, reducing friction between the rails and the cart, making it so that one motor mounted on the side can easily move all the cart by itself without it tilting, jamming or twisting.

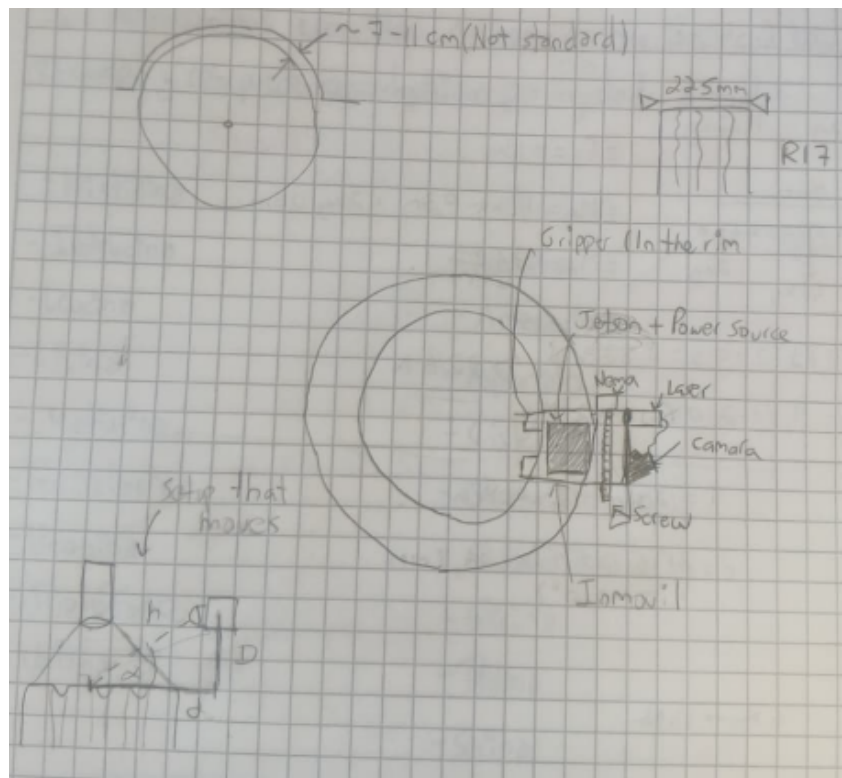


Fig. 2. Initial concept sketch

2.2.5 Conceptual Design Selection Matrix

Table 2 summarizes the design alternatives evaluated during this phase and the final selections chosen for the specific design section.

TABLE 2
Summary of Conceptual Design Decisions

Design Theme	Evaluated Options	Selected Option & Justification
Kinematic Strategy	1. Rotate the tire 2. Move the optical carriage	Move the optical carriage: Much lighter mass; requires significantly less actuator torque and power compared to rotating a full wheel.
Trajectory Architecture	1. Curved rail matching tire 2. Linear rail with software correction	Linear rail: Eliminates complex and costly manufacturing; software easily handles mathematical curve flattening.
Mounting Orientation	1. Top of tire (12 o'clock) 2. Side of tire (3 or 9 o'clock)	Top of tire (12 o'clock): Gravity assists in stabilizing the frame; prevents heavy cantilever stresses on the brackets.
Linear Guide System	1. Heavy steel linear rails 2. Passive V-wheel extrusions	Passive V-wheels: Meets budget and weight constraints while effectively preventing asymmetrical racking.

2.3 Risk Factors & Mitigation

Some risks were identified that could interfere with the overall conclusion of the project, as well as the solutions that were taken so the risks do not become major problems:

2.3.1 Risk 1: Mechanical Racking

To not obstruct the optical view of the system, it utilizes an asymmetrical drive layout, localizing the drive subsystem entirely to one side of the prototype. This uneven application of force introduces the possibility of the moving carriage stuttering, twisting or stalling.

Mitigation Strategy: This was resolved by integrating two polycarbonate V-slot wheel carts that were mounted on each side of the cart, one per rail. This reduced friction and prevented the motor from binding or stalling during scans.

2.3.2 Risk 2: Mounting Instability and Vibrational Drift

Mounting the prototype on a compressible material like rubber can make it so that the prototype could slip during actuation. If the force of motor makes the carriage switch positions while scanning, the results get compromised and the data becomes unusable.

Mitigation Strategy: Custom designed clamps were designed to securely hold the system to the tire. These clamps can slide to press onto the tire sidewalls, creating a secure hold to maintain the system stable.

2.3.3 Risk 3: Inductive Voltage Spikes and Logic Brownouts

Having all electronic components, both the microcomputer and high current actuators on one single energy loop can create interferences, voltage or current drops that can trigger reboots on the system, or worse, permanently damage the controller's chip.

Mitigation Strategy: The high current devices are powered by one power source, while the microcomputer is powered by a totally different power source, creating two totally separate power loops that do not interfere with each other, isolating critical components to protect them from electrical interferences.

2.3.4 Risk 4: Dynamic Optical Calibration Drift

Most commercial cameras have built-in autofocus, auto exposure and white balancing features. If the camera does a focal adjustment during a scan cycle, the pixel-to-mm ratio gets completely changed, giving false data and making the prototype useless.

Mitigation Strategy: Using software, all dynamic optical features were disabled, turned to static, and pre-calibrated to allow a permanent geometric scale throughout the entire testing and validation phase.

2.4 Specific Design

2.4.1 Mechanical Subsystem Design

This part denotes the design sections for the optical cart setup as well as the clamping mechanism, highlighting all components and the decisions taken to select them

2.4.2 Asymmetrical Gantry and Linear Actuation

To prevent obstruction of the optical path of the laser, a one side motor mount was constructed using 2020V-slot aluminum extrusions. Linear actuation was achieved using a stepper motor, T8 lead screw, T8 brass nut and KP bearing. Due to the resolution of the screw, the system is capable of achieving a resolution of 0.04 mm per motor step.

2.4.3 Structural Finite Element Analysis (FEA) and Component Redesign

When testing the initial pieces used to build the physical prototype, a slight sagging was seen on the main cart piece, leading to a subsequent analysis and redesign of the piece, so the sagging disappears and the piece can be usable for profilometry readings.

To compare both sides of the design process, a static Finite Element Analysis (FEA) was conducted in SolidWorks Simulator.

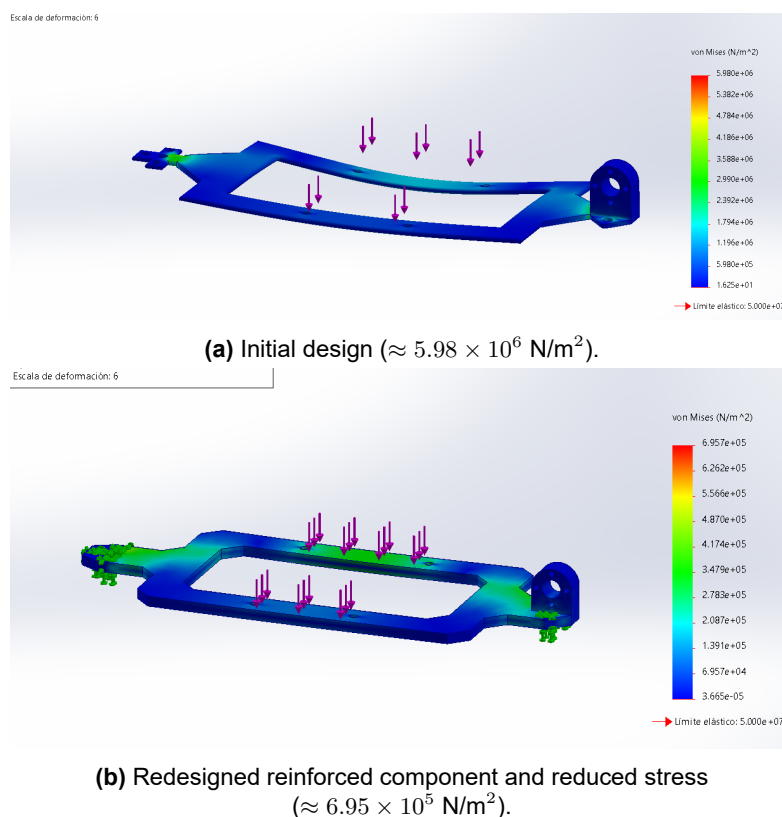


Fig. 3. SolidWorks FEA von Mises stress comparison between the initial flexible design and the final rigid redesign.

As shown in Figure 3(a) , The initial iteration of the structural base was modeled with a highly localized, low-profile geometry to minimize total weight. However, as shown in the static load simulation, this thin architecture exhibited significant geometric deflection across its central span under operational loads. While the maximum von Mises stress of $\approx 5.98 \times 10^6 \text{ N/m}^2$ remained below the material's yield strength ($5.00 \times 10^7 \text{ N/m}^2$), the severe elastic bending made the piece unsuitable in an optical setup scenario.

To fix this problem, the thickness of the piece was doubled, and the edge geometry was optimized so that the piece could resist bending moments on its axis

The FEA developed on both pieces demonstrated a much more stable system that does not sag or bend, ensuring that the optical setup always stays at the same height and distance of the laser reflected on the tire.

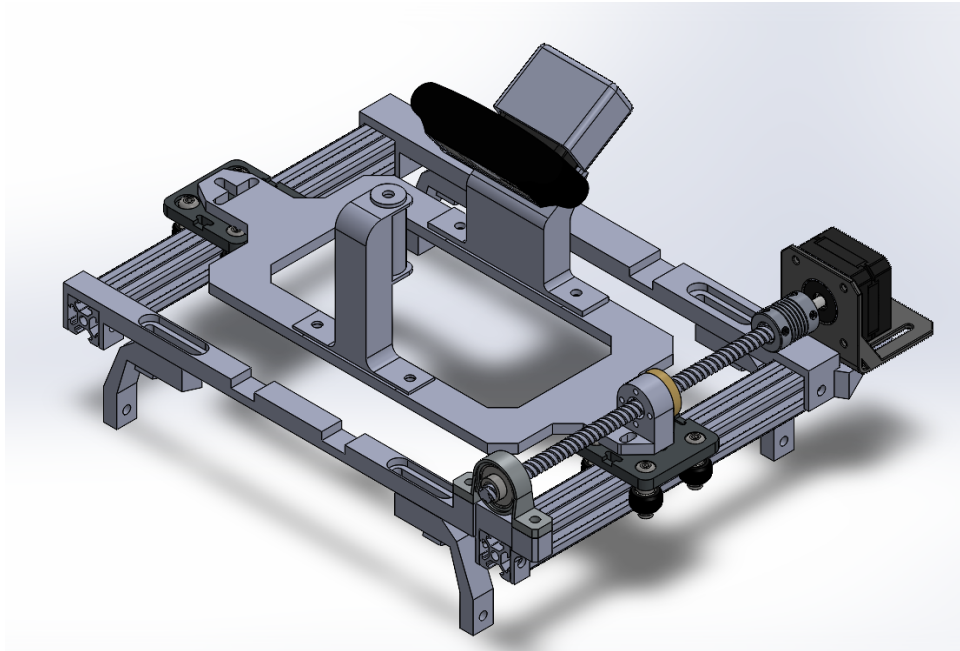


Fig. 4. Finalized CAD model of the prototype

2.5 Electronic and Control Subsystem

This subsystem was designed to manage power distribution, control mechanical movement and ensure connectivity between the different components implemented in this project.

2.5.1 Processing Core Selection

Table 3 justifies the microcomputer selection between 2 controllers that were suitable contenders for advanced image processing.

TABLE 3
Hardware comparison between Jetson Nano and Raspberry Pi 5

Specification	NVIDIA Jetson Nano	Raspberry Pi 5
CPU Architecture	Quad-core ARM Cortex-A57	Quad-core ARM Cortex-A76
Base Clock Speed	1.43 GHz	2.40 GHz
Memory Bandwidth	25.6 GB/s	Up to 42.6 GB/s (LPDDR4X)
Compute Focus	Parallel GPU Inference (CUDA)	Sequential CPU Processing
Project Advantage	Hardware-accelerated Deep Learning	Superior single-thread OpenCV performance
Cost	240 \$	120 \$

The selected microcomputer was the Raspberry Pi 5. Even though initial literature suggested using fast GPU boards, this project is focused on sequential CPU processing to carry out filters and calculations. This means the project will not take neural network intelligence or parallel inference, making the Nano is not suitable for it, while the Raspberry Pi 5 excels at continuous, sequential tasks, eliminating the needed for external cloud processing.

2.5.2 Power Distribution and Logic Conversion

The system divided power into 2 separate power loops, each containing different voltages values. The 5V DC 5A power supply directly powers the Raspberry Pi 5 on through its USB-C port, while the 24 V DC 5A power source is connecte to the NEMA driver, a buck converter stepping down to 5V, and a laser module connected to said 5V. A relay, controlled by the Raspberry, turns the laser on and off between scans.

In table 4, a maximum power consumption was highlighted to check if the sources do hold up in terms of power.

TABLE 4
Maximum power consumption of the project

Component	Voltage (V)	Max Current (A)	Peak Power (W)	Assigned Power Source
Raspberry Pi 5	5.0 V	3.00 A*	15.00 W	5V 5A USB-C Supply
Logitech C920	5.0 V	0.50 A	2.50 W	Pi 5 (USB Bus)
5V Relay Module	5.0 V	0.07 A	0.35 W	Pi 5 (5V GPIO Pin)
NEMA 17 (via TB6560)	24.0 V	1.40 A	33.60 W	24V 5A Main DC Supply
TB6560 (Logic Overhead)	24.0 V	0.10 A	2.40 W	24V 5A Main DC Supply
Red Line Laser	5.0 V	1.5 A	7.5 W	24V to 5V Buck Converter
Total System Peak	–	–	61.35 W	–

*Estimated peak processing load; official Pi 5 spec requires a 5A supply for full peripheral support.

2.5.2.1 Power Supply Justification. As outlined in the power budget, the total theoretical peak consumption of the system is approximately 61.35 W. However, powering these components from a single source would risk severe voltage drops during motor acceleration. Therefore, the load is distributed across two independent sources, both of which were selected to provide massive safety margins.

Primary Electromechanical Source (24V, 5A DC Supply): The main drive architecture, consisting of the NEMA 17 motor and the TB6560 driver, draws its power from a dedicated 24V DC supply rated at 5.0 Amps. This source provides a total power capacity of 120 W ($24\text{ V} \cdot 5\text{ A} = 120\text{ W}$). The peak draw of the electromechanical loop—including the minor load of the buck converter driving the 7.5 W laser—is approximately 43.50 W. This means the 120 W supply operates at roughly 33% of its maximum capacity.

Processing and Logic Source (5V, 5A USB-C Supply): The embedded microcomputer and its dependent peripherals (the Logitech C920 and the relay coil) draw from a completely isolated 5V USB-C power supply rated at 5.0 Amps, yielding a capacity of 25 W ($5 \text{ V} \cdot 5 \text{ A} = 25 \text{ W}$). The peak theoretical load of the Raspberry Pi 5 under heavy OpenCV processing, combined with the USB camera and GPIO logic, is approximately 17.85 W. The 25 W capacity provides an adequate 28% safety margin.

2.5.3 Motor Control and Peripheral Actuation

The NEMA control is done by a TB6560 driver. This driver was selected because of its enclosed chassis, large heatsink to prevent thermal brownouts, and highly configurable outputs.

The driver was configured to 1.4 A delivered to the motor to match NEMA 17 datasheet specifications. The holding torque was set to 50% to stop heat from building up in the motor when not scanning. 50 % decay was added to minimize electrical noise and current bounces. Finally, 1/16th microstepping was chosen to smooth down the vibrations from the motor, ensuring a faultless optical scan.

2.5.4 Kinematic and Motor Torque Calculations

In order to determine the right electromechanical actuator for the linear gantry, the dynamic torque requirements of the mobile optical carriage had to be estimated. The design incorporates a T8 lead screw with a lead of $l = 0.008 \text{ m}$ and a transmission efficiency (η) of 50%, due to the fact that the brass nut is employed as the interface component. The total moving weight (m) of the 3D-printed carriage, camera, laser, and fasteners is 0.5 kg.

To begin with, the total axial force (F_{total}) needed to move the carriage was calculated as the summation of the friction force (F_f) generated by the V-wheels and the force necessary for accelerating the moving mass (F_a). Assuming a relatively conservative coefficient of friction $\mu = 0.1$ for polycarbonate wheels sliding on aluminum with a desired linear acceleration $a = 0.1 \text{ m/s}^2$:

$$F_f = \mu \cdot m \cdot g = 0.1 \cdot 0.5 \text{ kg} \cdot 9.81 \text{ m/s}^2 = 0.4905 \text{ N}$$

$$F_a = m \cdot a = 0.5 \text{ kg} \cdot 0.1 \text{ m/s}^2 = 0.05 \text{ N}$$

$$F_{total} = F_f + F_a = 0.4905 \text{ N} + 0.05 \text{ N} = 0.5405 \text{ N}$$

Once the total axial force is calculated, mechanical torque needed (T_{req}) to drive the

lead screw through can be calculated via the power screw equation:

$$T_{req} = \frac{F_{total} \cdot l}{2\pi \cdot \eta} = \frac{0.5405 \cdot 0.008}{2\pi \cdot 0.5} \approx 0.00137 Nm$$

Incorporating a factor of safety 2.0 to ensure proper account is made for dynamic binding and particulate accumulation, a maximum design required driving torque of 0.00274 Nm is reached. For this prototype, any motors chosen should be rated with at least 2.0x of this specification in tandem with high definition angle resolution. Four popular models of standard stepper motors have been considered below:

- **28BYJ-48 (Geared):** Outputs ≈ 0.03 Nm. While incredibly inexpensive, it would require excessive mechanical complexity due to gear backlash to accurately translate micro-millimeter motion. **NEMA 11:** Outputs ≈ 0.06 Nm. An extremely compact industrial motor, but has limited local availability for replacement parts, driving up overall repair cost/downtime. **NEMA 14:** Outputs ≈ 0.10 Nm. More balanced size and power output, but requires custom mounting hardware and is more expensive due to lower mass-production scales. **NEMA 17:** Outputs ≈ 0.13 Nm (short-body variant). The standard for desktop CNC systems, offering massive over-power capacity, ubiquitous global availability and standardization of mounting, driving procurement cost down to a minimum.

Although the other motor options met the minimum 0.00274 Nm torque requirement, the NEMA 17 was chosen because it's the de facto standard in the mechatronics industry. It was the most readily available with significant cost-benefit, and its standardized mounting mechanism significantly reduced design complexity. Additionally, the tremendous over-capacity of the NEMA 17 (relative to the 0.00274 Nm torque needed to move the sled) allowed for a reduction in its holding torque via firmware configuration in the driver, minimizing heat dissipation from its coils when stationary for image capture.

2.5.5 Optical Geometry and Sensor Integration

The principle by which this profile is measured is using an active non-contact method. A fan of light emitted from a visible line laser is aligned perfectly perpendicular to the surface of the tread.

2.5.6 Vision Sensor Selection and Justification

Determining which vision sensor will provide the most accurate and reliable data to the system is a critical task, and so an analysis of potentially suitable hardware was completed

before proceeding with the design. Based on several design and implementation considerations, a comparison was made between three different models of camera: Logitech C920 HD Pro, Raspberry Pi Camera v2 (Sony IMX219), and Raspberry Pi Camera Module 3 Wide (Sony IMX708). The specifications of each are displayed in Table 5.

TABLE 5
Comparative analysis of vision sensors for mechatronic integration.

Specification	Logitech C920 HD Pro	RPi Cam v2 (IMX219)	RPi Cam 3 Wide (IMX708)
Interface	USB 2.0 (Shielded Cable)	CSI-2 (Ribbon Cable)	CSI-2 (Ribbon Cable)
Sensor Resolution	1080p (2.1 MP)	8.0 MP	12.0 MP
Field of View (FOV)	78° (Standard)	62° (Standard)	120° (Ultra-Wide)
Focus Mechanism	Auto (Software Lockable)	Fixed (Requires manual tool)	Phase Detection Auto Focus
Optical Distortion	Minimal	Minimal	Severe Barrel Distortion
OpenCV API	Native UVC / V4L2	libcamera / GStreamer	libcamera / GStreamer
Approx. Cost (USD)	≈ \$60 – \$70	≈ \$25 – \$30	≈ \$35 – \$40

Although the CSI-connected cameras offer superior sensor resolution for the price and are more integrated with a Raspberry Pi single-board computer, the Logitech C920 was selected based on the following three crucial reasons:

1.- Avoidance of optical distortion: The triangulation method described in equation 1.1 requires that optical projection occurs along a perfectly straight line. Unfortunately, at the precisely calibrated 100mm standoff distance required for this application, the wide 120° field of

view of a IMX708 Wide (Raspberry Pi) sensor will cause significant radial barrel distortion (or "fisheye effect") that badly warps the line near the edges of frame requiring software to remove the warping with much computationally expensive camera matrix manipulation. The Logitech C920's 78° camera provides much straighter projection over the relevant 100mm distance and, therefore works better for the current prototype.

2.- Electromagnetic immunity: This machine's vision sensor is driven by an active moving carriage.

Standard ribbon-style CSI cameras use relatively thin, unshielded cables susceptible to electronic noise (EMI) from interference caused by active NEMA17 coils and, if incorrectly managed, even the stepper motor controller itself. The C920, however, uses a substantial 2.0 USB shielded cable which offers much greater noise protection and mechanical durability over the repetitive, oscillating movement the camera undertakes.

3.- Total cost of implementation: Although Raspberry Pi camera modules have a relatively low purchase price, (\$25 - \$40), their inclusion into a moving mechatronic gantrys requires a number of further costs. You will need to print a custom housing for any simple PCB camera, purchase an additional, extra-long CSI cable, and additional EMI shielding, all in order to run the necessary leads from the image sensor to a Raspberry Pi micro-controller. A single Logitech C920 HD Pro includes the required sturdy housing, has a built-in standard 1/4" mount for simple positioning, and already uses a substantial insulated USB cable.

This results in the Logitech C920 proving to be the more inexpensive option in total terms when factoring in the cost of development and construction.

2.5.7 Optical Geometry and Focal Distance Calibration

In order to obtain perfectly sharp, sub-millimeter detail of the line cast onto the tire, we must calculate and hard code the optical system's exact Focal Distance to within the Logitech C920 HD Pro's UVC (USB Video Class) controls. Using a strictly perpendicular, triangulation method of viewing where the laser projects straight down onto the surface of the tire, the camera is positioned at a 30° angle to this laser plane. The optical rail holding the camera is situated precisely 100mm from the tire's base.

The path distance, D , from the center of the camera lens to where the laser line strikes the tire is the hypotenuse of this spatial triangle and can be derived as follows.

$$D = \frac{Z}{\cos(\theta)} \quad (2.1)$$

where Z is 100mm and $\theta = 30^\circ$. Therefore $D = \frac{100}{\cos(30^\circ)} = \frac{100}{0.866} \approx 115.47\text{mm}$. This necessitates the focal point of the webcam be set to approximately 115.5mm with a depth of field range spanning from 115.5mm to 124.7mm.

By computing this exact range, it's possible to lock out the focus ring, thus completely removing the potential of blur from autofocus and also perfectly focusing and guaranteeing the system's aperture prior to scan.

2.5.8 Laser Triangulation Profilometry

The pipeline executes the following steps sequentially:

1. Image capture: captures a single calibrated image with the laser active.
2. Laser isolation: filters and thresholds the image to obtain only laser line pixels. More on this in Section 2.6.
3. Centroid extraction: Calculates the intensity-weighted average column (row in this case) of laser line pixels, or columncentroid. (See Equation 1.2)
4. Spike removal: Uses a rolling-median filter to remove spurious peaks from the row of centroid columns.
5. Profile computation: Converts the rows to actual heights, optionally accounting for tilt.
6. Output generation: Outputs binary mask, isolated image, overlay, skeleton, and profile chart.

2.6 Laser Isolation Sub-pipeline

This is the core processing step and has seen a lot of tuning during the calibration iterations. It employs a multi-gate approach.

1. HSV RedHue range check - (24,000-38,000 and 154,000-169,000. These are in units of 10^{-4}) These thresholds target the color of red light emitted by the laser module.
2. Brightness (Value) check - The intensity must be above a threshold that varies from low in areas not directly illuminated by the laser, up to quite bright at the core laserline itself. This must be done on the original R channel, not on the V channel, or the process is very sensitive to background illumination intensity.
3. Vertical crop into an ROI - The laser is relatively consistent vertically, so we don't need to process areas away from it. The ROI must be wide enough that the laser never crosses out of the bounding Box.
4. Opening (morphological operation) in vertical orientation (tall $\times$ narrow - roughly 10-15 pixels vertically, 1 pixel horizontally) – to remove small, scattered points or noise that is

not long vertically like a laserline.

5. Closing (morphological operation) in vertical orientation (short $\times$ wide - roughly 5-10 pixels horizontally, 1 pixel vertically) – to fill small breaks or gaps in the laserline or to connect what was thought to be disjoint laserline regions. The widths and heights must be balanced - or else gaps become wide horizontal strips.
6. Select largest connected component - To remove any spurious objects that may have crept into the image. There must be at least one other object other than an extremely wide, flat "blob."
7. Per-pixel height analysis of peak in the narrow direction, within the largest connected component - In other words for a given image pixel in the ROI (a specific column), the highest value along the laser line will give a reasonable measure of the true intensity maximum, and thus is likely to be the center of the laserline

2.7 Calibration Iterations

Several iterations of calibrating the system with this pipeline were made. Each step solved the particular failing mode encountered in the previous step, revealing yet more in its wake. The history is presented in chronologic Order:

2.7.1 Iteration 1 - Initial Implementation

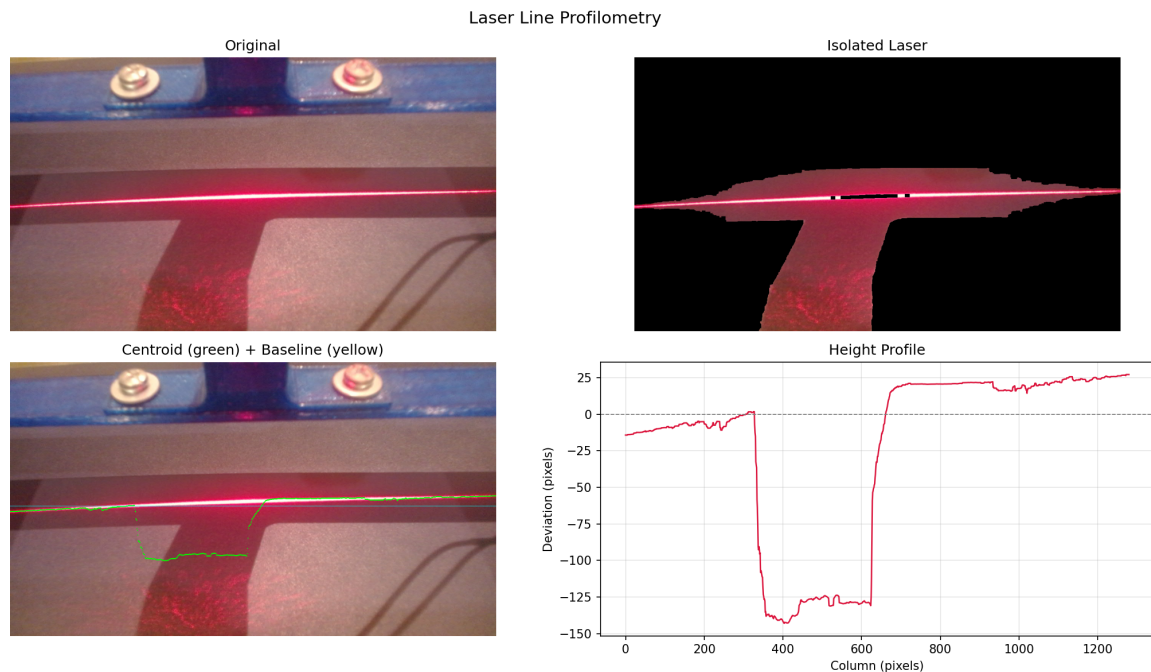


Fig. 5. Iteration 1 Processing test results

2.7.1.1 Failure:. The initial attempt at image isolation (Figure 5 left) produces a fairly amorphous red blob across much of the image - encompassing the laser core and also significant amounts of diffusely reflected laserline off of the black rubber surfaces. The resulting depth profile (5 right), as a result of the centroid calculation pulling on the diffuse scattering, reads as wildly out-of-bounds-exaggerated positive deviations are as much as 150px.

2.7.1.2 Diagnosis:. The developer selected a much too wide an area. The saturation threshold, was just way to wide, resulting in quite strong HSV components being accepted even for non direct reflections and diffuse reflection was accepted at up to 80 when applied to raw R channel data.

2.7.2 Iteration 2 — Brightness Gate and Larger Kernels

2.7.2.1 Changes. The laser core produces near-saturation red-channel intensities (typically 180–255 DN), while the diffuse glow falls in the range 60–150 DN. Raising the brightness threshold exploits this contrast. Increasing the square kernel size provides more aggressive noise removal.

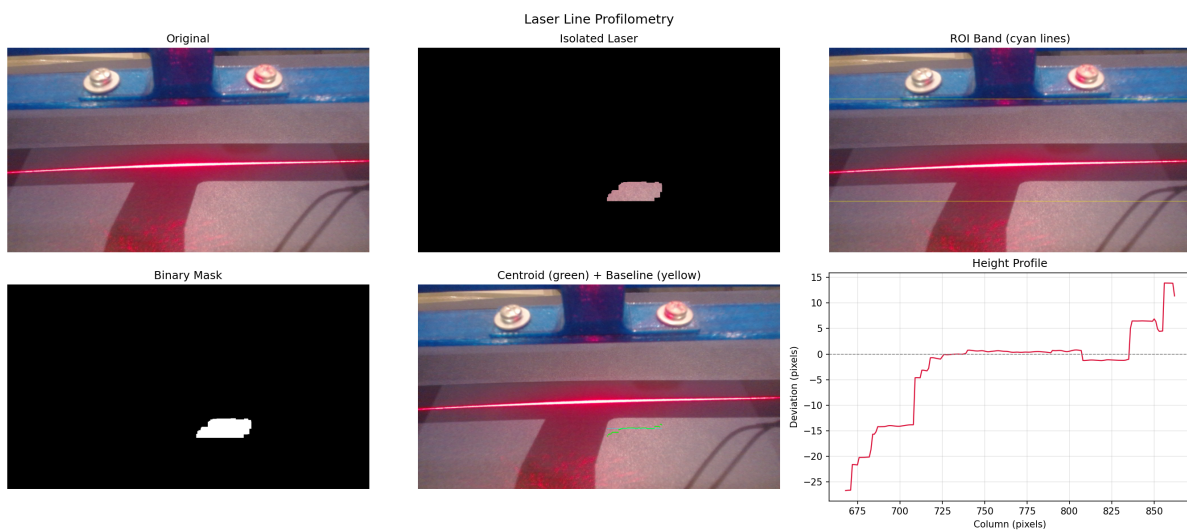


Fig. 6. Iteration 2 Processing test results

2.7.2.2 Observed Failure. The isolation became over-constrained. Only a small patch of pixels in the centre of the frame (columns 675–860) survived all gates; the rest of the laser line was rejected. The height profile covered fewer than 200 columns.

2.7.3 Iteration 3 — Rebalanced Thresholds and Band Thinning

2.7.3.1 Changes. The saturation gate was disabled (set to 255, effectively a no-op). The brightness threshold was relaxed to a moderate value. A new global band thinning step was introduced as a geometry-based glow suppressor: after morphological cleanup, the vertical

centre of mass of the entire surviving mask was computed, and all pixels beyond ± 6 rows of that global centre were zeroed.

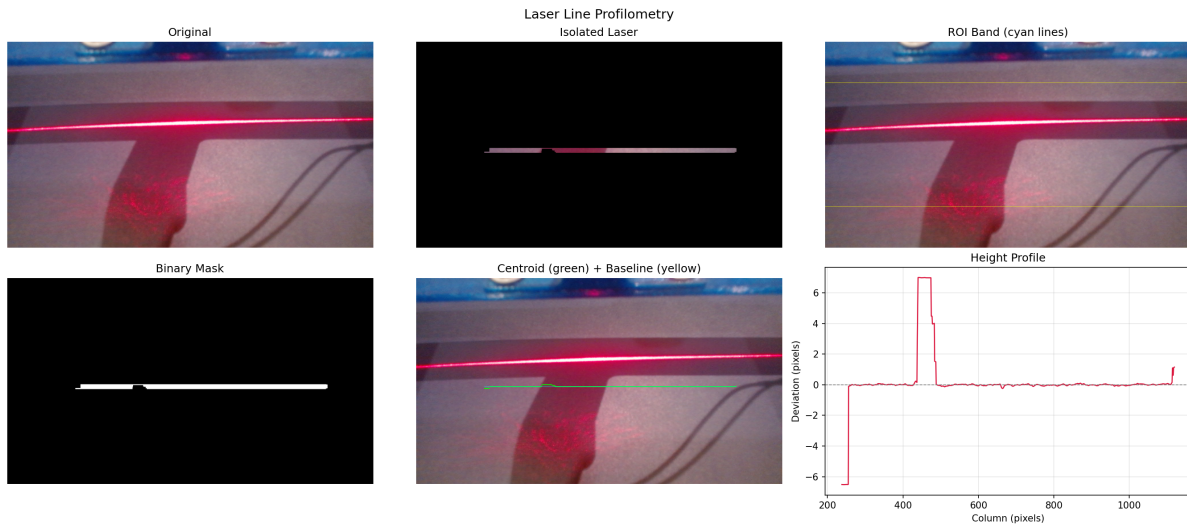


Fig. 7. Iteration 3 Processing test results

2.7.3.2 Observed Failure. The full laser line was detected across most columns, but the left portion of the frame (columns 0–200) showed a systematic upward bias of approximately 4 pixels in the height profile. Additionally, the right edge (columns > 900) was absent from the mask.

2.7.3.3 Diagnosis. The global band thinning assumed a uniform glow thickness across the frame. In practice, the glow was thicker on the left side (due to the proximity of the blue metal frame and bolt heads) than on the right. The global centre row was therefore pulled upward on the left, causing the thinning window to retain pixels from the top half of the glow blob rather than the laser core — producing the 4 px deviation.

2.7.4 Iteration 4 — Directional Morphological Kernels

2.7.4.1 Changes. This iteration introduced using directional structuring elements. The shape of the structuring element encodes prior knowledge about the object to be retained or removed:

- A tall, narrow kernel (9×1 px) applied in an opening removes objects taller than they are wide — i.e. vertical glow blobs. A horizontal laser line, being much wider than tall, is not erased by this operation because it extends continuously along the horizontal axis.
- A short, wide kernel (3×120 px) applied in a closing bridges horizontal gaps up to 120 pixels long without expanding the mask vertically (height constraint of 3 px).

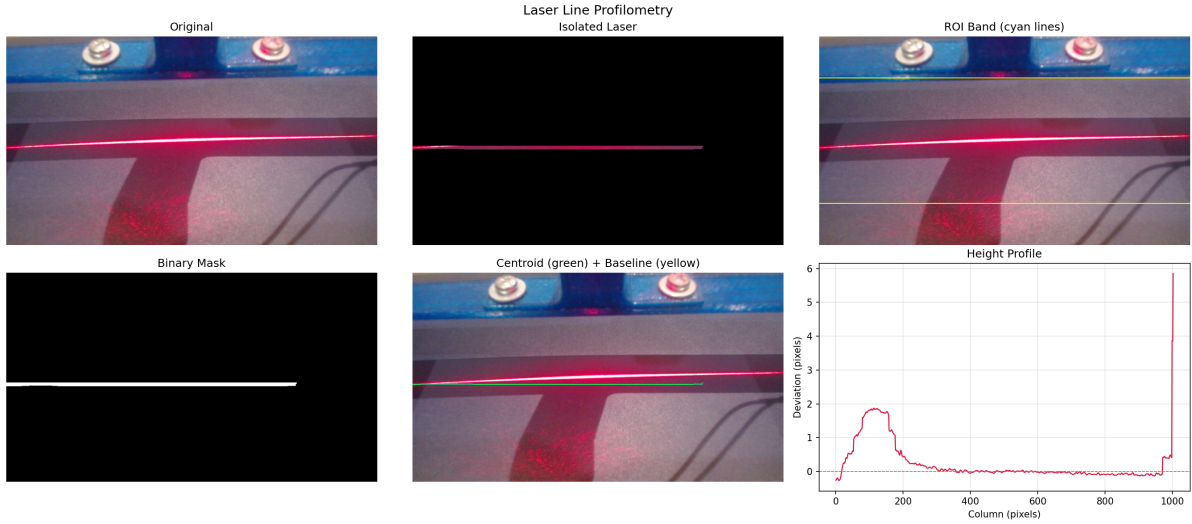


Fig. 8. Iteration 4 Processing test results

2.7.4.2 Observed Failure. The right-side gap persisted (the closing kernel width of 120 px was still insufficient to bridge the right-edge gap). The left-side deviation remained because the global band thinning issue was not yet resolved.

2.7.5 Iteration 5 — Wider Close Kernel and Spike Removal

2.7.5.1 Changes. The close kernel width was increased to 150 px to bridge the larger right-edge gap. A rolling-median spike filter was added as a post-processing step to remove isolated centroid outliers caused by reflections from the mounting bolts at the frame edges.

2.7.5.2 Spike Removal Algorithm. For each centroid value $r_{\text{centroid}}[i]$, a local median is computed over a symmetric window of 51 neighbouring columns:

$$\tilde{r}[i] = \text{median}(r_{\text{centroid}}[i - 25], \dots, r_{\text{centroid}}[i + 25]) \quad (2.2)$$

If $|r_{\text{centroid}}[i] - \tilde{r}[i]| > \tau_{\text{spike}}$, the value is replaced by $\tilde{r}[i]$. The threshold $\tau_{\text{spike}} = 2.5$ px was empirically selected.

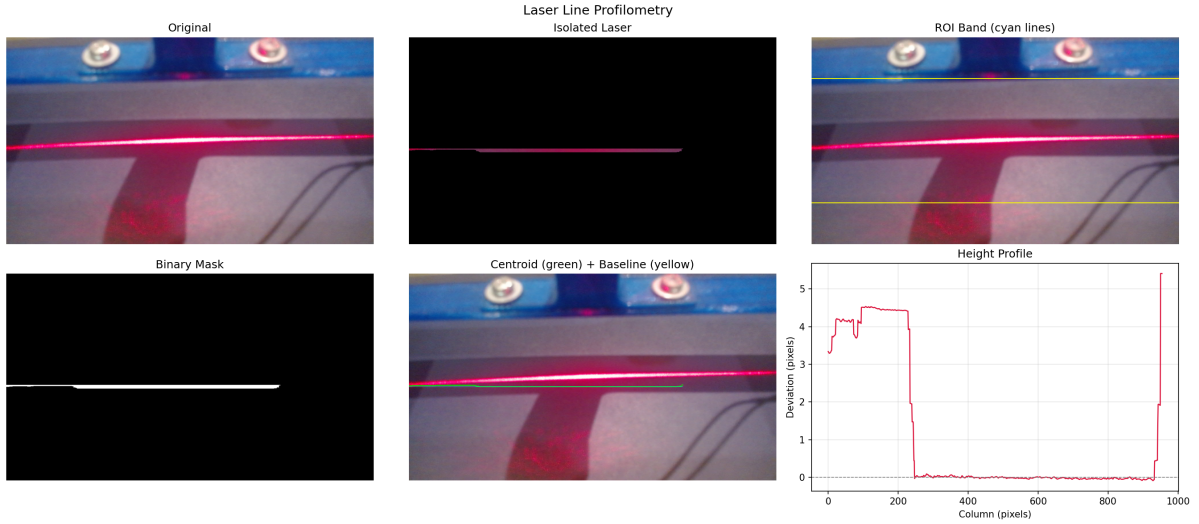


Fig. 9. Iteration 5 Processing test results

2.7.5.3 Observed Failure. The right edge and spike artefact were partially improved but the systematic left-side 4 px bias persisted. The root cause was confirmed to be the global band thinning.

2.7.6 Iteration 6 — Per-Column Local-Peak Band Thinning (Key Fix)

2.7.6.1 Changes. This iteration replaced global band thinning with per-column local-peak band thinning. Rather than finding a single centre row for the entire image and applying a uniform band, each image column independently identifies its own brightest masked pixel (the laser core peak) and retains only pixels within ± 6 rows of that column-specific peak.

$$r_{\text{peak}}[c] = \arg \max_{r: m(r,c)=1} I(r, c) \quad (2.3)$$

$$m'(r, c) = \begin{cases} m(r, c) & \text{if } |r - r_{\text{peak}}[c]| \leq d_{\text{band}} \\ 0 & \text{otherwise} \end{cases} \quad (2.4)$$

where $d_{\text{band}} = 6$ px is the half-height of the thinning band. This approach is robust to spatially non-uniform glow: each column self-corrects to its local laser core regardless of how much surrounding scatter is present in adjacent columns.

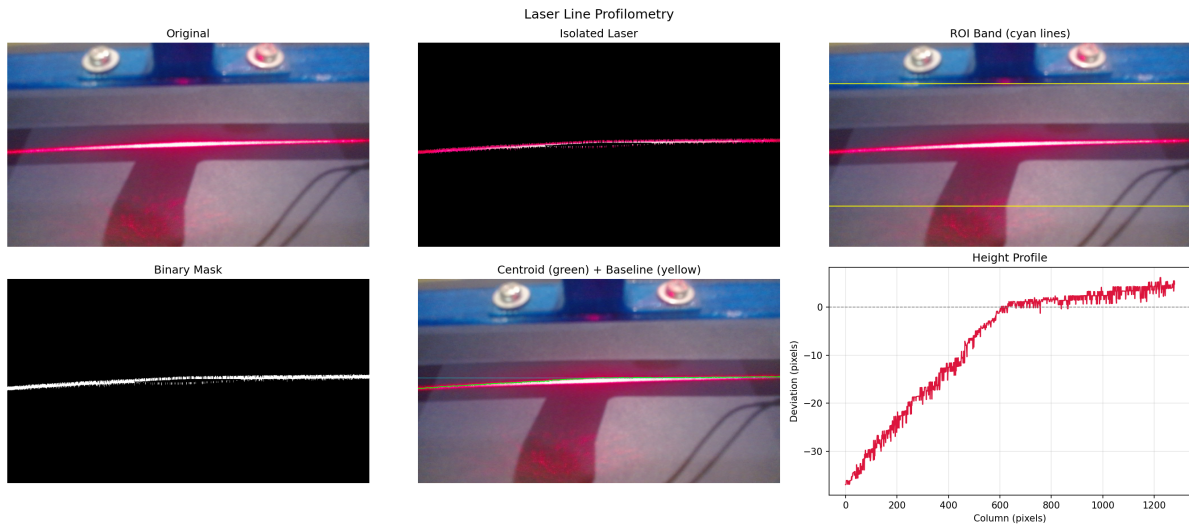


Fig. 10. Iteration 6 Processing test results

2.8 Advanced Profilometry Iterations: Tire Curvature Removal and Profile Stabilisation

Once the laser line isolation pipeline produced a clean, full-width centroid signal, two further software iterations were developed to address the physical characteristics of a tire tread scan.

2.8.1 Iteration 7 — Polynomial Tire Curvature Removal

When the laser line profilometry system was applied to a real tire tread, the raw height profile exhibited a large curved baseline spanning approximately 50 pixels from edge to edge of the image. The tire is a cylindrical body, and its surface curves away from the camera plane at the lateral edges of the scan. In image coordinates, this means the centroid row drifts smoothly across the frame even on a perfectly uniform tread surface.

Without removing this background curvature, the tread depth profile cannot be interpreted quantitatively. The apparent depth of a groove depends on its horizontal position in the image, because the curved baseline adds a position-dependent offset to every reading.

2.8.1.1 Upper-Envelope Polynomial Fitting. The background was estimated by fitting a polynomial to the upper envelope of the centroid data — the land areas between grooves. A simple polynomial fit to all centroid values would be biased downward by the groove regions, which displace the line significantly below the surface level. An iterative sigma-clipping approach was therefore used to converge the fit onto the land surface only, progressively excluding groove valleys.

The algorithm operates as follows:

1. The centroid data is pre-smoothed using a uniform moving average of window width $w_{\text{pre}} = 151$ columns. This collapses groove dips toward the land level, providing a less-biased starting signal for the polynomial fit.
2. A polynomial of degree n is fitted to the pre-smoothed data using all available columns.
3. Residuals are computed between each smoothed centroid and the fitted polynomial. A tolerance τ is set as a fraction of the residual standard deviation σ :

$$\tau_k = \sigma_k \cdot \max(0.8, 1.8 - 0.2k) \quad (2.5)$$

where k is the iteration index. The tolerance tightens with each iteration, progressively excluding groove pixels.

4. Only columns with residuals $\leq \tau_k$ (at or above the fitted surface, i.e. land areas) are retained for the next fit.
5. Steps 2–4 are repeated for N_{iter} iterations. The polynomial converges to the tire surface shape, unbiased by the groove valleys.

2.8.1.2 Configuration and Results. After empirical evaluation, the following parameters were selected:

TABLE 6
Polynomial background removal parameters (Iteration 7).

Parameter	Value	Rationale
Polynomial degree n	3	Cubic captures asymmetric tire curvature
Fit iterations N_{iter}	10	Sufficient convergence to land surface
Pre-smoothing window w_{pre}	151 cols	Wide enough to span the widest groove

Application of this stage to the tire scan reduced the background curvature from approximately 50 pixels peak-to-peak to a residual within ± 5 pixels on the land areas, clearly resolving four distinct tread grooves in the corrected profile. The grooves appeared as sharp negative deflections of approximately 26 pixels at their deepest points, superimposed on a near-zero baseline.

2.8.2 Iteration 8 — Profile Stabilisation via Savitzky-Golay Smoothing

Following polynomial background removal, the land areas of the tread profile exhibited residual oscillations of approximately $\pm 3\text{--}5$ pixels. These fluctuations arise from two sources: high-frequency shot noise in the camera sensor, and micro-texture of the tire rubber, which causes sub-millimetre surface variation. In either case, the land areas should ideally read at or near zero after background subtraction. The residual noise obscured the sharpness of the land-to-groove transitions and reduced the interpretability of the profile for quantitative analysis.

A post-processing smoothing stage was added to suppress this high-frequency noise while preserving the sharp edges at the groove walls — the latter being essential for accurate groove width and depth measurement.

2.8.2.1 Savitzky-Golay Filter. A simple Gaussian filter was rejected because both operations blur step discontinuities. The Savitzky-Golay (SG) filter was selected instead, as it is specifically designed to smooth noise while preserving the shape of sharp features.

The SG filter fits a polynomial of degree p to a sliding window of w_{SG} samples using least-squares, and replaces each central sample with the value of the fitted polynomial at that position. For a sequence $y[i]$, the filtered output is:

$$\hat{y}[i] = \sum_{j=-m}^m h_j \cdot y[i+j], \quad m = \frac{w_{\text{SG}} - 1}{2} \quad (2.6)$$

where the coefficients h_j are the least-squares weights for a degree- p polynomial fit over a window of w_{SG} points.

For the tread depth profile, the SG filter acts as a low-pass filter with a passband that retains groove-width-scale features ($> 30\text{--}50$ columns) while attenuating pixel-scale jitter (< 10 columns). The groove edges, which are spatially abrupt but span tens of columns, fall within the passband and are preserved.

2.8.2.2 Two-Stage Smoothing Architecture. In the final pipeline, smoothing is applied at two distinct stages, each targeting a different source of error:

Stage 1 — Pre-fit smoothing (window $w_{\text{pre}} = 151$): Applied to the centroid data before background polynomial fitting. Purpose: collapse groove dips toward the land level so the polynomial fits the tire surface without being pulled down by groove valleys. This is a uniform moving average, not SG, because only the overall shape matters here — not edge sharpness.

Stage 2 — Post-removal smoothing (SG, window $w_{\text{SG}} = 31$): Applied to the tread depth deviation profile after background subtraction. Purpose: suppress column-to-column centroid noise on the final measurement output while preserving groove wall sharpness.

TABLE 7
Savitzky-Golay smoothing parameters (Iteration 8).

Parameter	Value	Rationale
SG window w_{SG}	31 columns	Smooths pixel noise; preserves groove edges
SG polynomial order p	2	Parabolic fit; good noise rejection

2.8.2.3 Configuration and Results. After applying the SG filter, land areas stabilised to within approximately ± 1 –2 pixels of zero, compared to ± 3 –5 pixels before smoothing. The groove walls remained sharp and the deepest groove reading was not significantly altered.

The pipeline outputs both the raw (pre-SG) and smoothed profiles simultaneously to allow visual inspection of the filtering effect and to confirm that no genuine surface features are being suppressed.

2.9 Pixel-to-Millimetre Calibration

2.9.1 Calibration Principle

The profilometry pipeline produces tread depth values in units of image pixels. To convert these to physical millimetres, a scale factor k (pixels per millimetre) must be determined experimentally. This factor encodes the combined geometric relationship between the laser triangulation angle, the camera focal length, and the working distance from the lens to the measurement plane.

The scale factor is defined as:

$$k = \frac{\Delta r_{\text{px}}}{\Delta z_{\text{mm}}} \quad [\text{px/mm}] \quad (2.7)$$

where Δr_{px} is the vertical displacement of the laser centroid in pixels corresponding to a known physical height change Δz_{mm} at the measurement plane. Once k is known, any pixel depth reading is converted by:

$$d_{\text{mm}} = \frac{d_{\text{px}}}{k} \quad (2.8)$$

2.9.2 Calibration Methodology

The calibration procedure adopted in this work used the tire tread itself as the reference object, with independent measurement provided by a digital vernier calliper. This approach was chosen because it calibrates the system at the exact measurement plane and under the same optical and laser conditions as all subsequent measurements, avoiding any distance-related error that would arise from calibrating at a different height.

The procedure was as follows:

1. **Manual depth measurement.** A digital vernier calliper was used to measure the tread groove depth at multiple locations around the tire circumference. This provided an independent physical reference value Δz_{mm} . The mean measured tread depth was approximately $\Delta z_{\text{cal}} \approx 4.7 \text{ mm}$.
2. **Optical depth measurement.** The profilometry pipeline was executed on the tire. The maximum negative deflection in the smoothed tread depth profile — corresponding to the deepest groove — was read directly from the output chart. The measured optical depth was $\Delta r_{\text{px}} \approx 26 \text{ pixels}$.
3. **Scale factor calculation.** Applying Equation 2.7:

$$k = \frac{26 \text{ px}}{4.7 \text{ mm}} \approx 5.53 \text{ px/mm} \quad (2.9)$$

4. **CFG entry.** The computed value was entered into the pipeline configuration:

"pixels_per_mm": 5.53

All subsequent profile values are divided by this factor automatically, producing output in millimetres.

The legal minimum tread depth in most jurisdictions is 1.6 mm. At the calibrated scale of $k = 5.53 \text{ px/mm}$, this corresponds to:

$$d_{\text{min}} = 1.6 \text{ mm} \times 5.53 \frac{\text{px}}{\text{mm}} = 8.85 \text{ px} \quad (2.10)$$

This means that the absolute minimum value of pixels measured must be at least 8.85 px for the tire to be considered safe.

2.9.3 Web-Based User Interface and System Integration

To ensure the mechatronic prototype operates as a fully autonomous diagnostic tool, a custom web-based Graphical User Interface (GUI) was developed. The backend control server is configured as a background service that executes automatically upon the microcomputer's boot sequence.

The interface operates via a localized web server, allowing any device, such as a tablet, smartphone, or desktop computer (connected to the same local network) to access the control dashboard via a standard web browser. The communication between the web client and the hardware control scripts is done entirely through structured JSON payloads. This data interchange format ensures that motor actuation commands, camera initialization, and processed profilometry results are transmitted with no losses.

The GUI was structured to provide an intuitive operator experience with 2 functions:

- The module allows the operator to initiate an automated 100 mm profilometry sweep and save the results in a scan summary parsed from the real-time JSON outputs and displayed dynamically to the user.
- A registry of past scans to parse previously saved JSON result files. This allows the user to review past tire measurements, examine the extracted sub-pixel depths at specific mm intervals, and verify historical safety logs.

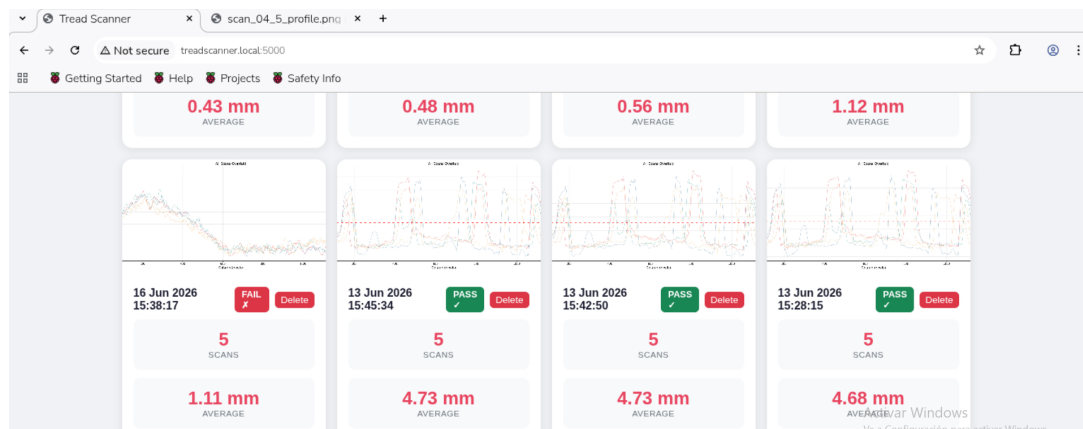


Fig. 11. Screenshot of the custom web-based Graphical User Interface,

Figure 12 denotes the logic sequence utilized to map out the results discussed in the next section.

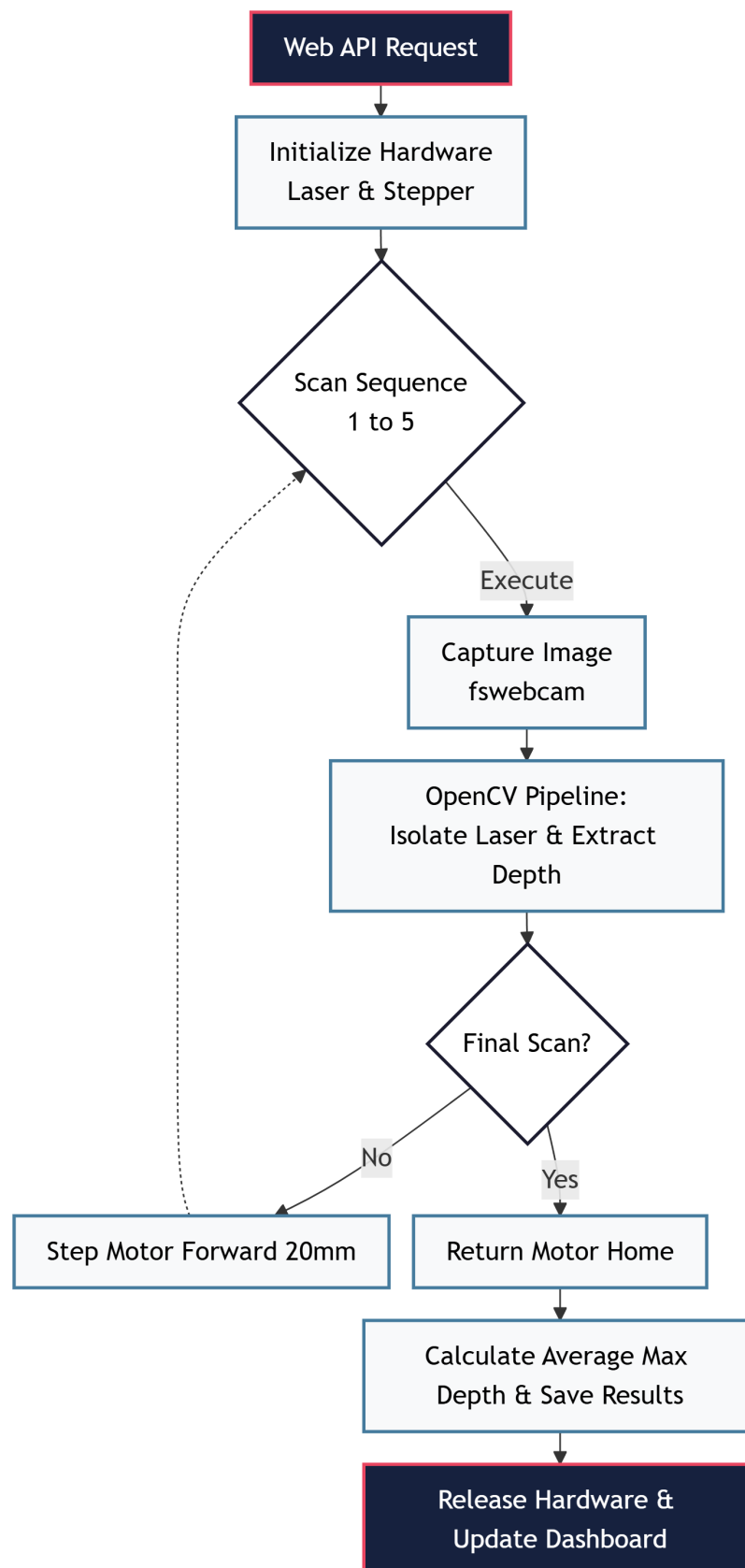


Fig. 12. Logic level Flowchart

Chapter 3

Results & Discussion

3.1 Results Acquisition

To validate the precision and repeatability of the mechatronic prototype, five independent measurement sweeps (sessions) were executed on 4 different tire sectors (0° , 90° , 180° , 270°) for 2 different tires. Tire 1 was an R17-225 tire, while Tire 2 was an R16-185 tire. During each session, the carriage autonomously halted at 25.0 mm intervals to extract the sub-millimeter profilometry. All depth values are recorded in millimeters (mm) as negative deviations from the median tread baseline.



Fig. 13. Tire 1: R17-225 tire



Fig. 14. Tire 2: R16-185 tire

3.1.1 Tire 1 Profilometry Results: 0° Sector Repeatability

TABLE 8
Repeatability analysis of automated optical scans for Tire 1 Sector 1 (0°)

Session ID	Pos 0 mm	Pos 25 mm	Pos 50 mm	Pos 75 mm	Pos 100 mm	Session Avg
115044	-4.958	-5.261	-4.953	-4.632	-4.303	-4.821
115421	-5.021	-5.062	-4.768	-4.637	-4.181	-4.734
124150	-4.927	-5.094	-4.862	-4.614	-4.271	-4.754
132421	-4.974	-4.890	-4.342	-4.903	-4.246	-4.671
132707	-4.933	-4.846	-4.356	-4.892	-4.252	-4.656
Overall 0° Sector Average Depth: -4.727 mm						

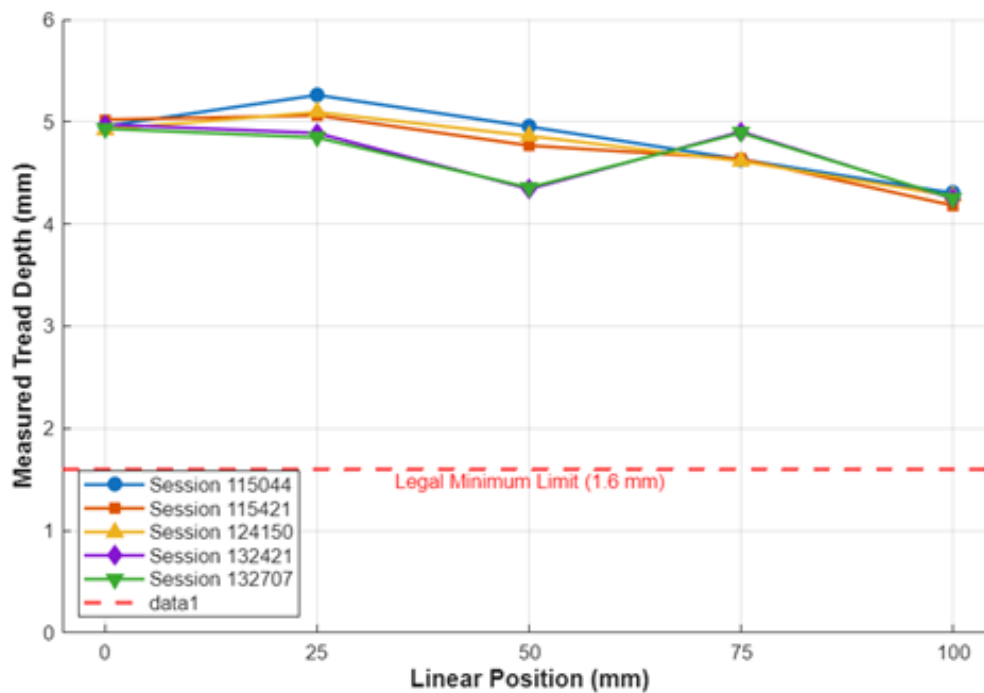


Fig. 15. Sector 0 Results Line Graph

3.1.2 Tire 1 Profilometry Results: 90° Sector Repeatability

TABLE 9
Repeatability analysis of automated optical scans for Tire 1 Sector 2 (90°)

Session ID	Pos 0 mm	Pos 25 mm	Pos 50 mm	Pos 75 mm	Pos 100 mm	Session Avg
133627	-5.254	-5.214	-5.470	-4.643	-4.818	-5.080
133917	-5.147	-5.280	-5.493	-4.496	-4.813	-5.046
134341	-5.169	-5.175	-5.499	-4.506	-4.749	-5.020
134623	-5.243	-5.237	-5.520	-4.565	-4.742	-5.061
135015	-5.098	-5.149	-5.531	-4.638	-4.842	-5.052
Overall 90° Sector Average Depth: -5.052 mm Status: SAFE						

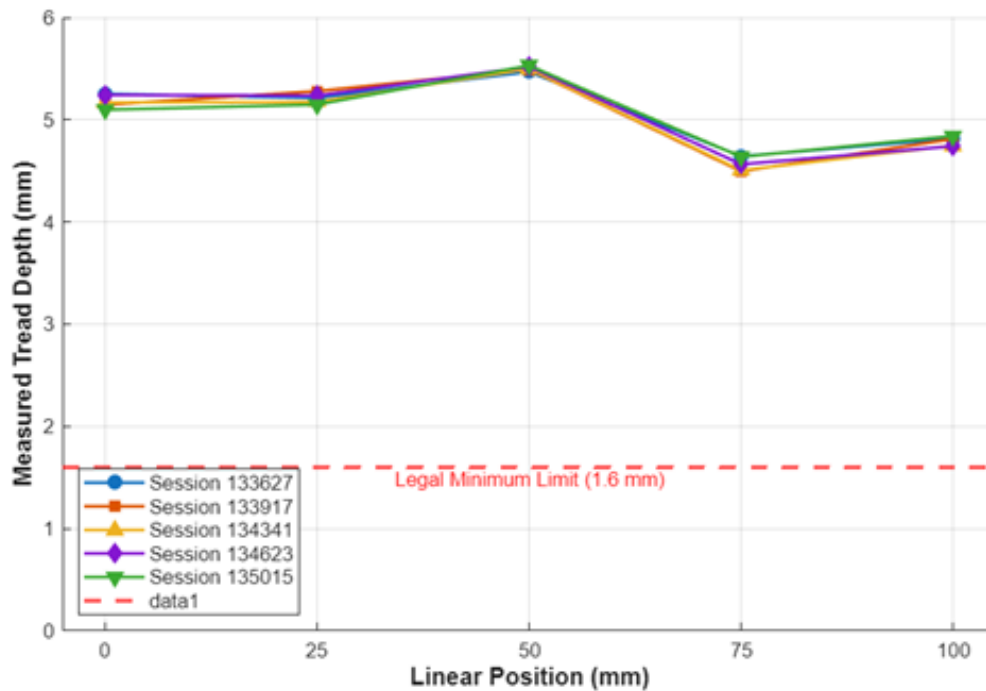


Fig. 16. Sector 90 Results Line Graph

3.1.3 Tire 1 Profilometry Results: 180° Sector Repeatability

TABLE 10
Repeatability analysis of automated optical scans for Tire 1 Sector 3 (180°)

Session ID	Pos 0 mm	Pos 25 mm	Pos 50 mm	Pos 75 mm	Pos 100 mm	Session Avg
142702	-5.307	-5.179	-4.796	-4.853	-5.163	-5.060
143031	-5.017	-5.245	-5.161	-4.671	-4.660	-4.951
143314	-5.105	-5.381	-4.987	-4.509	-4.529	-4.902
143558	-5.160	-5.100	-5.085	-4.591	-4.690	-4.925
143920	-5.204	-5.055	-5.020	-4.414	-4.591	-4.857
Overall 180° Sector Average Depth: -4.939 mm Status: SAFE						

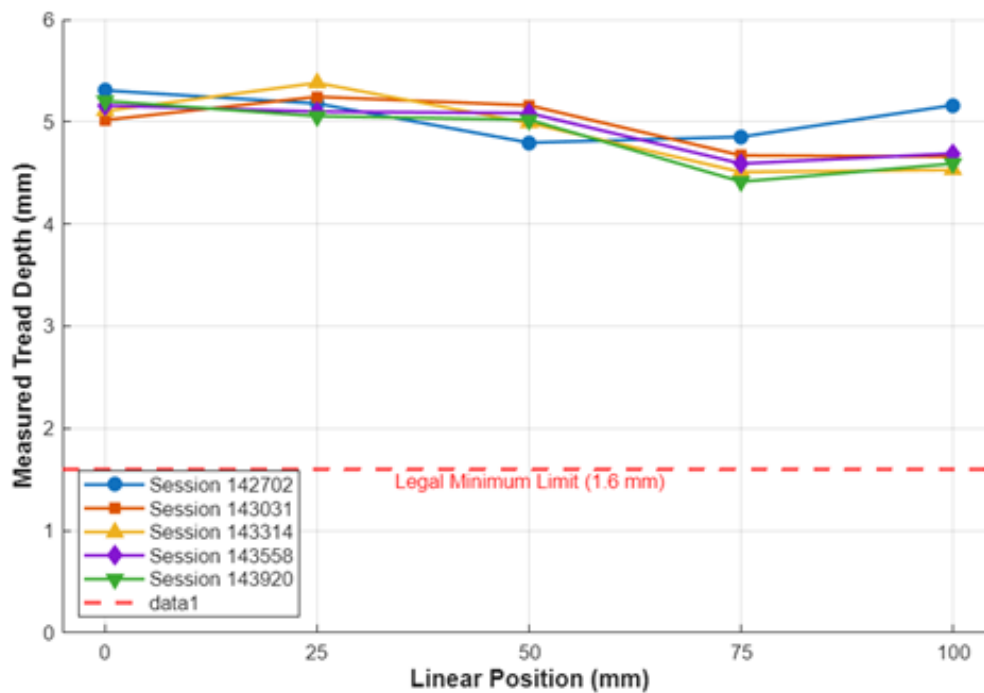


Fig. 17. Sector 180 Results Line Graph

3.1.4 Tire 1 Profilometry Results: 270° Sector Repeatability

TABLE 11
Repeatability analysis of automated optical scans for Tire 1 Sector 4 (270°)

Session ID	Pos 0 mm	Pos 25 mm	Pos 50 mm	Pos 75 mm	Pos 100 mm	Session Avg
152230	-5.449	-4.838	-4.840	-4.094	-4.200	-4.684
152516	-5.249	-5.016	-4.726	-4.037	-4.214	-4.648
152815	-5.267	-4.906	-4.807	-4.052	-4.392	-4.685
154250	-5.418	-5.031	-4.783	-4.171	-4.248	-4.730
154534	-5.452	-4.994	-4.728	-4.159	-4.298	-4.726
Overall 270° Sector Average Depth: -4.695 mm Status: SAFE						

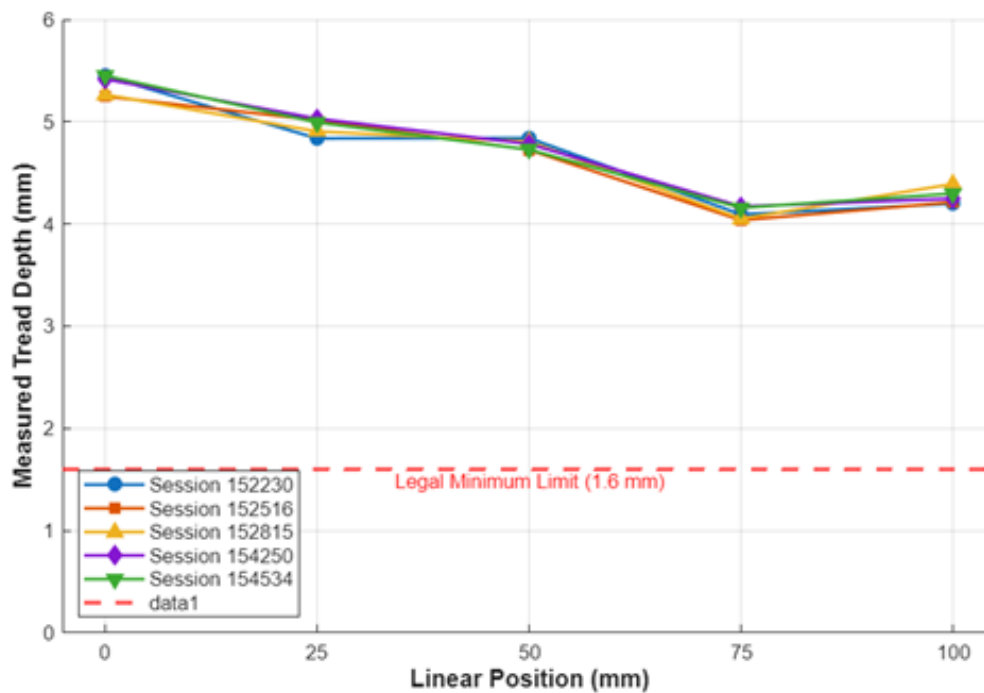


Fig. 18. Sector 270 Results Line Graph

3.1.5 Tire 2 Profilometry Results: 0° Sector Repeatability

TABLE 12

Repeatability analysis of automated optical scans for Tire 2 Sector 1 (0°)

Session ID	Pos 0 mm	Pos 25 mm	Pos 50 mm	Pos 75 mm	Pos 100 mm	Session Avg
094453	-3.741	-3.748	-3.802	-3.780	-3.847	-3.784
094953	-3.778	-2.503	-5.782	-1.914	-2.643	-3.324
095408	-3.890	-2.314	-5.716	-1.917	-2.008	-3.169
Overall 0° Sector Average Depth: -3.426 mm Status: SAFE						

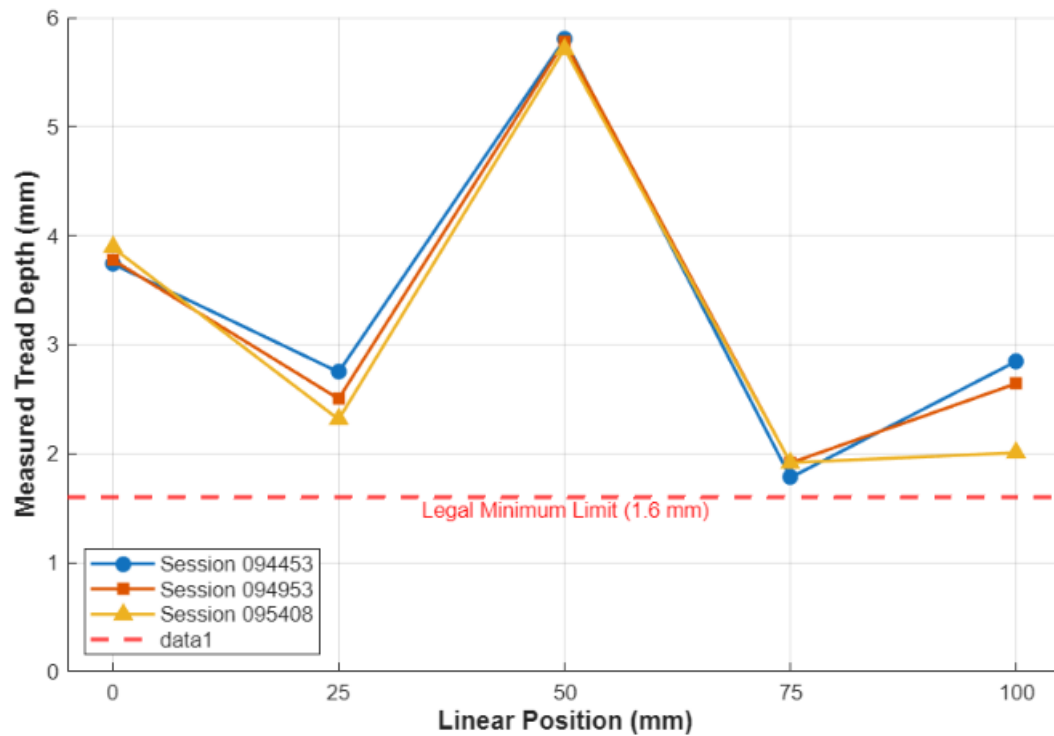


Fig. 19. Sector 0 Results Line Graph

3.1.6 Tire 2 Profilometry Results: 90° Sector Repeatability

TABLE 13

Repeatability analysis of automated optical scans for Tire 2 Sector 2 (90°)

Session ID	Pos 0 mm	Pos 25 mm	Pos 50 mm	Pos 75 mm	Pos 100 mm	Session Avg
100303	-4.487	-5.468	-2.959	-1.368	-3.071	-3.471
100712	-4.313	-5.383	-2.706	-1.403	-2.981	-3.357
101057	-4.572	-5.533	-2.764	-1.443	-3.592	-3.581
Overall 90° Sector Average Depth: -3.470 mm Status: SAFE						

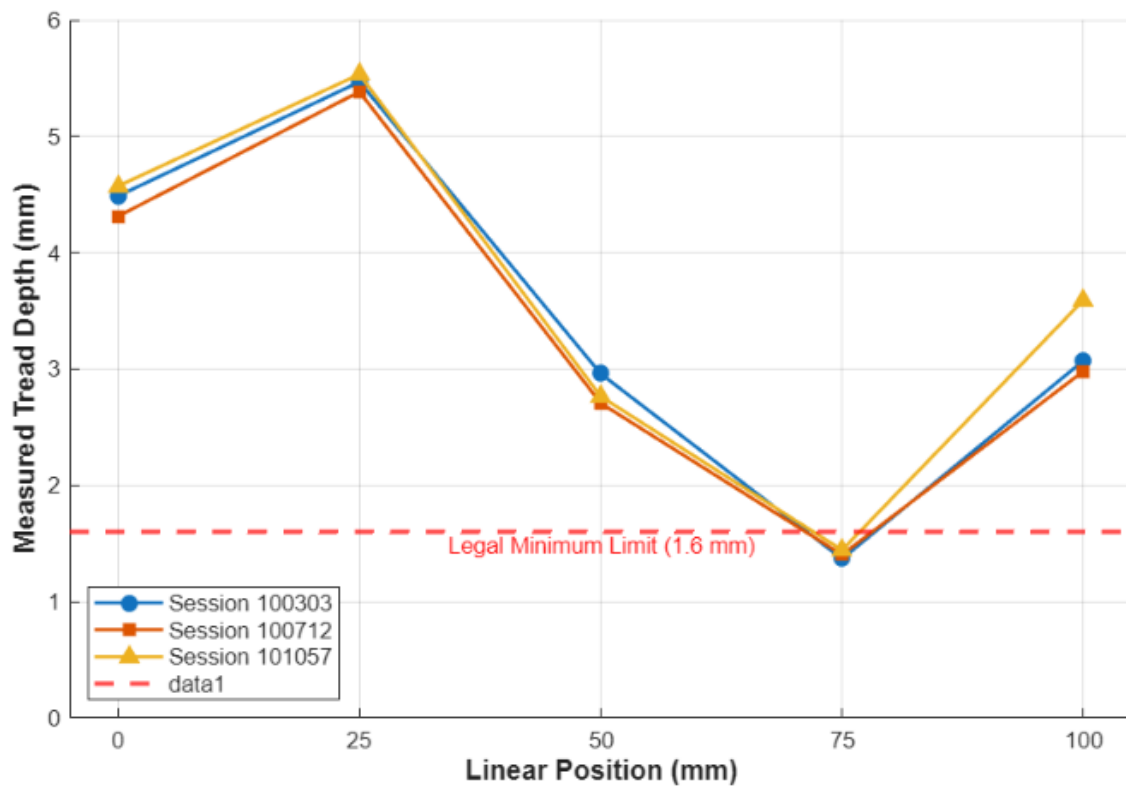


Fig. 20. Sector 90 Results Line Graph

3.1.7 Tire 2 Profilometry Results: 180° Sector Repeatability

TABLE 14

Repeatability analysis of automated optical scans for Tire 2 Sector 3 (180°)

Session ID	Pos 0 mm	Pos 25 mm	Pos 50 mm	Pos 75 mm	Pos 100 mm	Session Avg
152924	-3.928	-4.959	-1.656	-3.022	-5.636	-3.840
153207	-3.776	-4.720	-1.797	-3.038	-5.328	-3.732
153651	-3.834	-4.790	-1.611	-2.848	-4.979	-3.612
Overall 180° Sector Average Depth: -3.728 mm Status: SAFE						

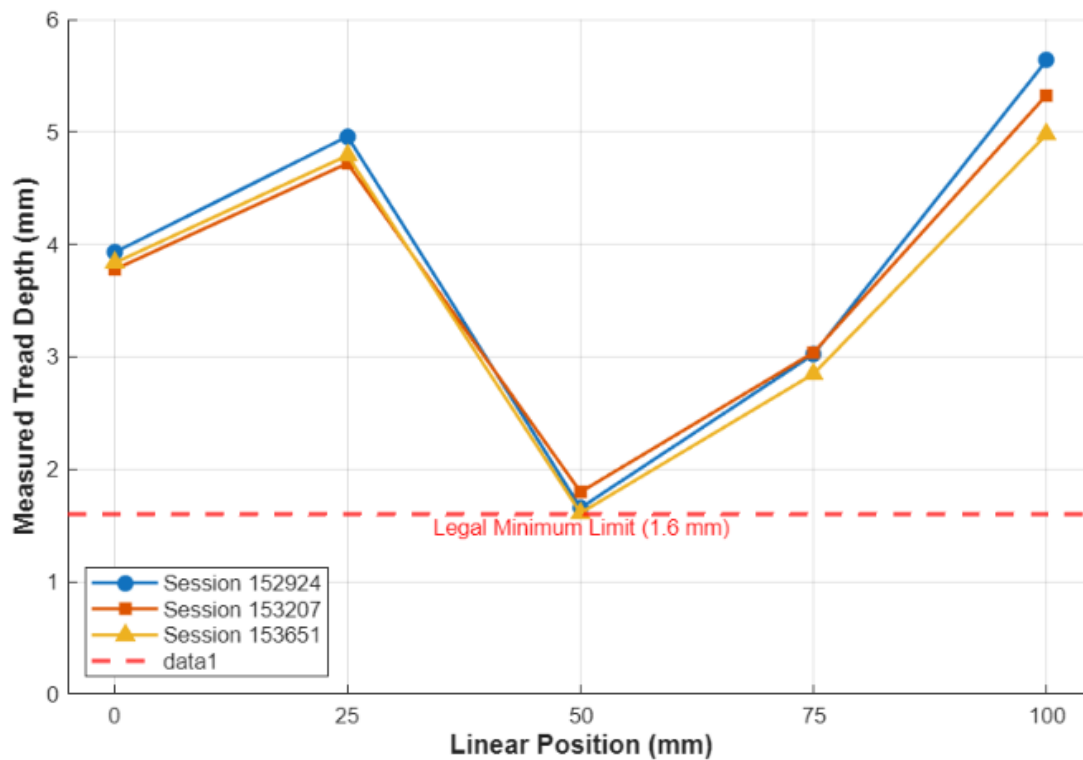


Fig. 21. Sector 180 Results Line Graph

3.1.8 Tire 2 Profilometry Results: 270° Sector Repeatability

TABLE 15

Repeatability analysis of automated optical scans for Tire 2 Sector 4 (270°)

Session ID	Pos 0 mm	Pos 25 mm	Pos 50 mm	Pos 75 mm	Pos 100 mm	Session Avg
154902	-3.190	-3.444	-2.183	-5.425	-2.859	-3.420
155151	-3.216	-4.546	-2.214	-5.391	-2.725	-3.618
155541	-2.607	-4.287	-2.288	-5.090	-2.695	-3.393
Overall 270° Sector Average Depth: -3.477 mm Status: SAFE						

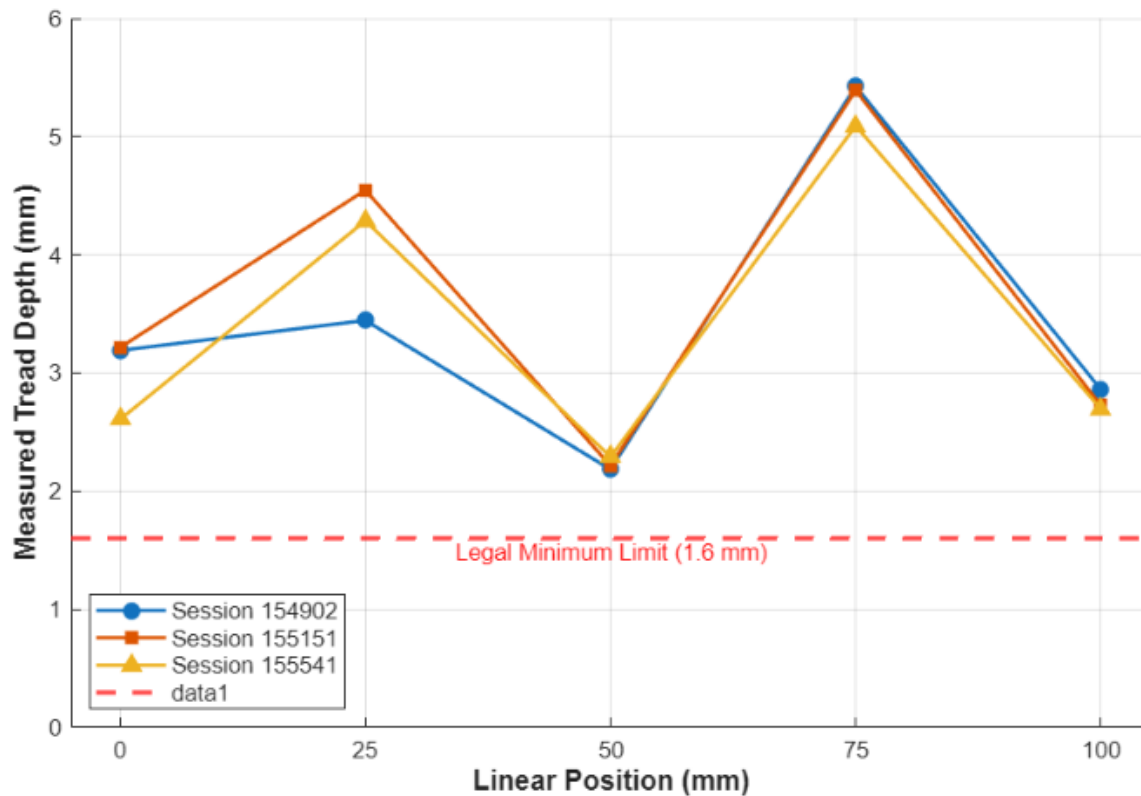


Fig. 22. Sector 270 Results Line Graph

3.1.8.1 Failure State Verification. To validate the software's conditional logic and the optical pipeline's sensitivity at extremely low depth values, a control test was conducted using a flat reference surface. The objective of this test was to verify that the OpenCV centroid extraction can accurately measure micro-deviations below the 1.6 mm legal threshold.

The mechatronic prototype executed three independent scanning sessions across the

flat reference plane. Table 16 shows the extracted profilometry data.

TABLE 16
Optical profilometry results on a flat reference surface.

Session ID	Pos 0 mm	Pos 25 mm	Pos 50 mm	Pos 75 mm	Pos 100 mm	Session Avg
155512	-0.646	-0.661	-0.478	-0.358	-0.667	-0.562
155843	-0.334	-0.467	-0.433	-0.512	-0.636	-0.476
160209	-0.440	-0.480	-0.381	-0.468	-0.364	-0.427
Reference Average: -0.488 mm						

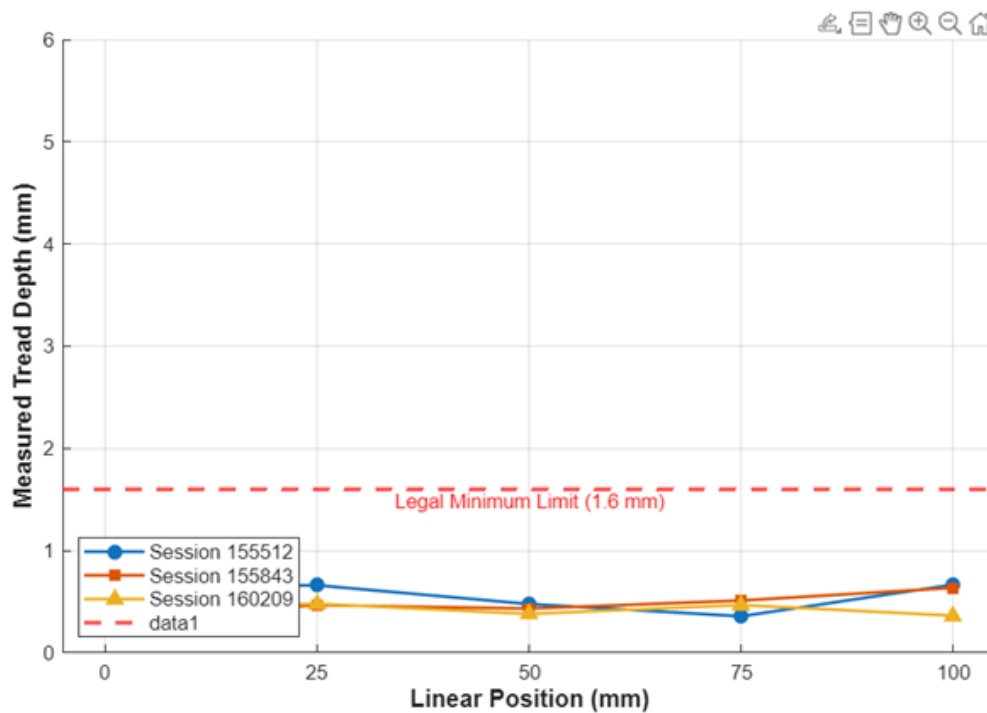


Fig. 23. Flat Surface Line Graph

The data successfully proves the robustness of the software pipeline. Over the 15 total measurement points, the system recorded an overall average depth of -0.488 mm. These sub-millimeter values represent the texture of the reference material and the sensitivity of the centroid extraction.

The system also classified these bad reading into the FAIL section, confirming that the prototype is capable of identifying not only legal tires, but also worn tires, fulfilling the safety

requirements dictated by the NTE INEN 2204:20213 and UNECE R30 standard.

3.1.9 Tire 1 Precision and Repeatability Error

Table 17 evaluates the precision of the prototype, the variance was calculated by extracting the mean, maximum spread between variables, and the standard deviation for each of the 4 sectors, and evaluating the mechanical repeatability of Tire 1.

TABLE 17
Error and variance analysis

Tire Sector	Sector Mean (μ)	Min / Max Avg	Max Spread (Error)	Std. Deviation (σ)
Sector 1 (0°)	-4.727 mm	-4.821 / -4.656 mm	0.165 mm	≈ 0.061 mm
Sector 2 (90°)	-5.052 mm	-5.080 / -5.020 mm	0.060 mm	≈ 0.020 mm
Sector 3 (180°)	-4.939 mm	-5.060 / -4.857 mm	0.203 mm	≈ 0.069 mm
Sector 4 (270°)	-4.695 mm	-4.730 / -4.648 mm	0.082 mm	≈ 0.031 mm
Global Prototype Precision (Mean σ): ± 0.045 mm				

The data presents a high level of accuracy. the standard deviation across all scanning sectors is of 0.045 mm, with the maximum spread between data never exceeding 0.203 mm at any given point.

3.1.10 Tire 2 Validation: Error and Variance Analysis

TABLE 18
Absolute Error and Data Variance Analysis for Tire 2 Profilometry

Sector	Real Max Depth	Absolute Error (ϵ)	Relative Error (%)	Sector Variance (σ^2)
Sector 1 (0°)	5.60 mm	0.182 mm	3.25%	1.65 mm ²
Sector 2 (90°)	4.93 mm	0.603 mm	12.23%	2.01 mm ²
Sector 3 (180°)	5.58 mm	0.056 mm	1.00%	1.85 mm ²
Sector 4 (270°)	5.30 mm	0.125 mm	2.36%	1.26 mm ²

Note: The exceptionally high variance ($\sigma^2 > 1.0$) across all sectors mathematically correlates to the severe non-uniformity and misalignment present in Tire 2.

3.1.11 Tire 1 Manual Verification and Comparison

To have a manual baseline for data comparison between automated results and traditional methods, measurements were taken using a standard digital caliper.

TABLE 19
Comparison analysis of automated prototype versus manual measurements

Tire Sector	Automated (mm)	Manual (mm)	Absolute Diff. (mm)	Percentage Error (%)
Sector 1 (0°)	4.727	4.70	0.027	0.57%
Sector 2 (90°)	5.052	4.90	0.152	3.10%
Sector 3 (180°)	4.939	4.80	0.139	2.90%
Sector 4 (270°)	4.695	4.60	0.095	2.07%
Average System Error: ± 0.103 mm Mean Percentage Error: 2.16%				

The maximum deviation is of 0.152 mm with a percentage error of 3.1%, with the overall percentage error being 2.16%, demonstrating a prototype that can accurately measure a tire tread with minimal deviations from traditional manual methods, higher repeatability, and database capabilities.

3.1.12 Tire 2 Manual Verification and comparison

TABLE 20
Comparison of System Measured Depths vs. Manual Reference Values (Tire 2 - Non-Uniform Wear)

Sector	Manual Max	System Max	Manual Min	System Min
Sector 1 (0°)	5.60 mm	5.782 mm	0.71 mm	1.914 mm
Sector 2 (90°)	4.93 mm	5.533 mm	0.71 mm	1.368 mm
Sector 3 (180°)	5.58 mm	5.636 mm	0.71 mm	1.611 mm
Sector 4 (270°)	5.30 mm	5.425 mm	0.71 mm	2.183 mm
<i>Note: The manual gauge detected a bald spot (0.71 mm) consistent across the inner circumference. The system's 25 mm measurement steps failed to capture the exact bald spot, highlighting a limitation of scanning on non-uniform tread wear.</i>				



(a) 0° Sector



(b) 90° Sector



(c) 180° Sector



(d) 270° Sector

Fig. 24. Manual caliper measurements across four tire sectors.

3.1.13 Wear Analysis

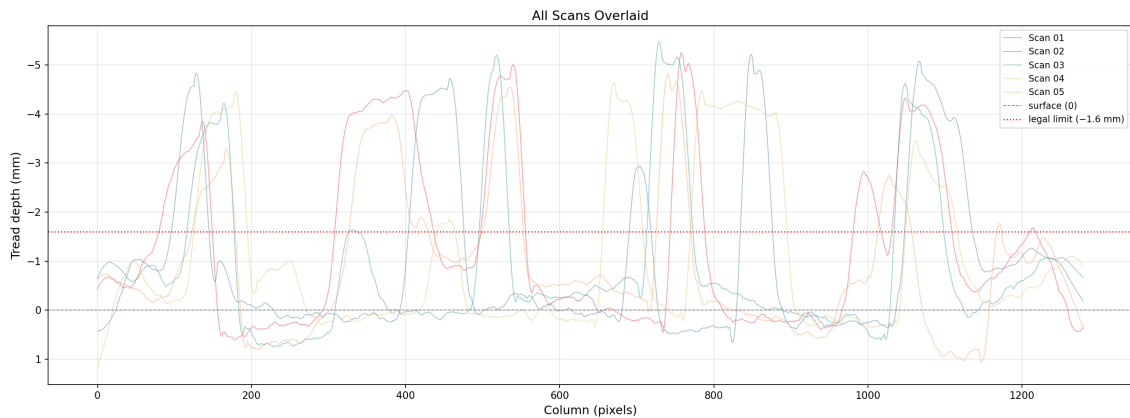


Fig. 25. Wear pattern distribution for the R17-225 tire.

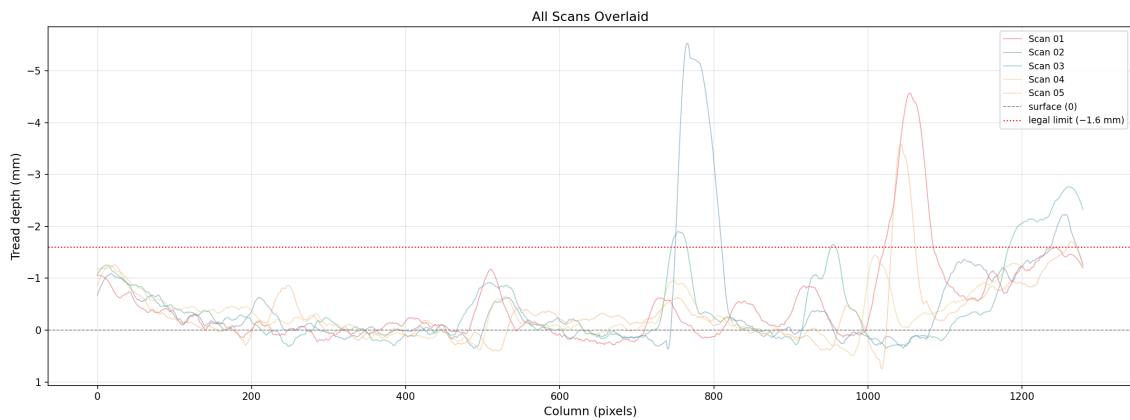


Fig. 26. Wear pattern distribution for the R16-185 tire.

The dataset confirms the system's capacity to detect uneven wear patterns on the tire. A comparison between the 4 sectors reveals that the tire tread depth varies slightly, varying from 5 mm to 4.6 mm, representing a total variance of 0.357 mm. This signifies that the system can verify conditions that affect the quality of a tire, like loading heavy objects to a vehicle, tire deflation, or asymmetric braking instances. Still, the tires were deemed legal to operate, regardless of any external factors that could be identified with in-depth review of the data.

3.1.14 Conclusion of System Verification

The data obtained adapts to the requirements dictated by the V-Model. The combination of the lead screw and the isolated power subsystem prevented any missed steps or jams coming from the stepper motor. This transitions the prototype from a laboratory idea to a fully functional instrument capable of extracting accurate tread depth data.

- **Calliper measurement variability.** Tread depth is not uniform around the tire circumference. Multiple calliper readings at different positions produced a spread of values rather than a single fixed depth. The optical measurement therefore cannot be expected to match any single calliper reading exactly.
- **Centroid noise.** The deepest pixel value read from the profile carries the residual ± 1 – 2 pixel noise of the centroid estimator, corresponding to approximately ± 0.2 – 0.4 mm at the calibrated scale.
- **Groove wall angle.** Tire tread grooves are not perfectly vertical-walled; they taper slightly. The calliper measures the full groove depth at the widest opening, while the laser centroid measures the depth at the point of highest red-channel intensity within the groove, which may not be the geometric deepest point if the groove wall reflects the laser asymmetrically.

3.1.15 Material list & Cost

Table 21 details the complete Material list & costs for the laboratory-scale prototype.

TABLE 21
Material list & Costs with Engineering Labor (Ecuador)

Component Description	Qty	Unit Cost (USD)	Total (USD)
Raspberry Pi 5 (8GB)	1	\$120.00	\$120.00
NEMA 17 Stepper Motor	1	\$15.00	\$15.00
T8 Lead Screw (w/ Brass Nut)	1	\$12.00	\$12.00
TB6560 Stepper Motor Driver	1	\$14.00	\$14.00
Logitech C920 HD Pro Webcam	1	\$65.00	\$65.00
Laser Module (Red)	1	\$5.00	\$5.00
24V DC Power Supply	1	\$18.00	\$18.00
LM2596 5V Buck Converter Step-Down	1	\$5.00	\$5.00
2020 V-Slot Aluminum Extrusion (0.4m)	1	\$3.00	\$3.00
Polycarbonate V-Wheels & Bearings	2	\$10.00	\$20.00
3D Printing Filament (PETG - 1kg Roll)	1	\$21.00	\$21.00
Misc. Fasteners (M3/M4, T-Nuts)	1	\$10.00	\$10.00
Shielded Wiring & Connectors	1	\$10.00	\$10.00
Labor	Hours	Hourly Rate	Total
Engineering Labor	202	\$5.00	\$1,010.00
Material Cost			\$318.00
Total Project Cost (Materials + Labor):			\$1,328.00

3.2 Discussion

The most significant result of this prototype is the precision that was achieved by this project. Across 20 different measurement instances, conveying the 4 different sectors of the

tires, it got a standard deviation of 0.045 mm, which proves the mechanical repeatability of the system.

The accuracy of the optical measurement was validated doing a direct comparison between the automated results and manual measurements using mechanical calipers. The OpenCV pipeline results had a percentage error of 2.16%, while the maximum deviation was of just 0.152 mm, less than the human viewing error of ± 0.5 mm. This validates previously established literature in utilizing theoretical triangulation and tracking frameworks to extract sub-millimeter data. [6, 15]

This project confirms the usability of microcomputers for machine vision environments. The Raspberry Pi 5 was able to execute complex sequential operations without relying of external cloud computing [21]. It proves that CPU-centered controllers are highly capable of executing heavily taxing computing tasks with localized processing

As discussed in Chapter 1, over 25% of vehicles in circulation operate with tires under the legal limit [5]. Due to lack of traceable data, human negligency, and delays in workshop revision, this study aims to lower this safety concern.

Chapter 4

Conclusions & Recomendations

4.1 Conclusions

Based on the primary goal established at the start of the project, which was the research, design, development, and validation of a mechatronic prototype capable of measuring tire tread depth for R15,R16,R17, and R18 tires, the following conclusions can be defined based on the project results.

The design and construction of the physical prototype was done using a CAD modelling system to construct a linear moving cart which houses the optical setup within it. The cart is moved by a NEMA 17 motor put on one side of the prototype, leaving the middle space open for optical scans. A system of sliders in the clamp section made so that the prototype can be adjusted for all tire diameters specified in the objectives.

A 5V red line laser module was implemented as the device that creates a tire profile, while a Logitech C920 HD Camera was chosen to extract the images to be processed. The optical setup was designed based on optical calculations that defined a standoff distance of 100 mm, and a laser-to-lens distance of 115mm, successfully capturing high fidelity tire profile images.

After the physical prototype was built and the images were extracted, a computer vision algorithm was implemented in Python using OpenCV as the main way to process data and output tire tread depth data. The algorithm was executed in a Raspberry Pi 5 and utilized HSV color segmentation, morphological elements, sub-pixel centroid extraction and per-column band-thinning to isolate the laser line and calculate its height in pixels. A pixel-to-mm calibration was done in order to convert the data obtained into physical values. The final measurements had a standard deviation of 0.045 mm and an error rate of 2.16% when compared against manual measurements for the R17 tire, while also correctly identifying a discrepancy in the tread of the R16 tire, detecting uneven tire tread across its surface. .

When the results were verified, a graphical user interface was implemented to remotely start and visualize scans in real time, display results based on safety margins, and keep track of past results.

4.2 Recommendations

Even though the system successfully achieved all proposed objectives, it is still a laboratory-scaled prototype. To transform this proof-of-concept into a fully commercial product, some recommendations are listed.

First of all, the project was built in an enclosed environment. For it to be accepted as a product, it needs better environmental protection. Designing a housing that fully encloses the prototype can protect the scan sequence from external factors like weather, physical hits or light interference.

The current system uses only sequential GPU processing to process information, but future implementation could add Artificial Intelligence into the programming. Using CNNs or detection models like YOLOv11, the system could be trained to automatically identify other tire anomalies, such as embedded debris, or uneven wear patterns, indicating misalignment.

From a kinematic perspective, the prototype could be adapted so that, instead of the linear cart having to go on top of the tire to read it, a floor plate is installed with an optical setup, making it so that the tire can be driven over the floor plate and the tread can be measured without any tire removal need.

Finally, the software could be expanded to connect into a cloud API, allowing for data storage in an external server, and have data for data wear predictive models, allowing users to accurately predict when a tire needs to be changed, based on previous scans.

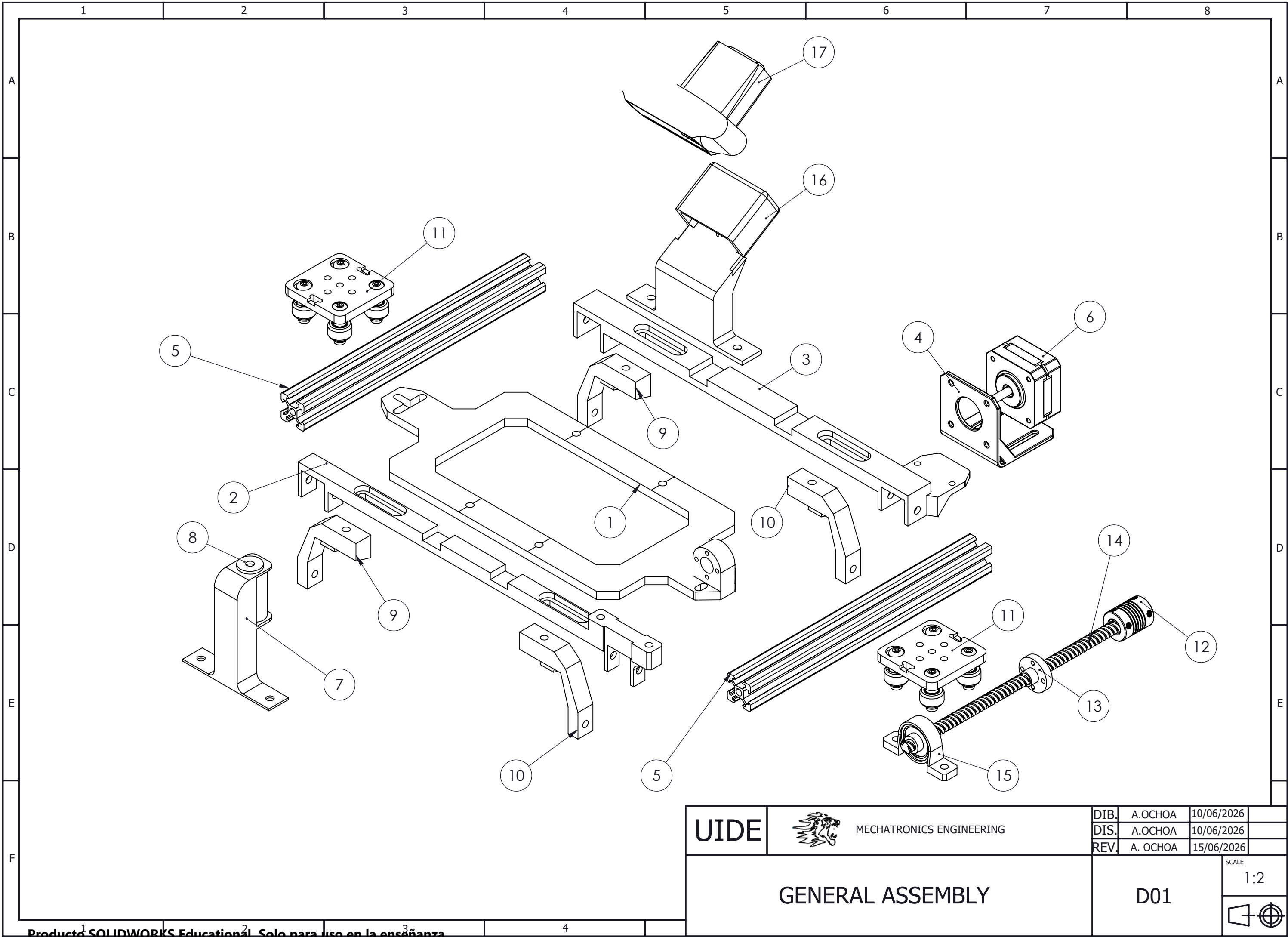
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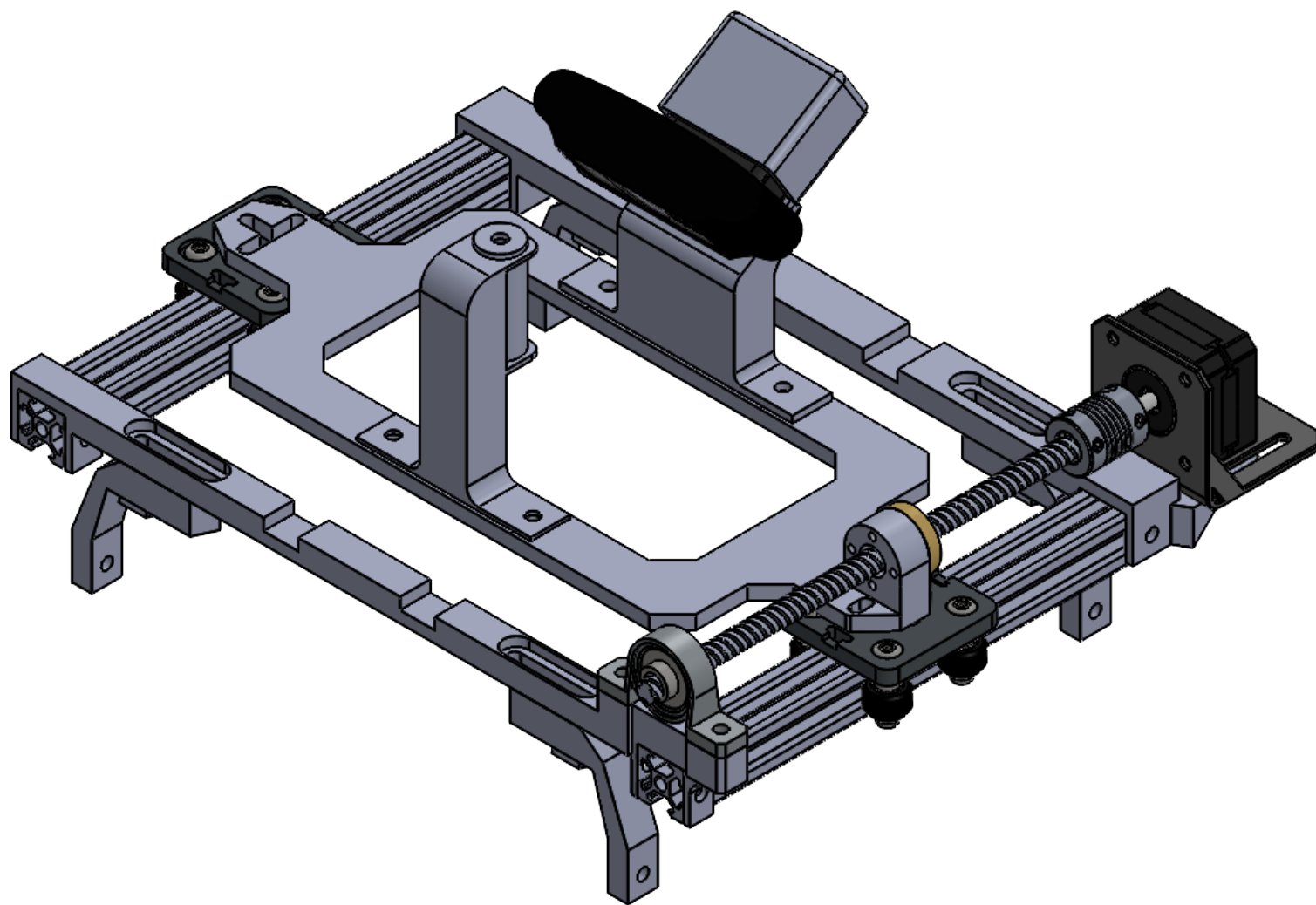
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Appendix
DRAWINGS



UIDE		MECHATRONICS ENGINEERING	DIB.	A.OCHOA	10/06/2026	
			DIS.	A.OCHOA	10/06/2026	
			REV.	A. OCHOA	15/06/2026	
GENERAL ASSEMBLY			D01			SCALE
						1:2



17	Logitech_C920_Cam	1080p, 78° FOV	1
16	Camera_Support	D01-112	1
15	KP-08_Bearing	Diam: 8mm	1
14	Lead_Screw	Diam: 8mm	1
13	T8_Brass_Nut	Joins screw to setup	1
12	Flexible_Coupling	8mm screw - NEMA 17	1
11	V_Slot_cart	Slides along V Slot	2
10	LeftClamp	D01-108	2
9	RightClamp	D01-107	2
8	Laser_Lid	D01-106	1
7	Laser_Support	D01-105	1
6	NEMA_17_Stepper_Motor_23mm	24V - 1.4A	1
5	2020_V_Slot	Length: 210 mm	2
4	Stepper_Bracket	D01-104	1
3	Motor_Crossbeam	D01-103	1
2	Bearing_Crossbeam	D01-102	1
1	Optical_Setup_Cart	D01-101	1
ELEMENT N°	ELEMENT NAME	DESCRIPTION	QUANTITY

UIDE



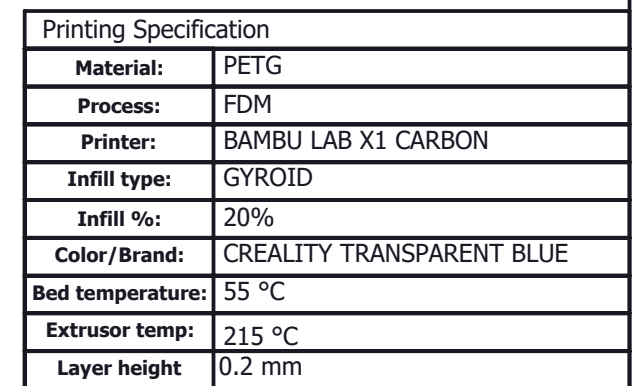
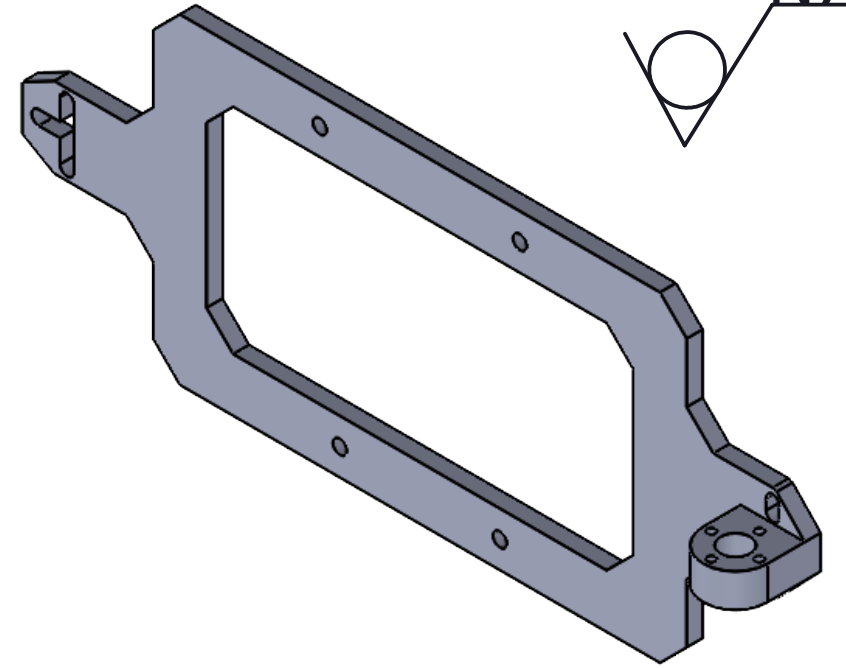
MECHATRONICS ENGINEERING

DIB.	A.OCHOA	10/06/2026
DIS.	A.OCHOA	10/06/2026
REV.		

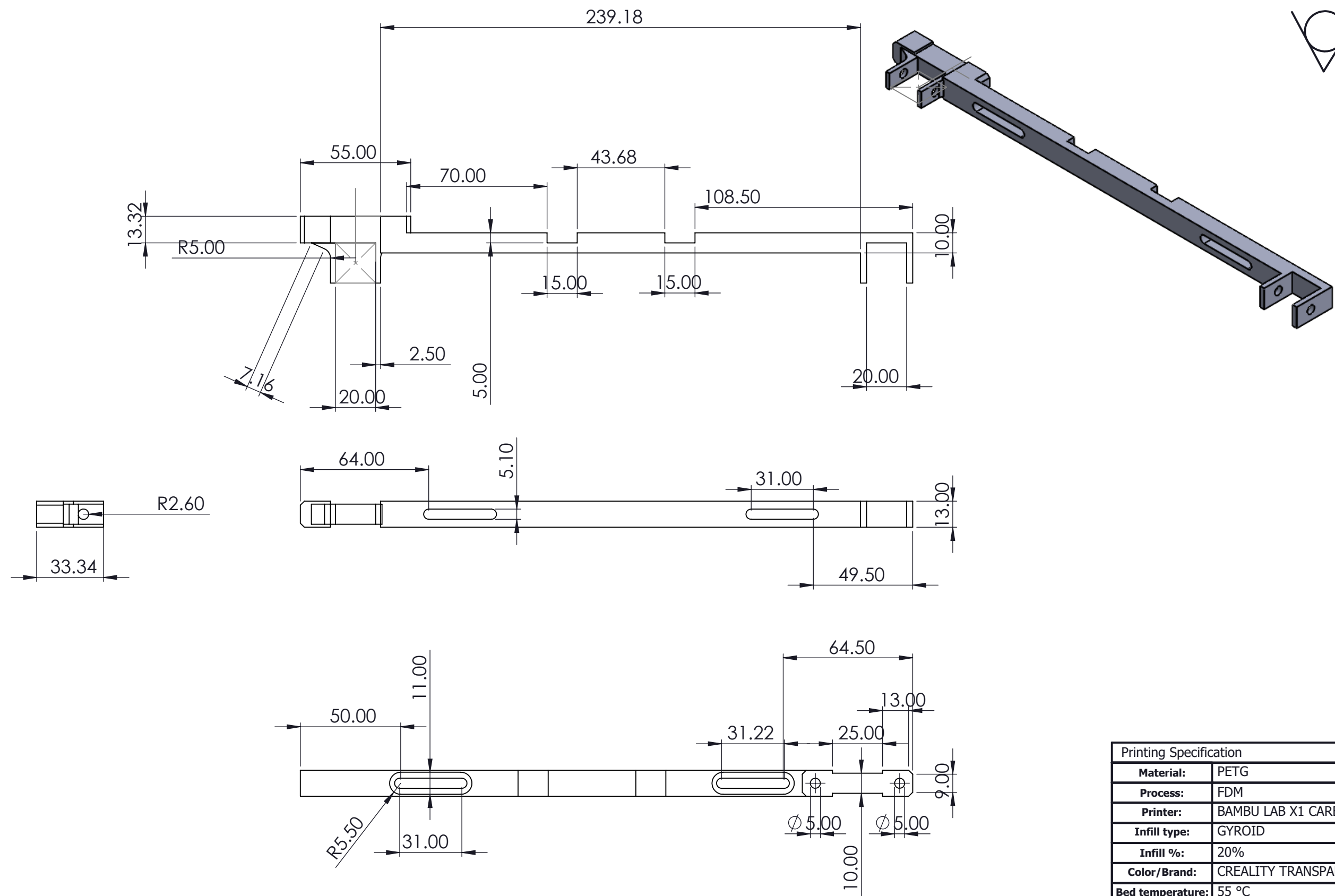
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SCALE



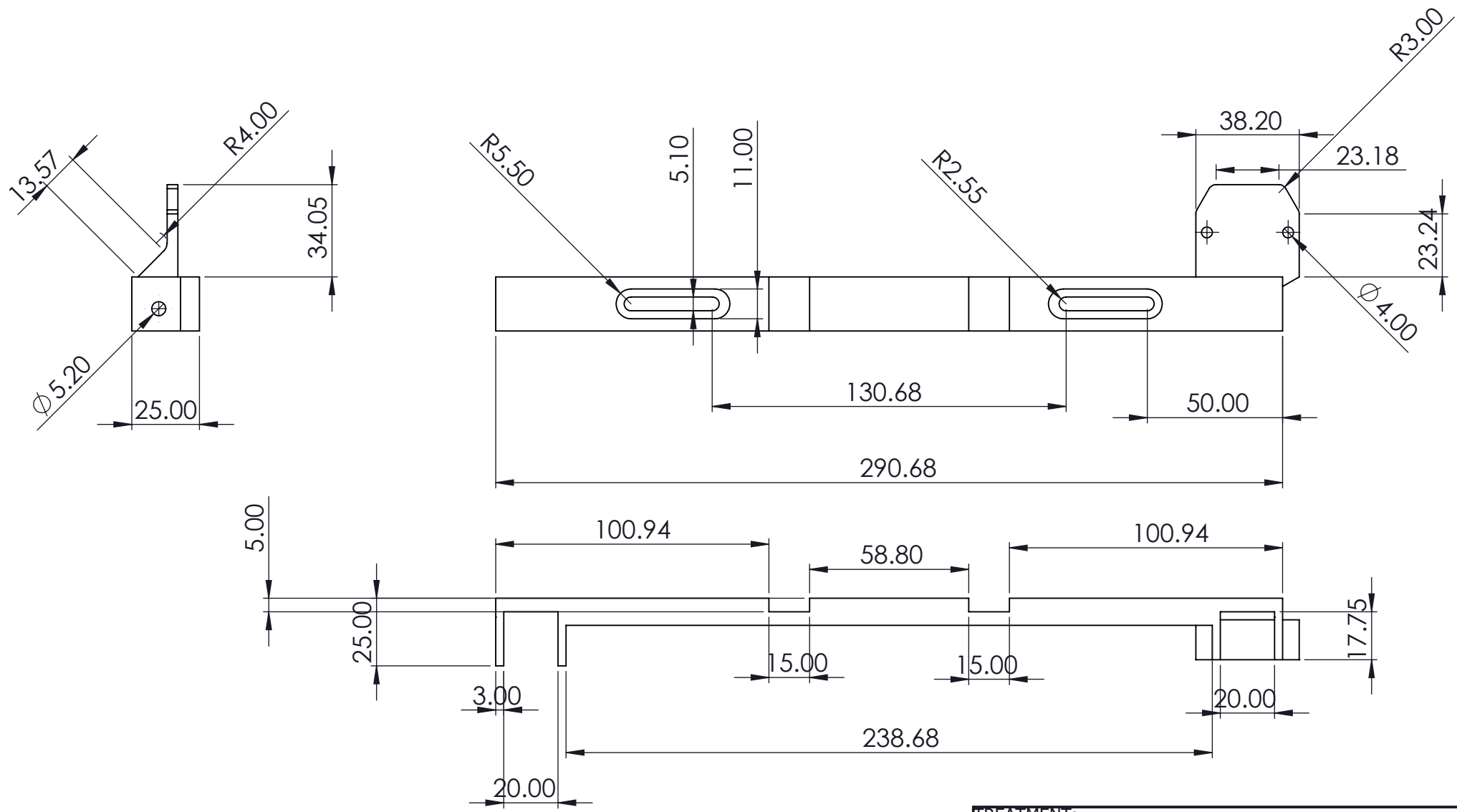
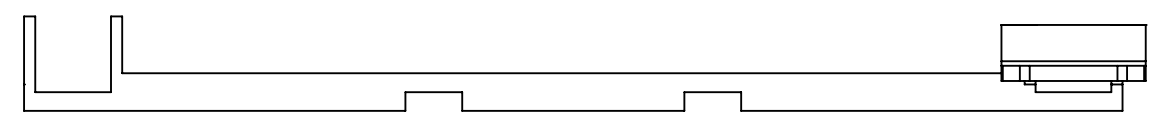
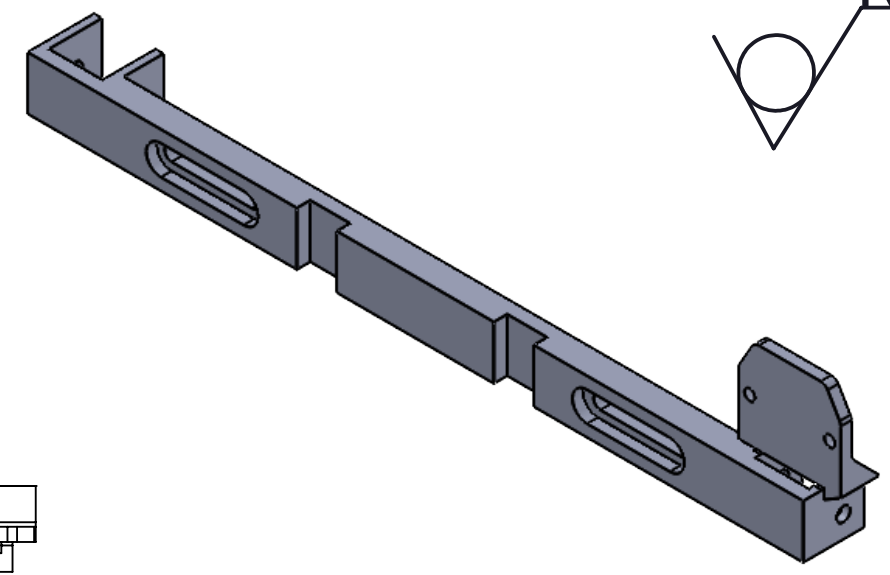


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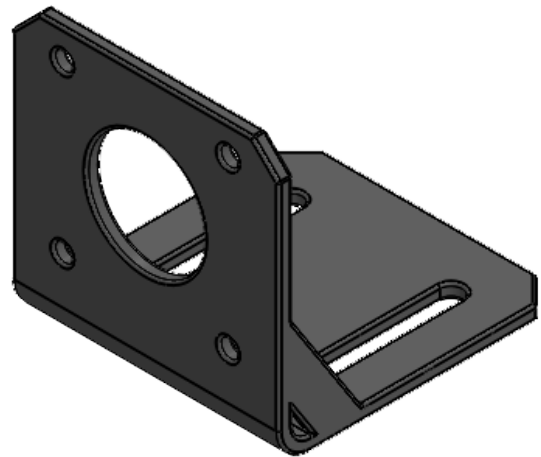
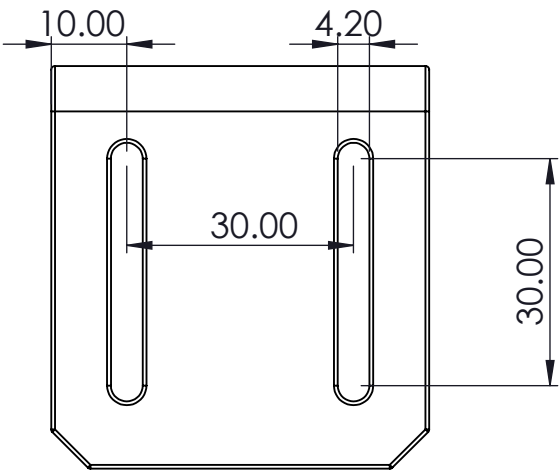
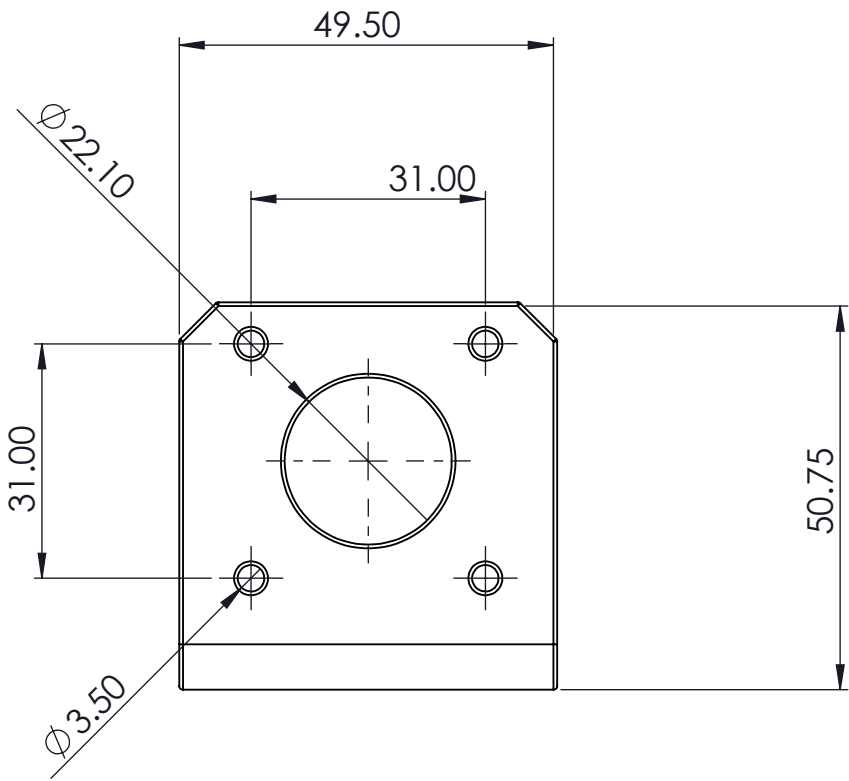
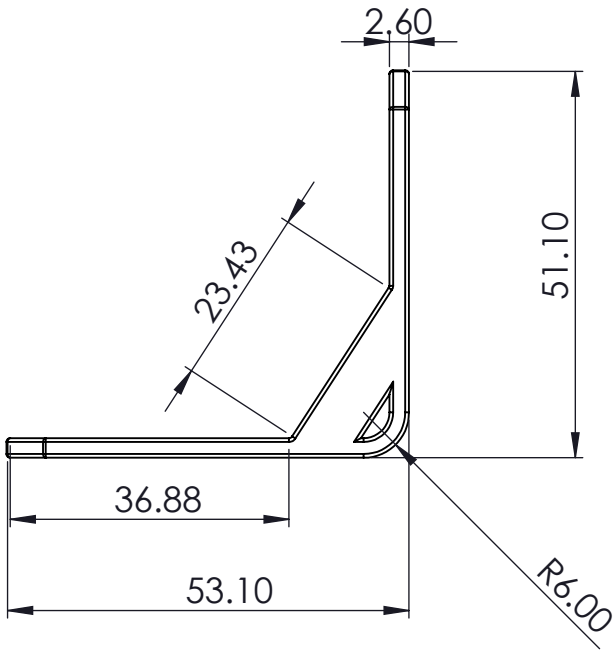
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Extruder temp:	215 °C
Layer height	0.2 mm

TREATMENT:		N/A		UIDE		 MECHATRONICS ENGINEERING								
COATING:		N/A												
MATERIAL:			TOL. GRAL:		SCALE		DIB.		A.OCHOA		10/06/2026			
							DIS.		A. OCHOA		10/06/2026			
							REV.		A. OCHOA		10/06/2026			
MOUNTED BEARING CROSSBEAM					D01-102									



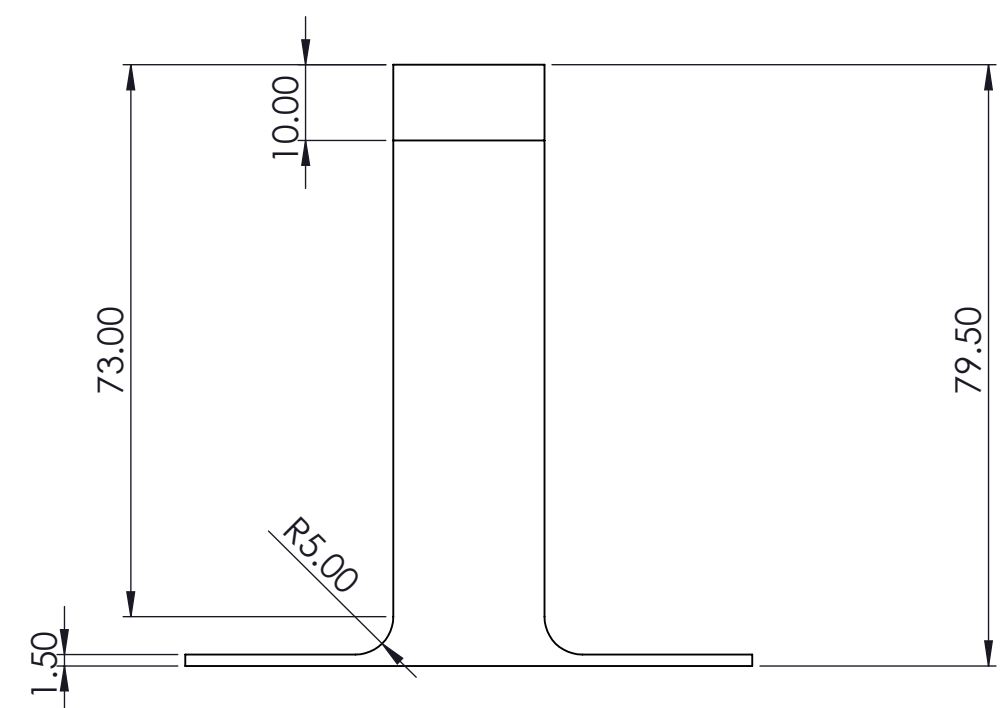
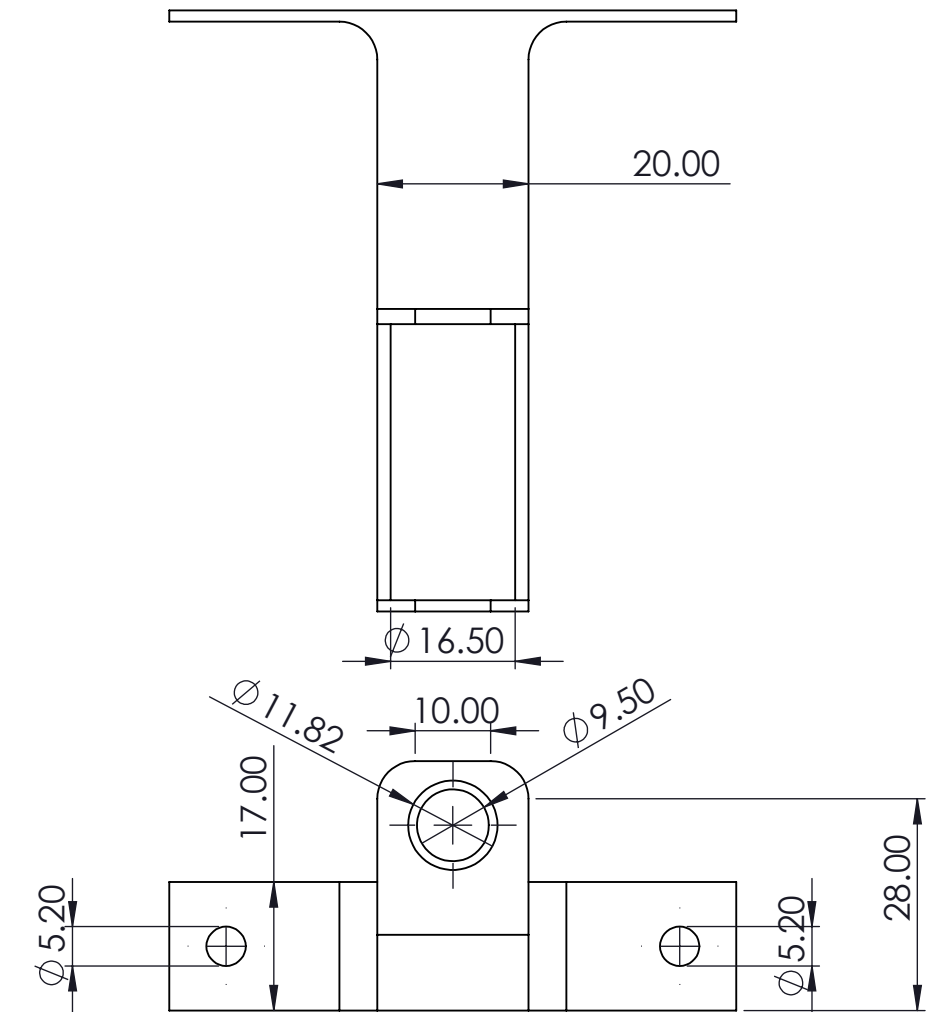
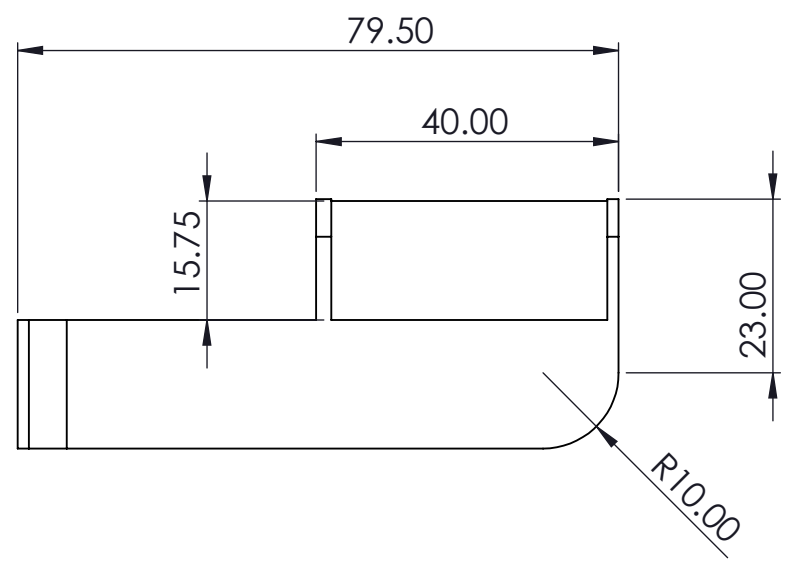
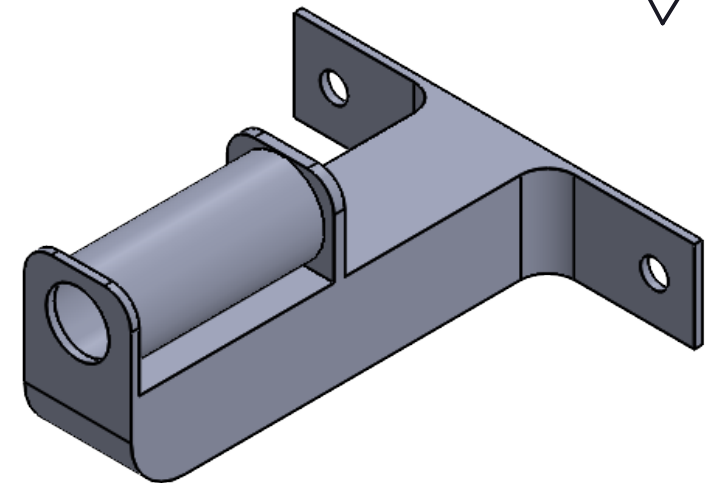
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Extruder temp:	215 °C
Layer height	0.2 mm

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COATING:		N/A							
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						REV.	A. OCHOA	10/06/2026	
MOTOR SIDE CROSSBEAM				D01-103					



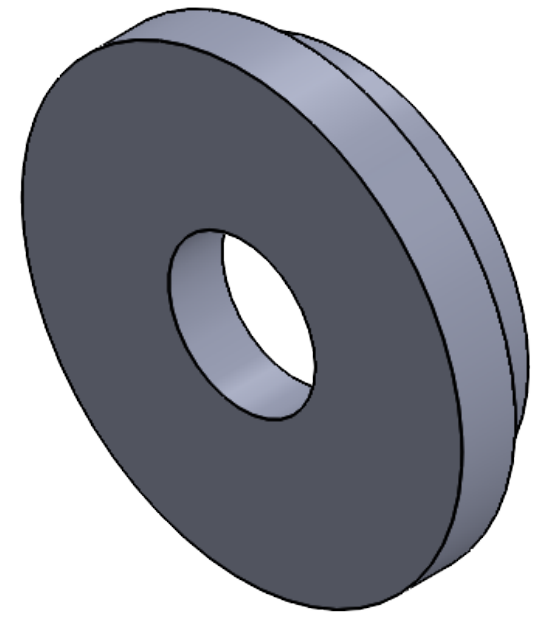
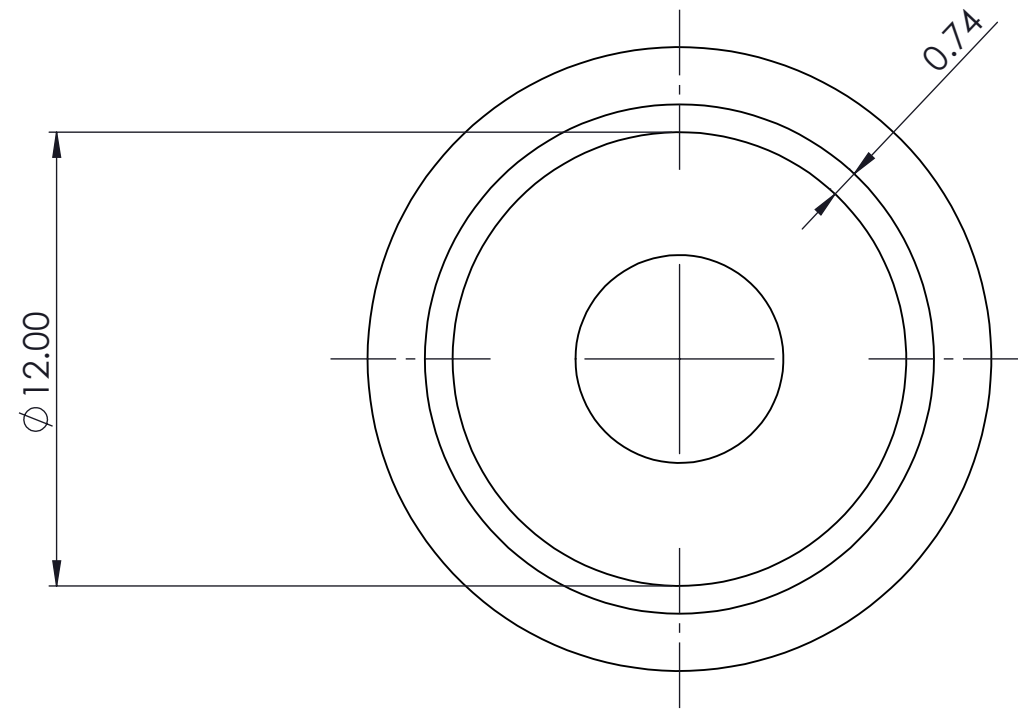
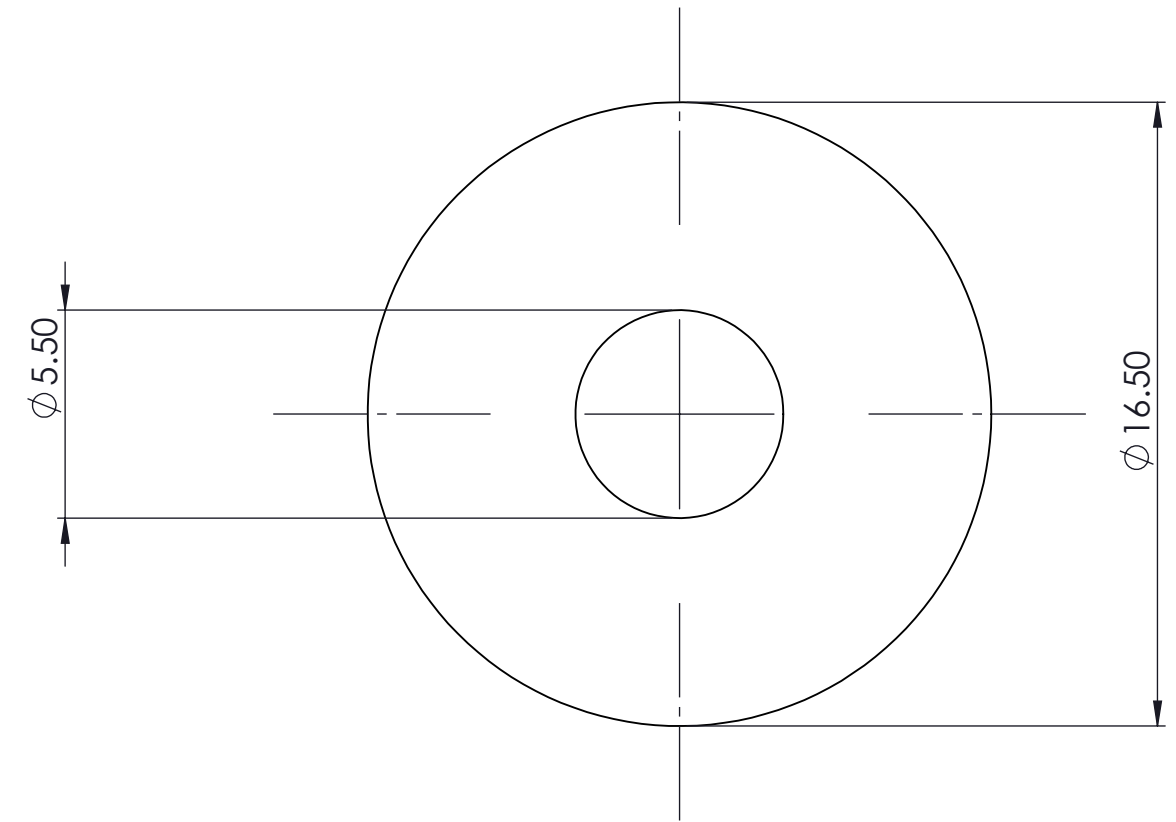
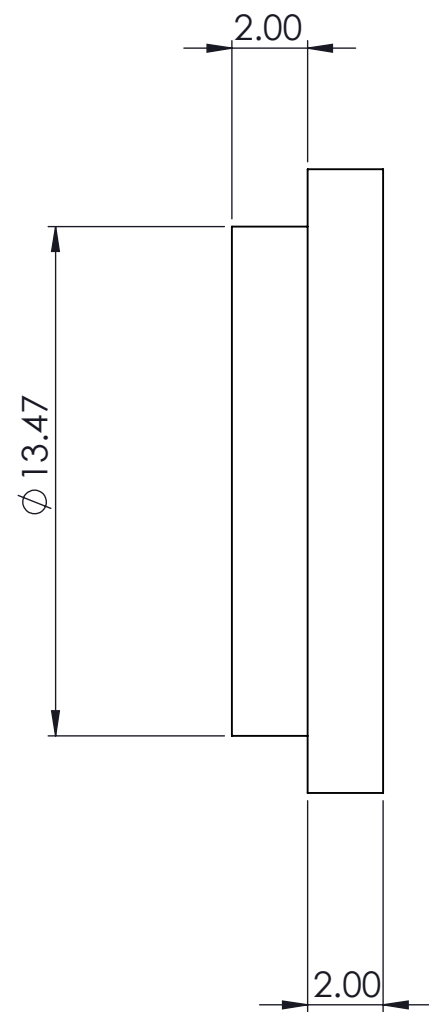
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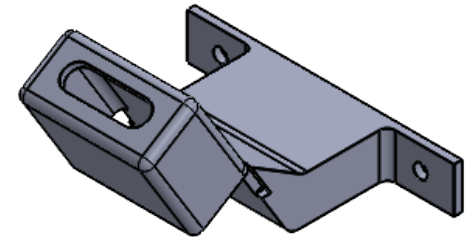
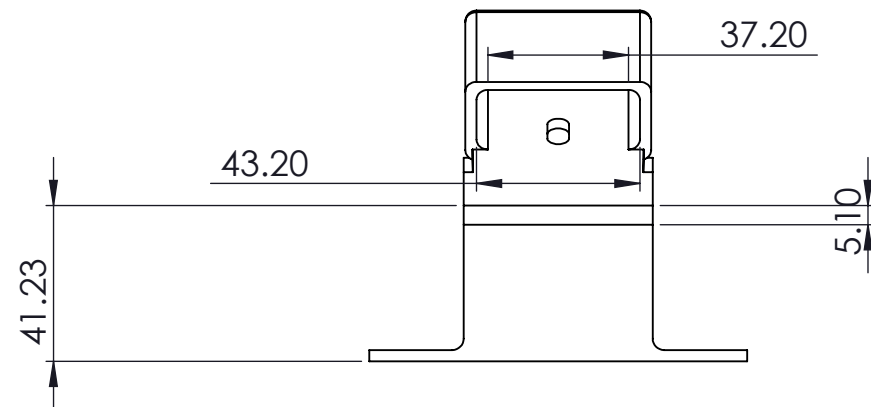
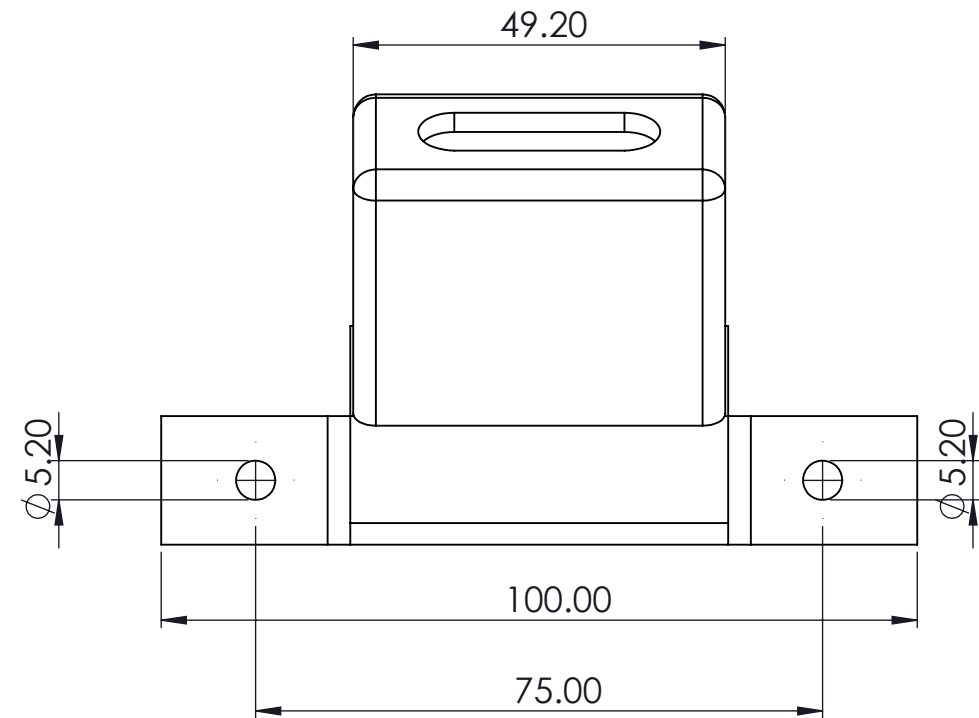
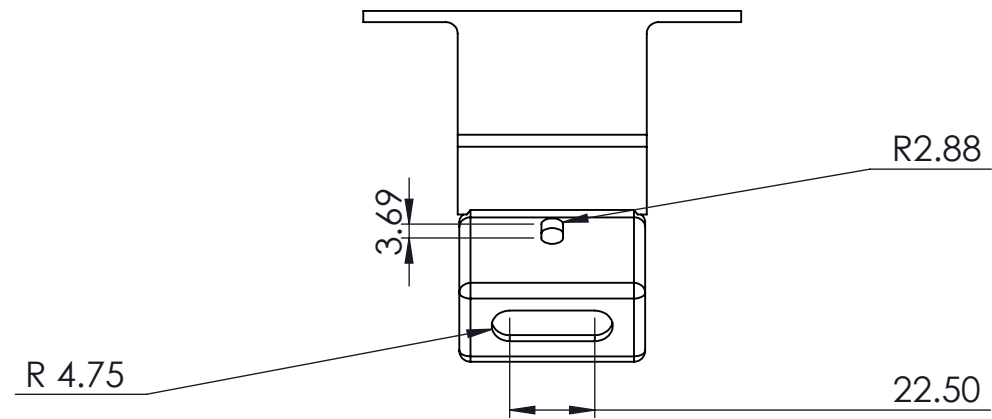
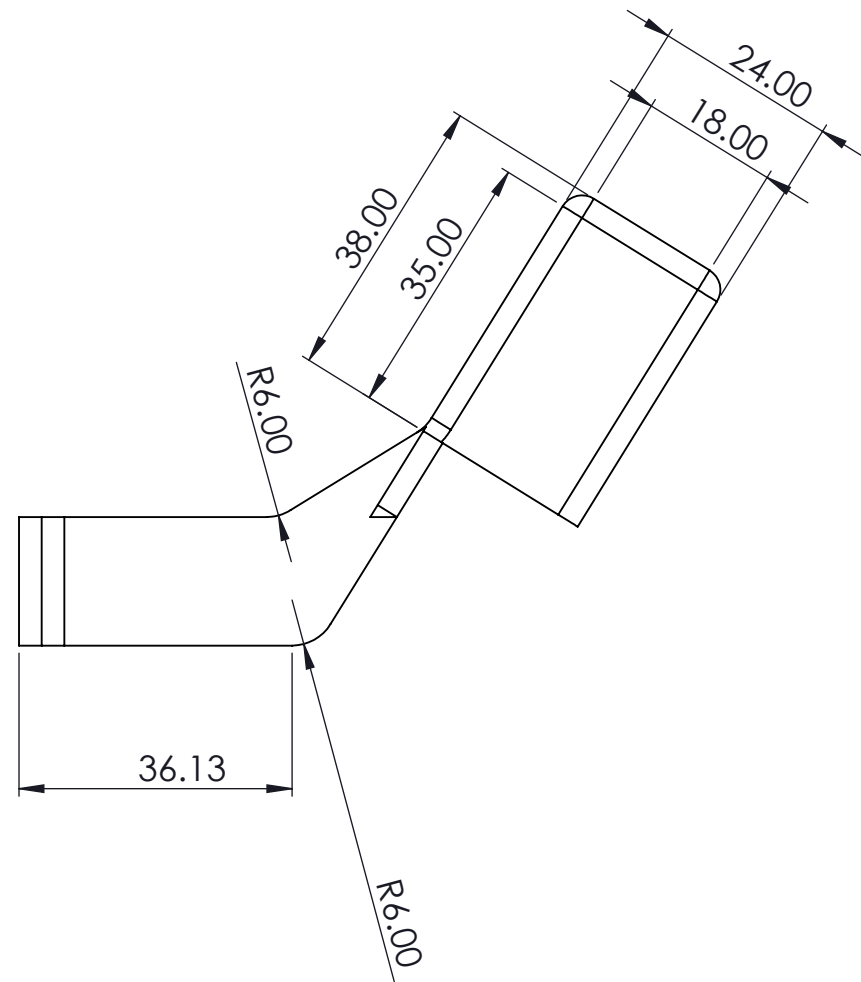
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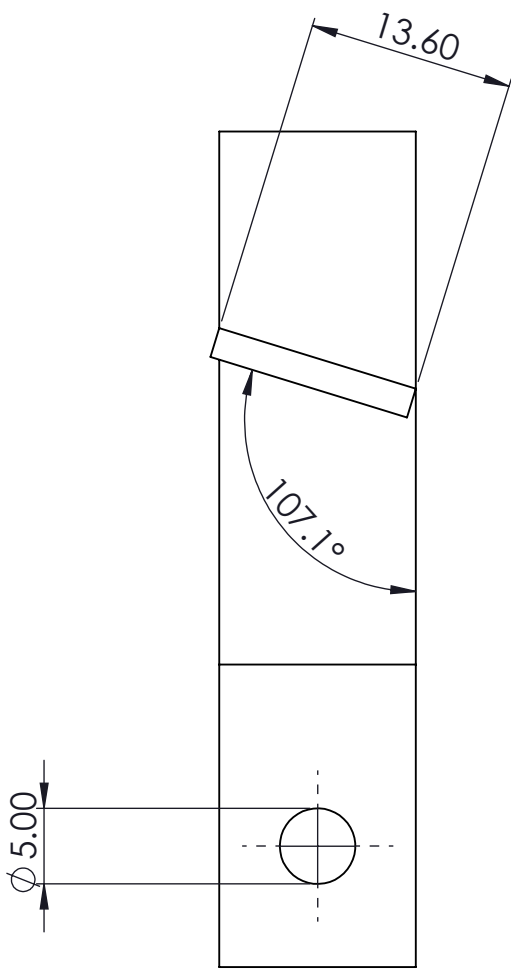
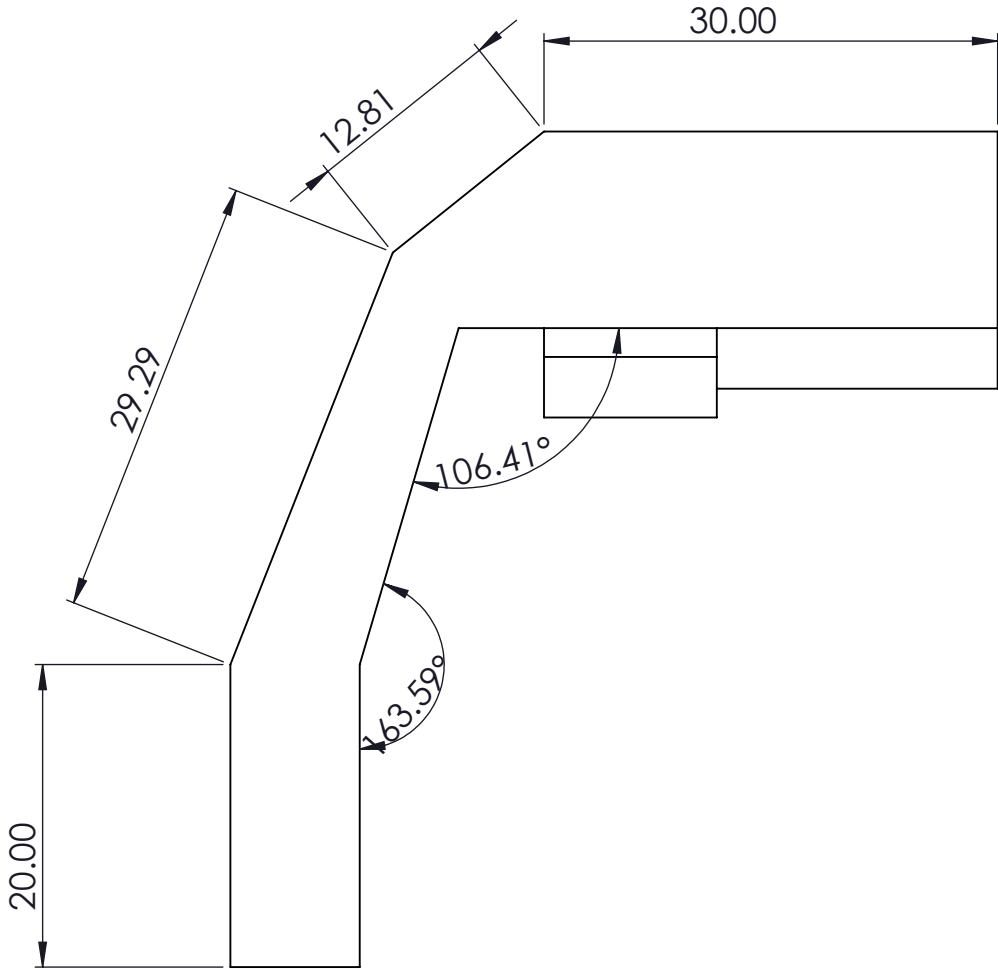
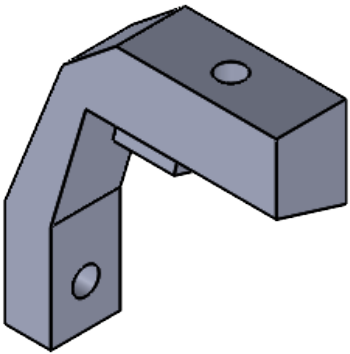
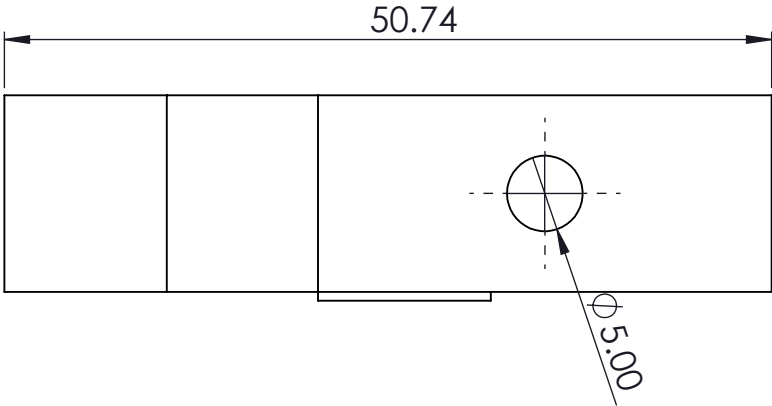
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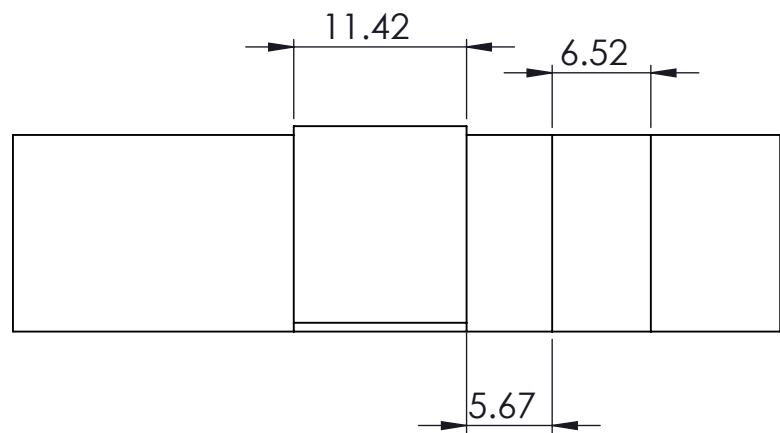
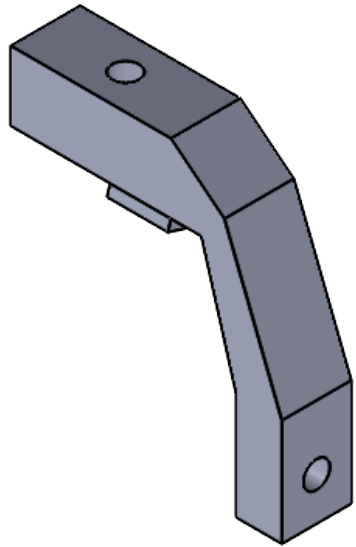
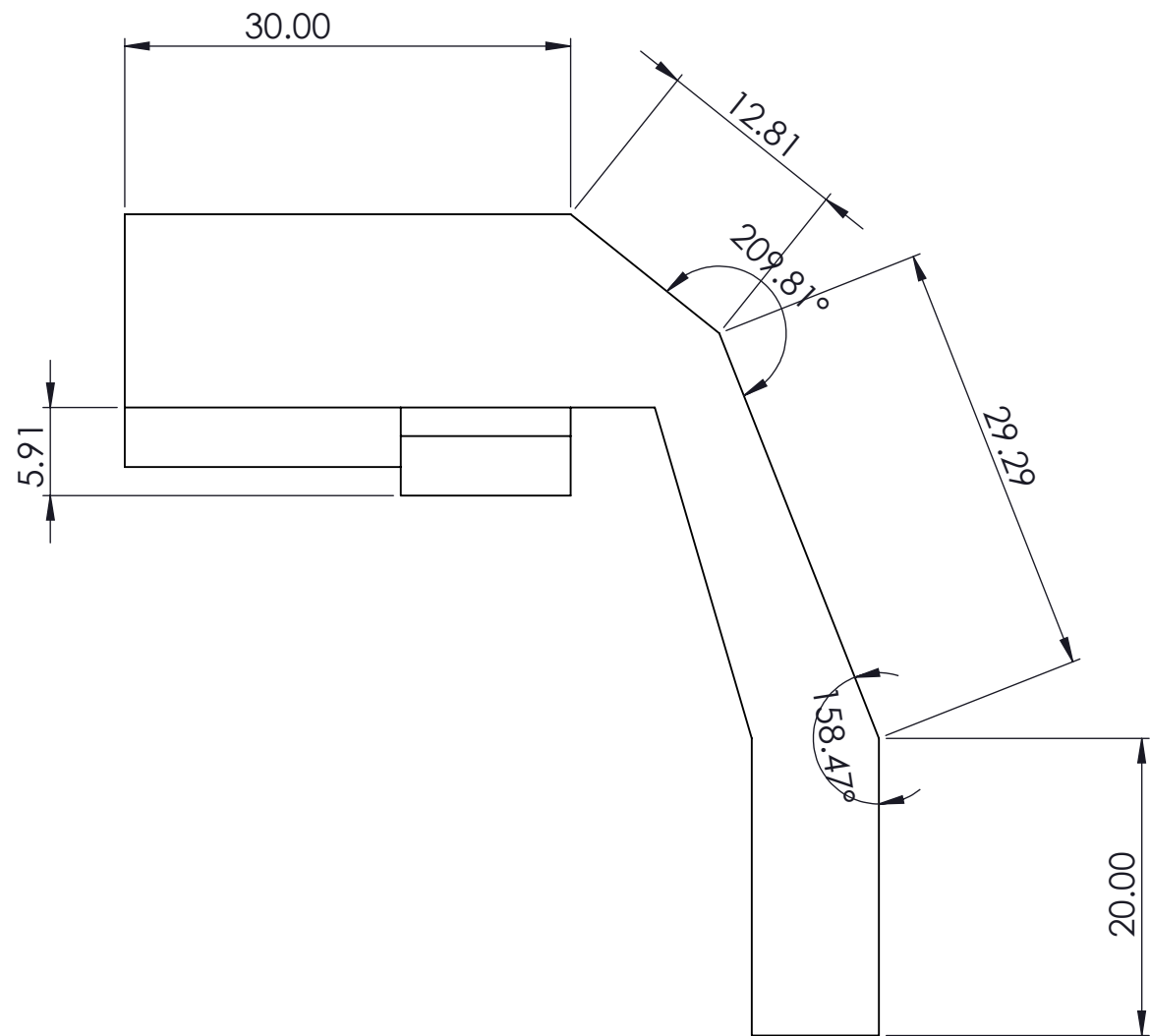
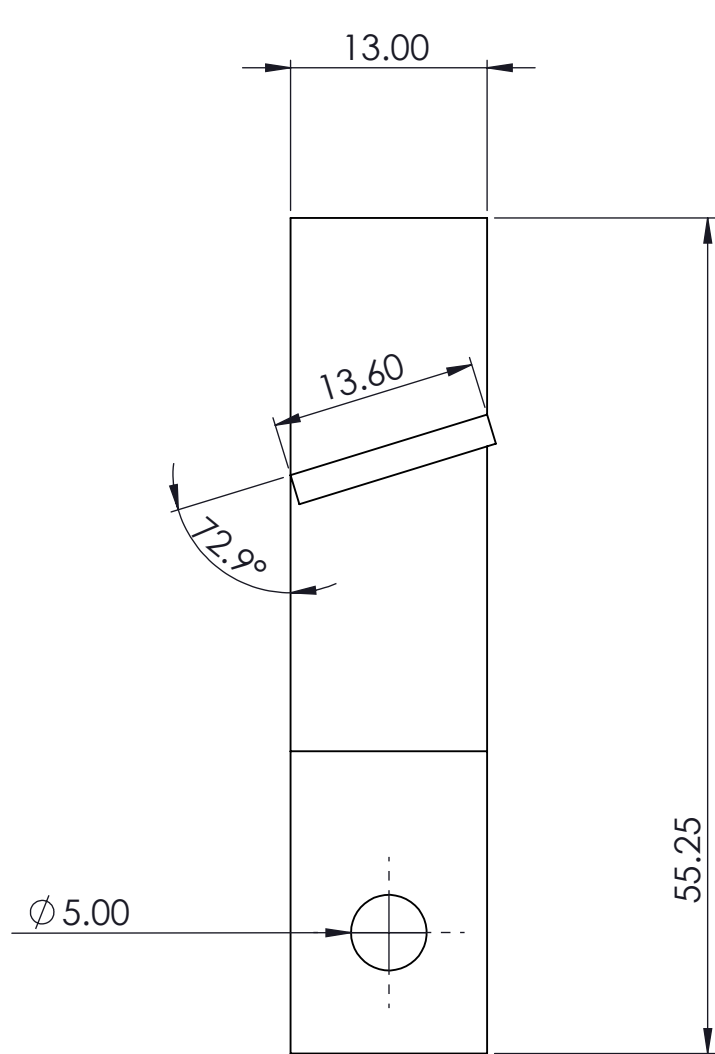
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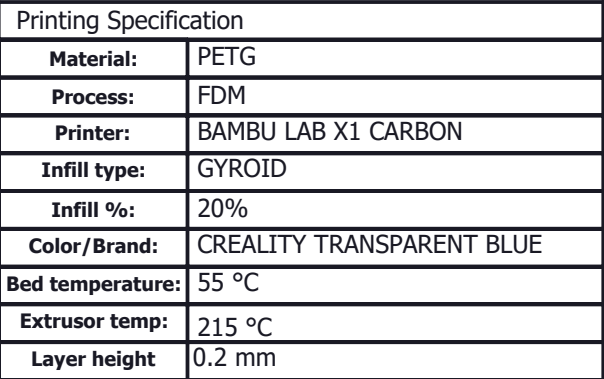
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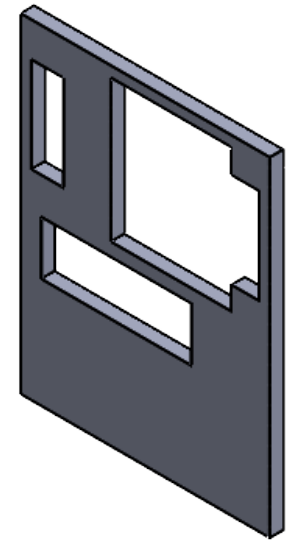
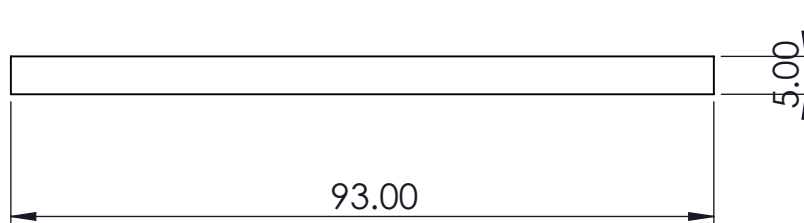
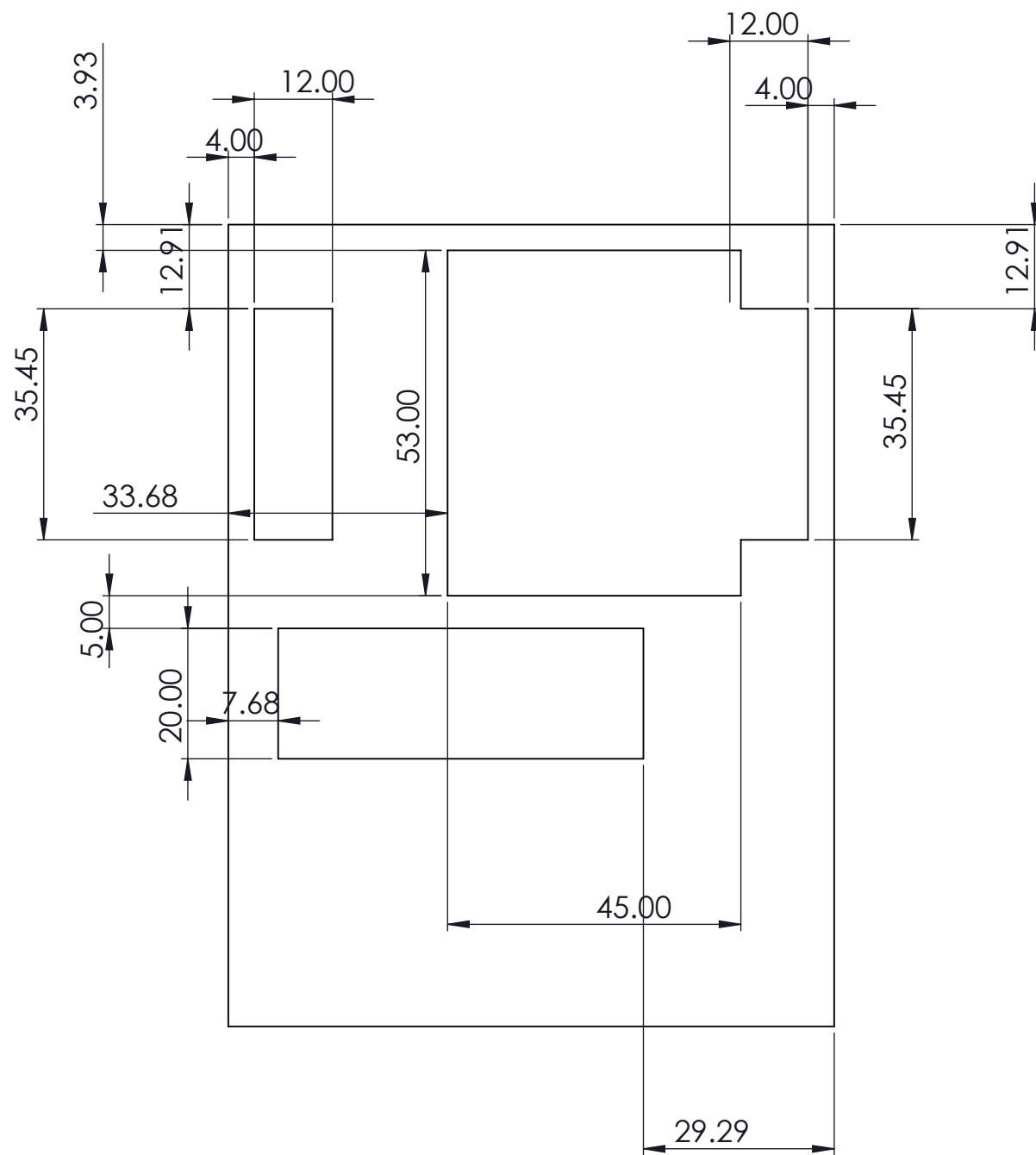


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COATING:		N/A						
MATERIAL:		TOL. GRAL:	SCALE	DIB.	A.OCHOA	10/06/2026		
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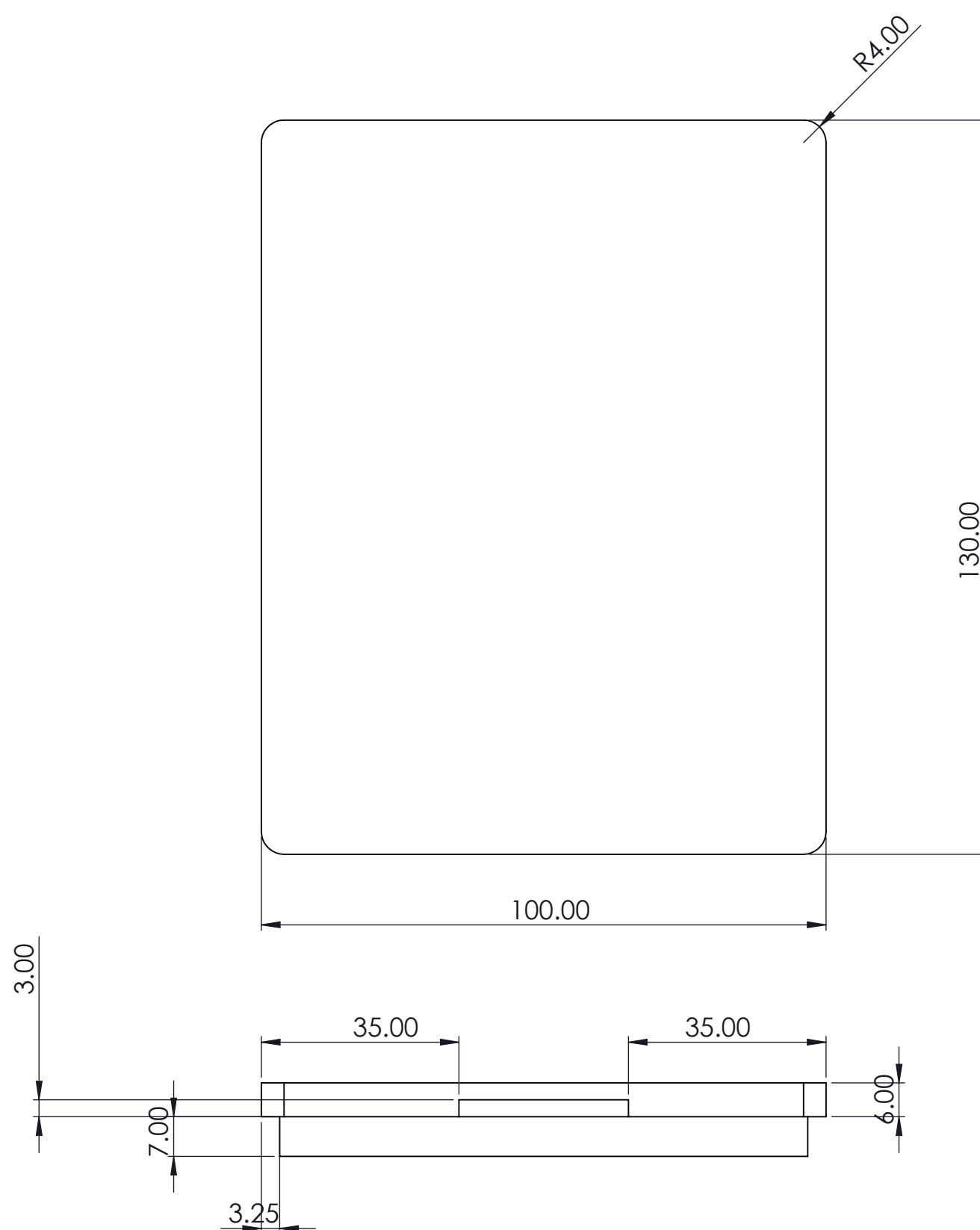
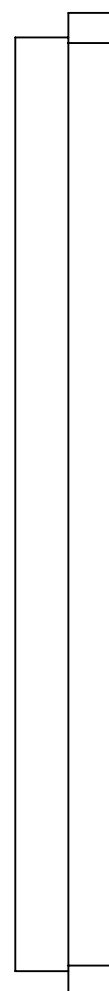
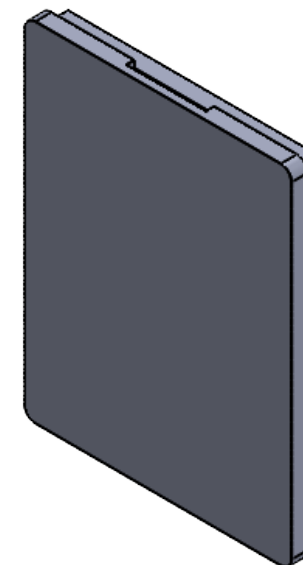


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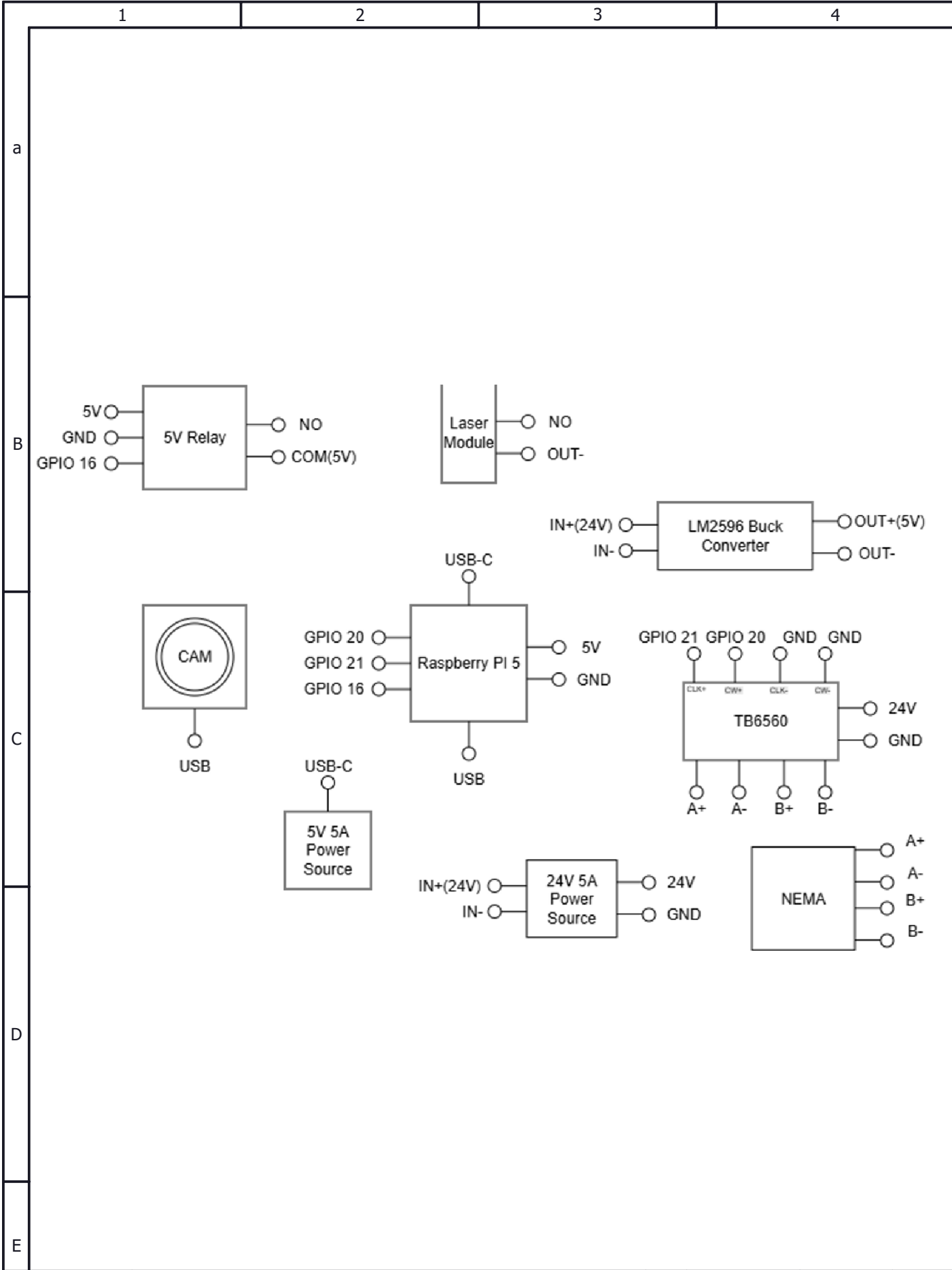


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Extruder temp:	215 °C
Layer height	0.2 mm

TREATMENT:		N/A		UIDE		 MECHATRONICS ENGINEERING							
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						REV.		A. OCHOA		10/06/2026			
ELECTRONIC BOX SECOND FLOOR				D01-110									
										 			



TREATMENT:		N/A		UIDE		 MECHATRONICS ENGINEERING							
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ELECTRONICS BOX LID				D01-111									



UIDE		MECHATRONICS ENGINEERING	DIB.	A. OCHOA	10/06/2026	
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			REV.	A. OCHOA	10/06/2026	
ELECTRONIC DIAGRAM			D02		SCALE:	
						