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Diseño e Implementación de un Robot Delta para la Enseñanza Práctica de la Robótica

Design and Implementation of a Delta Robot for Practical Robotics Education

Quito-2026

Aprobación del Tutor del Trabajo de Integración Curricular

Yo Ing. Guillermo Mosquera MSc., en calidad de tutor del Trabajo de Integración Curricular denominado: *Diseño e Implementación de un Robot Delta para la Enseñanza Práctica de la Robótica*, realizado por Esteban Santiago Osejo Taco, 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

A todas las personas que, con su esfuerzo y dedicación diaria, contribuyen al avance del conocimiento y al progreso de la humanidad. A quienes creen en el valor de la educación, la ciencia y el trabajo bien hecho. A la curiosidad que nos impulsa a aprender, crear y compartir para construir un futuro mejor.

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Resumen

La enseñanza de la cinemática, la dinámica y el control de robots paralelos en cursos introductorios suele quedarse en el plano teórico debido al costo y a la complejidad de los equipos. Este trabajo presenta el diseño y la implementación de un robot delta de bajo costo, acompañado de una interfaz web educativa que refuerza estos conceptos mediante la interacción directa. La estructura se fabricó con corte láser e impresión 3D; cada articulación emplea un motor a pasos con reductor planetario y un driver de lazo cerrado, y sensores de posición angular verifican el ángulo articular alcanzado. La interfaz guía la cinemática directa e inversa, la dinámica y el control PID en cinco secciones, donde el usuario arma cada ecuación paso a paso y elige una de dos predicciones antes de cada resultado. Las pruebas sobre el prototipo mostraron una repetibilidad de 1,6 mm y lecturas articulares dentro del requisito de un grado, con un error rms de 0,78 grados. Doce participantes completaron el mismo cuestionario antes y después de la práctica: el puntaje subió de 53,0% a 70,4%, una ganancia normalizada de 0,384, media en la escala de Hake, con las mayores mejoras en cinemática directa y en la distinción entre gravedad e inercia: los participantes aprendieron.

Palabras clave: robot delta, robótica educativa, cinemática paralela, interfaz web, control PID.

Abstract

Teaching the kinematics, dynamics, and control of parallel robots in introductory courses often remains theoretical because of the cost and complexity of the equipment. This work presents the design and implementation of a low cost delta robot together with an educational web interface that reinforces these concepts through direct interaction. The structure was fabricated with laser cutting and 3D printing; each joint uses a stepper motor with a planetary gearbox and a closed loop driver, and angular position sensors verify the reached joint angle. The interface guides forward and inverse kinematics, dynamics, and PID control in five sections, where the user assembles each equation step by step and chooses one of two predictions before each result. Tests on the prototype showed a repeatability of 1.6 mm and joint readings inside the one degree requirement, with an rms error of 0.78 degrees. Twelve participants completed the same questionnaire before and after practice: scores rose from 53.0% to 70.4%, a normalized gain of 0.384, medium on Hake's scale, with the largest gains in forward kinematics and in the distinction between gravity and inertia: the participants learned.

Keywords: delta robot, educational robotics, parallel kinematics, web interface, PID control.

ABET Criteria/Final Report Cross Reference Table

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.	Analysis, Comprehension	Sections 2.3.1, 2.3.2
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.	Analysis, Comprehension	Sections 2.2, 2.3
3. An ability to communicate effectively with a range of audiences.	Analysis	Section 2.2, Chapter III
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.	Analysis	Chapter I
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.	Analysis	Sections 2.2.2, 2.6.2
6. An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.	Analysis, Comprehension	Section 2.6, Chapter III
7. An ability to acquire and apply new knowledge as needed, using appropriate learning strategies.	Analysis	Sections 2.3.2, 2.3.8

Chapter I

Introduction

In higher education, educational robotics is recognized as a valuable tool that allows students to apply theoretical knowledge in practical environments, develop technical and digital competencies, and enhance motivation and engagement [1,2]. However, its implementation remains limited by cost, infrastructure limitations, hardware complexity, and resource availability [1, 3]. Students in introductory robotics courses learn the mathematical formulations of forward kinematics and inverse kinematics through classroom lectures and textbook derivations but rarely have the opportunity to interact with a physical robot. This theory practice gap prevents the development of spatial intuition and troubleshooting skills needed to relate abstract kinematic equations to real three dimensional motion [4].

Robot based interventions produce statistically significant improvements in academic achievement, computational thinking, and student motivation across STEM disciplines [5, 6]. Evidence from 17 articles shows a moderate but significantly positive effect of educational robots on learning outcomes, with an overall effect size of $g = 0.57$, meaning that students who learn with educational robots score on average slightly more than half a standard deviation higher than those who learn without them, and the effect is stronger at the higher education level than in primary and pre school settings [7]. However, the implementation of physical robots in higher education remains limited by cost, hardware complexity, infrastructure requirements, and resource availability [3]. A systematic mixed studies review involving 1689 students across 14 countries identified these factors as the primary institutional barriers to robot assisted education [3]. This means that even when the pedagogical benefits of physical robots are well established, most programs cannot afford to integrate them into their curricula.

The ideal solution for introductory robotics instruction would be to use industrial robotic arms, which require direct control of each joint motor and consideration of physical dynamics through joint programming [8]. In practice, industrial arms are large, expensive, require specialized maintenance, pose safety risks, and typically do not allow direct motor level control [8]. As a result, courses commonly rely on two alternatives: simulation environments and construction kits. Simulations provide mathematical models and virtual visualization of kinematic behavior but lack the embodied experience of physical interaction [8, 9]. Construction kits offer hands

on assembly and programming activities but do not incorporate rigorous kinematic models that connect joint level mathematics to end effector motion [4]. Neither approach fully bridges the gap between kinematic theory and physical robot behavior.

Several projects have addressed the challenge of making physical robots accessible for education. A low cost robotic arm platform developed for undergraduate engineering courses emphasized design based learning experiences, and students rated the platform positively for reinforcing theoretical concepts through physical interaction [4]. Čehovin Zajc et al. presented an open source robotic platform built with affordable components that supports inverse kinematics for path planning and state visualization, demonstrating that educational robots can be built at low cost while still providing meaningful kinematic control [9]. Gonzalez proposed a hybrid approach that connects a small physical arm (the DOBOT) with a virtual simulation tool to emulate the dynamic behavior of industrial arms, allowing students to experience the consequences of ignoring arm dynamics without the cost and risk of a full scale industrial robot [8]. In that study, when the physical arm was added alongside the simulation, student completion rates on joint programming assignments rose from 57.02 % to 78.13 %, with the improvement attributed directly to the presence of the physical robot [8].

Similarly, low cost physical manipulators integrated into university robotics courses have been shown to improve both student motivation and knowledge acquisition by providing direct access to joint level control and sensor feedback [9]. These works share a common objective: reducing the cost and complexity barrier so that students can interact with physical kinematic systems during their courses.

Despite these advances, the existing literature lacks studies that specifically combine a physical parallel robot prototype with a dedicated web based interface designed to teach kinematics, dynamics, and control through direct interaction. Most reported platforms use serial manipulators, and the educational interfaces tend to focus on either joint level control or simulation visualization, but not both within a structured pedagogical framework that progressively covers the core topics of a robotics course.

This project addresses the identified gap by designing and implementing a low cost delta robot prototype with angular position sensors and a web based interface operated from a laptop connected to the physical robot. The delta configuration, a parallel kinematic structure with three degrees of freedom, was selected because its geometry provides a clear and direct mapping between joint angles and end effector position in Cartesian space, making it well suited

for demonstrating robotics concepts.

The web interface is organized into five educational sections: forward kinematics, inverse kinematics, forward dynamics, inverse dynamics, and the PID control strategy. The forward kinematics section allows the user to input joint angles and observe the resulting end effector position, and the inverse kinematics section allows them to specify a Cartesian target and see the computed joint angles executed on the physical robot. Both kinematics sections provide immediate physical feedback by sending the computed joint angles to the prototype, connecting the mathematical formulations taught in the classroom to observable behavior on the actual robot.

The forward dynamics and inverse dynamics sections enable the user to explore the torque and force relationships that govern the motion of the delta robot linkages. The PID control strategy section presents an interactive simulation, where the user adjusts the proportional, integral, and derivative gains and observe how the simulated joint response and tracking error change, building intuition for the position loop that the closed loop drivers execute internally on the physical robot.

The same quiz is administered before and after the five sections, together with a survey on the interface and its sections. By making the platform affordable and operational from a single laptop connected to the physical prototype, the project directly addresses the institutional barriers identified in the literature and provides practical experience across kinematics, dynamics, and control to people interested in learning robotics.

The general objective of this project is to implement a delta robot prototype with a web interface so that people interested in learning parallel robotics understand forward and inverse kinematics concepts through practical interaction. The specific objectives are the following:

- Design the delta robot mechanical structure using CAD software and fabrication methods.
- Integrate angular position sensors for joint state feedback.
- Develop a web interface with forward and inverse kinematics, forward and inverse dynamics, and PID control sections.
- Validate the system through functional tests and validation sessions with participants and professors.

Chapter II

Methodology and Design

The requirements were derived from the needs of people interested in learning parallel robotics, observed among mechatronics students who had not yet taken a robotics course, mechatronics graduates who had already taken two robotics courses, and the course instructor, who constituted the primary stakeholders. Based on cost, infrastructure, and hardware complexity, the adoption barriers identified in Chapter 1, the system requirements were defined: low cost to remain accessible within a university budget, joint feedback so the user could observe the relationship between angles and end effector position, and a web interface operable from a single laptop connected to the robot, so that each requirement supports the goal of letting the user connect the kinematic and dynamic formulations and the PID control strategy to observable behavior on a real delta robot.

Delta robots are rarely used for this type of educational project, and that is the reason to build one: the platform exposes a parallel kinematics that people interested in learning parallel robotics would otherwise not encounter on real hardware. The delta was therefore not selected because its kinematics is easier; its forward kinematics is the analytically demanding direction and is treated in Section 2.3.1 as the object of study.

The three architectural views of the concept are then developed: the functional architecture decomposes the system into mechanical structure, actuation, sensing, control and communication, and educational interface; the logical architecture defines that the web interface sends joint angle or Cartesian commands to the controller, which emits Step, Direction, and Enable signals to the closed loop drivers through the CNC Shield and reads back the angular position sensors to display on the interface; and the physical architecture arranges the three motors on the fixed base platform, the linkages and end effector below, and the laptop connected over USB.

In the specific design stage, the robot geometry was modeled with parametric CAD software, the workspace volume was computed numerically and imported into the assembly to verify target reachability, torque calculations were performed to size the actuators, and a comparison of commercially available electronic components was carried out against the defined requirements. Mechanical simulations validated the structural design against the computed

reachable set. During integration, the physical prototype was built through 3D printing, laser cutting, sensor mounting, firmware development, and web interface integration.

Finally, the verification stage executed a test protocol where target joint angles were sent through the web interface and the angular position sensor readings were compared against the commanded values to confirm that the robot reached the expected positions. The five teaching sections of the web interface were also verified: the forward kinematics section by confirming that it returns the home position from the home joint angles, the inverse kinematics section by confirming that it recovers those angles from that position, the forward and inverse dynamics sections by confirming that the inertia matrix, the gravity vector, and the per joint torques are rendered with the live values substituted, and the PID section by confirming that the simulated joint response converges on the target and that the tracking error reaches zero.

2.1 Requirements

2.1.1 Stakeholders

The requirements were shaped by the people interested in learning parallel robotics who use the platform. The platform was tested at the two ends of that audience, with mechatronics students who had not yet taken a robotics course and with mechatronics graduates who had already taken two robotics courses. Their needs converge on a low cost, transportable, and observable robot whose internal computations are exposed rather than hidden.

2.1.2 Functional Requirements

- **FR1.** The system shall move the end effector to commanded Cartesian positions within the validated workspace.
- **FR2.** The system shall report each joint measured angle continuously to a host computer.
- **FR3.** The system shall present forward and inverse kinematics, forward and inverse dynamics, and PID control through the host side interface.
- **FR4.** The system shall present the forward kinematics, inverse kinematics, forward dynamics, inverse dynamics, and PID control contents as guided sections in which the user assembles each equation step by step.
- **FR5.** The system shall check each expression the user assembles and report whether it is correct before the section continues.

2.1.3 Nonfunctional Requirements

- **NFR1.** The system shall keep the joint position error against the commanded target below $\pm 1^\circ$ at the joint after homing.

- **NFR2.** The system shall operate from a single laptop connected over USB, without external network infrastructure.

2.1.4 Requirements Traceability Matrix

Table 1 presents the requirements traceability matrix.

TABLE 1
Requirements traceability matrix.

Req.	Design element that satisfies it	Verification activity	Section
FR1	Inverse kinematics algorithm, embedded on the microcontroller and duplicated on the host, plus the per joint trajectory generator on the microcontroller	Commanded Cartesian target reached within workspace	2.3.1, Chapter 3
FR2	Angular position sensors read on A0, A1, A2 and returned over serial on request	Measured angles returned on request	2.3.5, Chapter 3
FR3	Host side kinematics, dynamics, and PID sections	Each section exercised in the validation session	Chapter 3
FR4	The five guided sections of the web interface, in which the user assembles each equation step by step	Interface screens of the five sections, Figures 14 to 20	2.3.9
FR5	Server side check of each assembled expression before the section continues	The same screens show the assembly and its check, Figures 14 to 20	2.3.9
NFR1	Driver closed loop positioning, verified by the post gearbox angular position sensor	Commanded against measured angle below $\pm 1^\circ$	Chapter 3
NFR2	USB serial host link, no network stack	Connect from a laptop with no network	2.3.7

2.2 Conceptual Design

The two manipulator topologies are described first, the choice of the delta is justified, and only then are the three architectural views, functional, logical, and physical, developed for the selected concept.

2.2.1 Design Alternatives

Two manipulator topologies were carried forward from the review of educational platforms in Chapter 1 and evaluated against the requirement set of Section 2.1.

2.2.1.1 Alternative A: Serial Manipulator

A serial articulated arm places one actuator at each joint along an open kinematic chain: the distal actuators are carried by the proximal joints, raising the moving mass and the torque demand, and the chain accumulates the positioning error of every joint. Figure 1 shows the topology as sketched, one motor with encoder at each of the joints J_1 to J_4 , a metal base, and printed links.

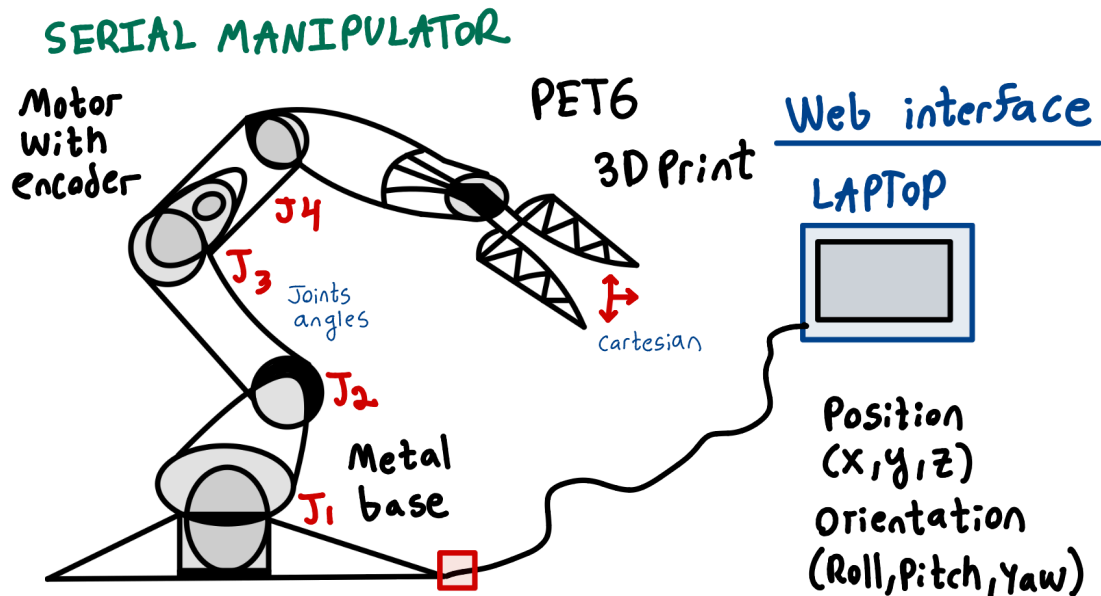


Fig. 1. Alternative A, serial articulated arm.

2.2.1.2 Alternative B: Delta Parallel Manipulator

A delta parallel manipulator fixes all three actuators to the base. The twin rod parallelogram of each chain constrains the platform to pure translation, so one chain derivation serves all three. The three chains carry the load in parallel, so positioning error is distributed, not accumulated. The inverse kinematics is one planar trigonometric equation per chain; the forward kinematics, requiring the intersection of three spheres, is the analytically demanding direction.

The work cell was sketched by hand before any component was ordered. Figure 2 reproduces the sketch, which fixed the laser cut panel layout, the arrangement of the three actuation units on the upper frame, and the conical work volume below the moving platform.

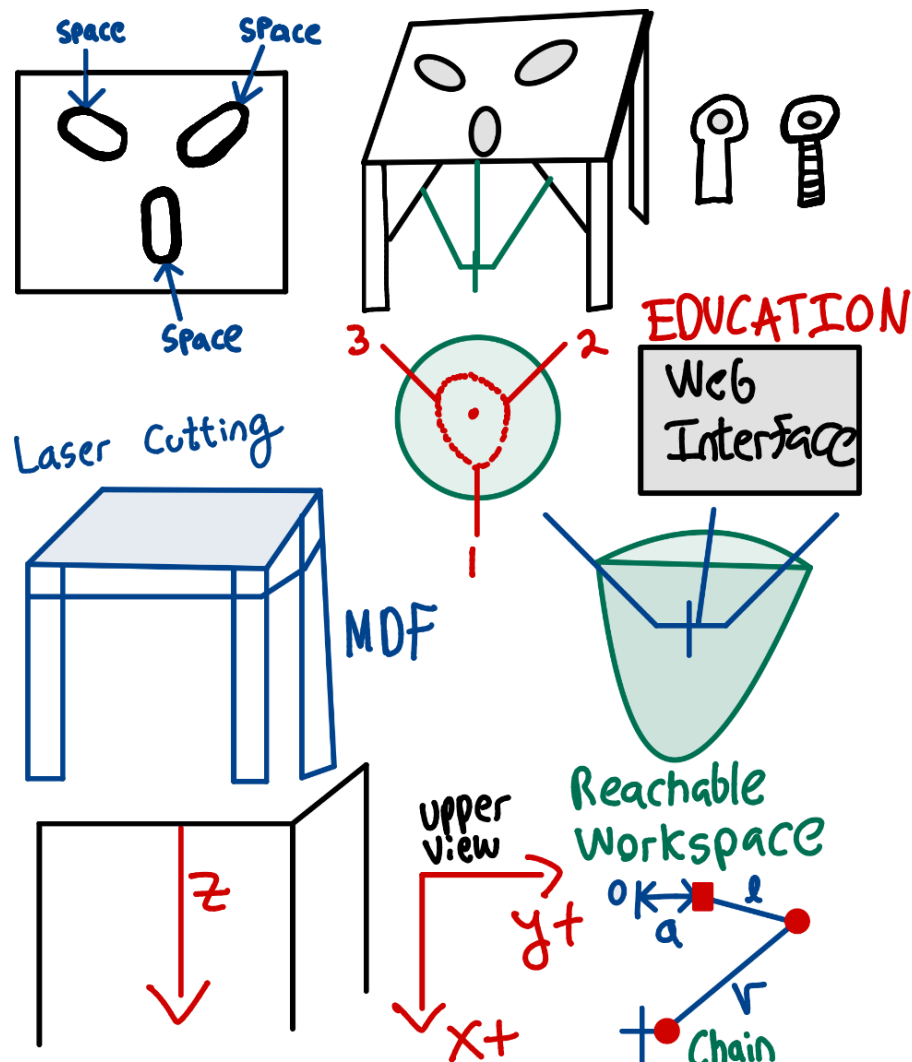


Fig. 2. Hand sketch of the delta robot.

Overall, serial manipulator prototypes are the most common robots used to teach robotics, so a delta robot is not a common choice for this type of education. The concept developed here adopts the delta deliberately, placing a parallel topology in front of the user on real hardware.

2.2.2 Functional Architecture

The main function, to demonstrate delta robot kinematics, is decomposed into six sub-functions: acquire the user command, compute the joint angles, drive each joint, position the end effector, measure each joint angle, and measure the effector position. The last two are the verification functions, whose instruments are specified in Chapter 3. Figure 3 shows the tree.

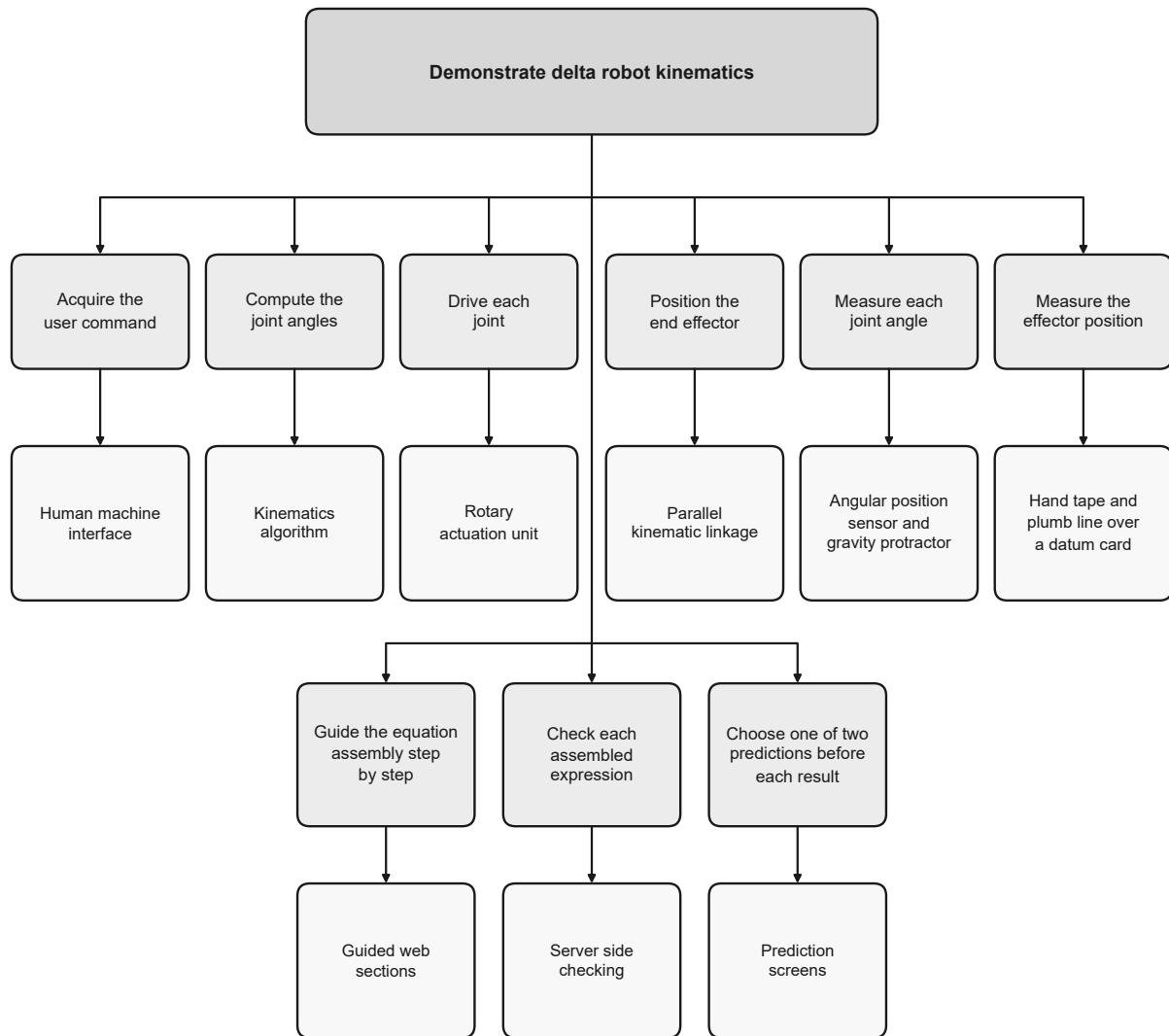


Fig. 3. Functional architecture: main function, subfunctions, and solution elements.

2.2.3 Logical Architecture

The command path runs from the user through the host and embedded processing units, the driver and the actuator to the parallel kinematic linkage, and the measurement path returns through the sensor and the signal conditioning to the embedded processing unit. The power supply feeds the driver. Figure 4 shows the arrangement.

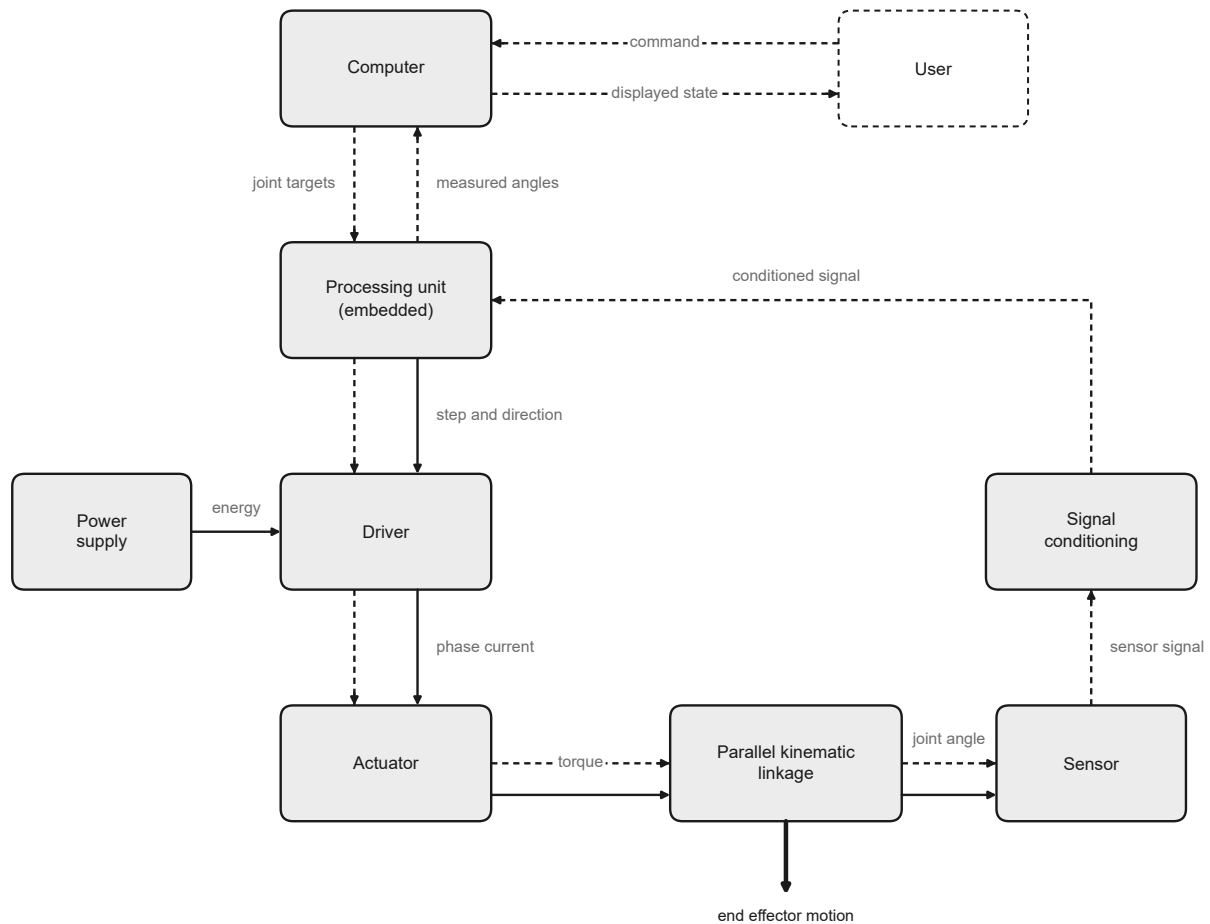


Fig. 4. Logical architecture: the command path, the measurement path, and the connections between them.

2.2.4 Physical Architecture

The system decomposes into five subsystems: mechanical structure, actuation, sensing, control and interface, and power. Each component is listed with the parameters that decide whether it is designed or acquired, and the lengths and masses of the mechanical parts are those the dynamic analysis of Section 2.3.2 consumes. The actuation subsystem repeats three times, one per joint. Figure 5 shows the hierarchy.

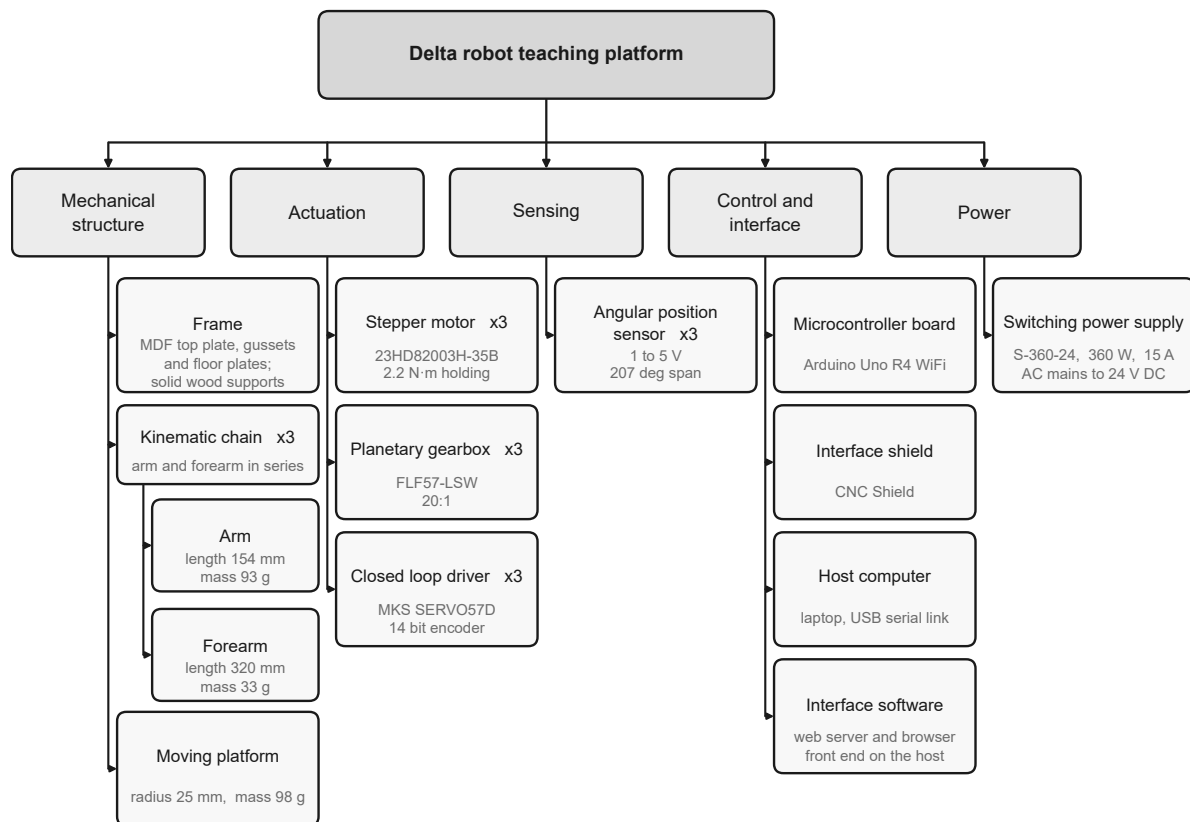


Fig. 5. Physical architecture: subsystems, components, and the parameters of each component.

2.2.5 Concept of the Educational Interface

The educational interface is the only block the user operates directly. The screen divides in two, a working place where each equation is assembled from symbol tiles and the ordered steps beside it, with the stages reached from the numbered strip along the top; the completed result is sent to the robot and watched through a webcam. Figure 6 shows the arrangement.

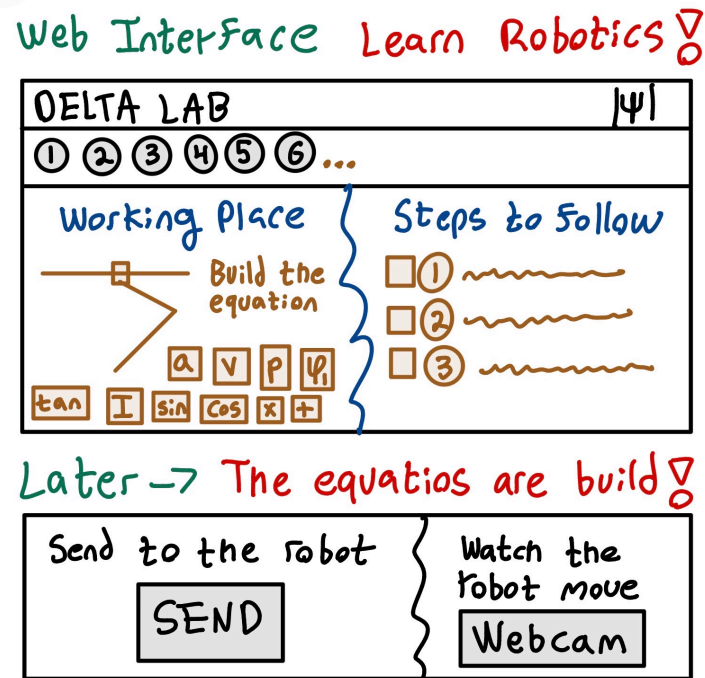


Fig. 6. Concept of the educational web interface.

2.3 Specific Design

The specific design follows the selection order: geometry and loads, then structure, actuators, sensors, and last the microcontroller and its port assignment, whose requirements are only then fully known.

2.3.1 Kinematic Design

This subsection derives the forward and inverse kinematics of the delta robot from a single set of homogeneous transformation matrices. Both procedures share the same geometric constraint and the same chain of elementary transforms.

The three identical kinematic chains of the delta robot are arranged symmetrically around a vertical axis. Each chain k consists of an arm of length l , articulated at the base by a rotary motor at angle θ_k , and a parallelogram forearm of length v that connects the elbow to the moving platform. Figure 7 shows the four geometric parameters on one chain; the robot has three such chains.

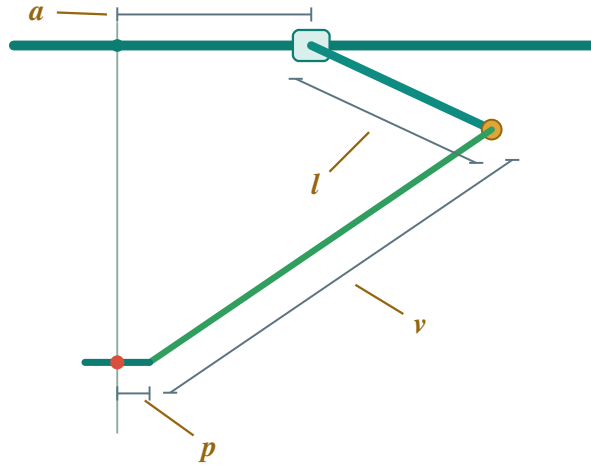


Fig. 7. Geometric parameters of the delta robot on one kinematic chain.

Each of the four lengths is fixed by an independent driver:

- $a = 150$ mm, the base radius from the motor pivot to the center: set by the envelope of the actuation unit, the motor frame with its reducer, driver and sensor bracket, three of which must sit at 120° without interference.
- $l = 154$ mm, the arm length: follows from a and v , placing the home configuration at $\theta_k = 76.5^\circ$ and $(0, 0, -200)$ mm with the elbow inside the frame footprint.
- $v = 320$ mm, the forearm length: sets the reach of the robot at the working height.
- $p = 25$ mm, the effector radius: the smallest that accepts the three pairs of ball joints, and subtracts from the reach through $a - p$ in Eq. (2.28).

The global reference frame $\{O\}$ is placed at the center of the base platform with the Z axis pointing upward, so the end effector operates at negative z . The three motors are located at the azimuthal angles

$$\phi_k = \frac{2\pi}{n}(k-1), \quad k = 1, 2, 3 \quad (2.1)$$

and each joint angle θ_k is measured from the downward vertical. The mechanical envelope restricts θ_k to the band from -23.5° to 76.5° , so the horizontal is never reached; the home configuration $\theta_k = 76.5^\circ$, effector at $(0, 0, -200)$ mm, is the upper limit of travel. Figure 8 shows the convention and the band.

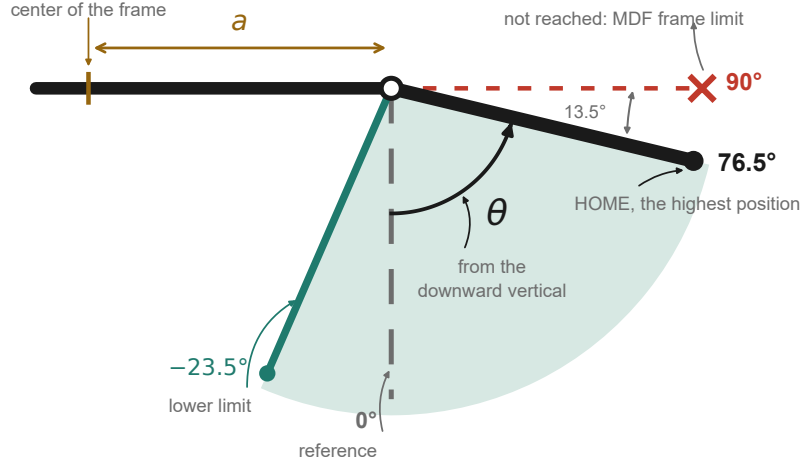


Fig. 8. Joint angle convention and the reachable band from -23.5° to 76.5° .

Elementary transformations. Four homogeneous 4×4 matrices generate every position used in this subsection.

The azimuthal rotation $\mathbf{R}(\phi_k)$ orients the local frame of arm k relative to the global frame:

$$\mathbf{R}(\phi_k) = \begin{pmatrix} \cos \phi_k & -\sin \phi_k & 0 & 0 \\ \sin \phi_k & \cos \phi_k & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (2.2)$$

The base translation $\mathbf{T}_a$ moves the origin from the center of the base to the motor pivot, a distance a along $-Y$ local:

$$\mathbf{T}_a = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & -a \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (2.3)$$

The arm translation $\mathbf{T}(\theta_k)$ moves from the motor pivot to the elbow, following the arm

rotated by θ_k :

$$\mathbf{T}(\theta_k) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & -l \sin \theta_k \\ 0 & 0 & 1 & -l \cos \theta_k \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (2.4)$$

The effector translation $\mathbf{T}_p$ and its inverse $\mathbf{T}_p^{-1}$ model the effector radius p as a displacement of $-p$ (respectively $+p$) along Y local:

$$\mathbf{T}_p = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & -p \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \quad \mathbf{T}_p^{-1} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & +p \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (2.5)$$

Kinematic chain of arm k and adjusted point $\mathbf{C}_k$. The chain from the global origin to the elbow of arm k is

$$\mathbf{H}_k = \mathbf{R}(\phi_k) \mathbf{T}_a \mathbf{T}(\theta_k) \quad (2.6)$$

and the connection point of the forearm with the effector (the **adjusted point $\mathbf{C}_k$**) adds the inverse effector translation, rotated to the global frame:

$$\mathbf{C}_k = \mathbf{H}_k \mathbf{T}_p^{-1} \quad (2.7)$$

Applying the chain to the homogeneous origin $\mathbf{0}_h = (0, 0, 0, 1)^\top$, the elbow in global coordinates is

$$\boxed{H_k^x = (a + l \sin \theta_k) \sin \phi_k, \quad H_k^y = -(a + l \sin \theta_k) \cos \phi_k, \quad H_k^z = -l \cos \theta_k} \quad (2.8)$$

and, after rotating the local offset $+p$ to the global frame, the adjusted point is

$$\boxed{C_k^x = H_k^x - p \sin \phi_k, \quad C_k^y = H_k^y + p \cos \phi_k, \quad C_k^z = H_k^z} \quad (2.9)$$

The squared norm of the adjusted point is the auxiliary scalar

$$w_k = \|\mathbf{C}_k\|^2 = (C_k^x)^2 + (C_k^y)^2 + (C_k^z)^2 \quad (2.10)$$

The fundamental geometric constraint, valid for both forward and inverse kinematics, is that the forearm of length v connects $\mathbf{C}_k$ to the effector $\mathbf{e} = (x, y, z)^\top$:

$$\|\mathbf{e} - \mathbf{C}_k\|^2 = v^2, \quad k = 1, 2, 3 \quad (2.11)$$

2.3.1.1 Forward Kinematics Derivation

Problem. Given $(\theta_1, \theta_2, \theta_3)$, find the effector position (x, y, z) .

Because the joint angles are known, $\mathbf{C}_k$ is computed directly from Eqs. (2.8) to (2.9) and the constraint (2.11) becomes a system of three equations in the three unknowns (x, y, z) .

Step 1: Compute $\mathbf{C}_k$ and w_k . For each $k \in \{1, 2, 3\}$ evaluate in order Eqs. (2.8), (2.9), and (2.10).

Step 2: Three sphere equations. The effector must lie at distance v from each $\mathbf{C}_k$. Expanding (2.11) yields three sphere equations:

$$x^2 + y^2 + z^2 - 2(C_1^x x + C_1^y y + C_1^z z) + w_1 = v^2 \quad (2.12)$$

$$x^2 + y^2 + z^2 - 2(C_2^x x + C_2^y y + C_2^z z) + w_2 = v^2 \quad (2.13)$$

$$x^2 + y^2 + z^2 - 2(C_3^x x + C_3^y y + C_3^z z) + w_3 = v^2 \quad (2.14)$$

Step 3: From spheres to planes. Solving the system directly is costly because of the quadratic terms $x^2 + y^2 + z^2$. Subtracting the first sphere from the second and third cancels the quadratic terms exactly, leaving two linear plane equations in (x, y, z) :

$$2(C_2^x - C_1^x)x + 2(C_2^y - C_1^y)y + 2(C_2^z - C_1^z)z = w_2 - w_1 \quad (2.15)$$

$$2(C_3^x - C_1^x)x + 2(C_3^y - C_1^y)y + 2(C_3^z - C_1^z)z = w_3 - w_1 \quad (2.16)$$

The intersection of these two planes is a line, and the effector lies on that line.

Step 4: Direction of the intersection line. The direction $\mathbf{d}$ is perpendicular to both

plane normals

$$\mathbf{n}_{12} = \begin{pmatrix} C_2^x - C_1^x \\ C_2^y - C_1^y \\ C_2^z - C_1^z \end{pmatrix}, \quad \mathbf{n}_{13} = \begin{pmatrix} C_3^x - C_1^x \\ C_3^y - C_1^y \\ C_3^z - C_1^z \end{pmatrix} \quad (2.17)$$

$$\boxed{\mathbf{d} = \mathbf{n}_{13} \times \mathbf{n}_{12}} \quad (2.18)$$

and the line is parametrized using z as the free parameter

$$x(z) = X_0 + r_x z, \quad y(z) = Y_0 + r_y z, \quad r_x = \frac{d_x}{d_z}, \quad r_y = \frac{d_y}{d_z} \quad (2.19)$$

Step 5: Base point of the line. Evaluating (2.19) at $z = 0$ in the two planes gives the 2×2 system

$$\begin{pmatrix} C_2^x - C_1^x & C_2^y - C_1^y \\ C_3^x - C_1^x & C_3^y - C_1^y \end{pmatrix} \begin{pmatrix} X_0 \\ Y_0 \end{pmatrix} = \frac{1}{2} \begin{pmatrix} w_2 - w_1 \\ w_3 - w_1 \end{pmatrix} \quad (2.20)$$

with closed form solution

$$\boxed{\begin{aligned} X_0 &= \frac{(w_2 - w_1)(C_3^y - C_1^y) - (w_3 - w_1)(C_2^y - C_1^y)}{2 \det(\mathbf{M})}, \\ Y_0 &= \frac{(w_3 - w_1)(C_2^x - C_1^x) - (w_2 - w_1)(C_3^x - C_1^x)}{2 \det(\mathbf{M})} \end{aligned}} \quad (2.21)$$

where $\mathbf{M}$ is the 2×2 matrix in (2.20) and $\det(\mathbf{M}) = (C_2^x - C_1^x)(C_3^y - C_1^y) - (C_3^x - C_1^x)(C_2^y - C_1^y)$.

Step 6: Line and sphere intersection. Substituting (2.19) into the first sphere (2.12) yields a quadratic in the single unknown z . With auxiliaries

$$E_x = X_0 - C_1^x, \quad E_y = Y_0 - C_1^y, \quad E_z = -C_1^z \quad (2.22)$$

the quadratic is

$$\underbrace{(r_x^2 + r_y^2 + 1)}_{a_q} z^2 + \underbrace{2(E_x r_x + E_y r_y + E_z)}_{b_q} z + \underbrace{E_x^2 + E_y^2 + E_z^2 - v^2}_{c_q} = 0 \quad (2.23)$$

with two roots

$$z_{1,2} = \frac{-b_q \pm \sqrt{b_q^2 - 4a_q c_q}}{2a_q} \quad (2.24)$$

Because the delta robot effector hangs below the base, the physical solution is always the smaller z :

$$z = \min(z_1, z_2), \quad x = X_0 + r_x z, \quad y = Y_0 + r_y z \quad (2.25)$$

Numerical validation (symmetric input). With $\theta_1 = \theta_2 = \theta_3 = 76.5^\circ$ the symmetry of the mechanism produces an effector centered on the vertical axis:

$$x \approx 0 \text{ mm}, \quad y \approx 0 \text{ mm}, \quad z \approx -200 \text{ mm} \quad (2.26)$$

which matches the prototype's home configuration.

2.3.1.2 Inverse Kinematics Derivation

Problem. Given the desired effector position $\mathbf{e} = (x, y, z)^\top$, find the joint angles $(\theta_1, \theta_2, \theta_3)$.

By the symmetry of the delta robot, the three dimensional problem decomposes into three independent two dimensional subproblems, one per arm. For each arm k the procedure finds the θ_k that places the adjusted point at distance v from the effector.

Step 1: Project the effector to the local plane of arm k . Each arm operates in its own local plane, oriented by ϕ_k . The effector is rotated by ϕ_k from (2.1):

$$x_k = x \cos \phi_k + y \sin \phi_k, \quad y_k = -x \sin \phi_k + y \cos \phi_k, \quad z_k = z \quad (2.27)$$

Step 2: Local distances. In the local plane of arm k , the net horizontal distance from the motor pivot to the connection point on the effector (discounting the base radius a and the effector radius p that already appear in (2.9)) is

$$\Delta y_k = y_k + a - p, \quad \Delta z_k = z_k \quad (2.28)$$

and the squared distance between motor pivot and effector is

$$W_k = x_k^2 + \Delta y_k^2 + \Delta z_k^2 \quad (2.29)$$

Step 3: Trigonometric equation of the forearm. The constraint (2.11), written in local coordinates and expanded using $\sin^2 \theta_k + \cos^2 \theta_k = 1$, gives

$$\Delta y_k \sin \theta_k + \Delta z_k \cos \theta_k = -\frac{W_k + l^2 - v^2}{2l} \quad (2.30)$$

which has the canonical form $A_k \sin \theta_k + B_k \cos \theta_k = -c_k$ with

$$\boxed{A_k = \Delta y_k, \quad B_k = \Delta z_k, \quad c_k = \frac{W_k + l^2 - v^2}{2l}} \quad (2.31)$$

Step 4: Closed form solution. Applying the identity $A \sin \theta + B \cos \theta \equiv R \sin(\theta + \alpha)$ with

$$R_k = \sqrt{A_k^2 + B_k^2}, \quad \alpha_k = \text{atan2}(B_k, A_k) \quad (2.32)$$

the equation reduces to $R_k \sin(\theta_k + \alpha_k) = -c_k$. The point **e** is unreachable for arm k whenever

$$\left| \frac{c_k}{R_k} \right| > 1 \quad (2.33)$$

otherwise the joint angle is

$$\boxed{\theta_k = \arcsin\left(-\frac{c_k}{R_k}\right) - \alpha_k} \quad (2.34)$$

Numerical validation (round trip). For the desired position $(x, y, z) = (0, 0, -200)$ mm the inverse kinematics returns $\theta_1 = \theta_2 = \theta_3 \approx 76.5^\circ$. Feeding these angles into the forward kinematics recovers the original position with a consistency error

$$\varepsilon = \|\mathbf{e}_{\text{FK}} - \mathbf{e}_{\text{desired}}\| < 4 \times 10^{-3} \text{ mm} \quad (2.35)$$

confirming the algebraic consistency of the two derivations.

2.3.1.3 Workspace Analysis

Figure 9 shows the reachable workspace of the built geometry: the bowl in the xz plane and the threefold footprint at $z = -300$ mm. On the central axis it extends from about $z = -160$ to -456 mm; at $z = -300$ mm the reachable radius is about 243 mm, with the home pose $(0, 0, -200)$ mm near the top. The outer region is link geometry only, to be confirmed by physical jog tests.

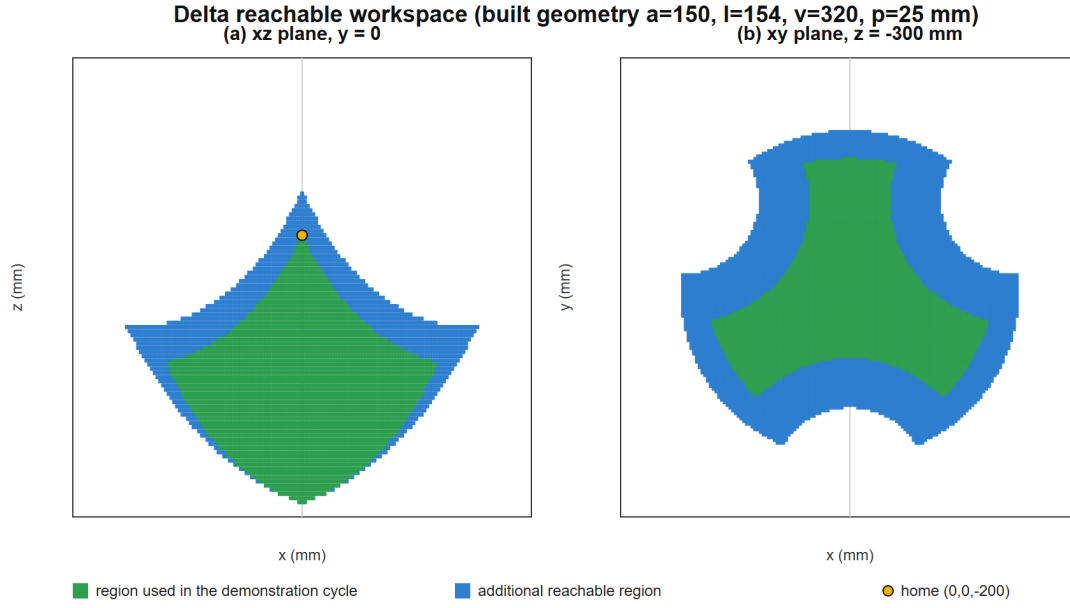


Fig. 9. Computed reachable workspace of the delta robot.

2.3.2 Dynamic Design

This subsection derives the equation of motion of the delta robot from the Euler Lagrange formulation and applies it numerically to size the actuators. The equation of motion in the motor space is

$$\mathbf{D}(\theta) \ddot{\theta} + \mathbf{G}(\theta) = \tau \quad (2.36)$$

where:

- $\mathbf{D}$: generalized inertia matrix
- $\mathbf{G}$: gravitational torque vector
- τ : vector of motor torques
- θ : vector of joint angles

Coriolis terms are neglected because the operating velocities of an educational pick and place cycle are well below the regime where centripetal coupling becomes relevant. The implementation also includes a small viscous damping term $b \dot{\theta}$ proportional to the joint velocity, which vanishes in the static holding analysis used for the torque sizing.

2.3.2.1 Forward and Inverse Dynamics Derivations

Geometric Jacobian. The Jacobian relates motor velocities to Cartesian effector velocity through $\dot{\mathbf{e}} = \mathbf{J}_g \dot{\theta}$ and is factorized as $\mathbf{J}_g = \mathbf{J}_v^{-1} \mathbf{J}_\theta$, with rows assembled from the forearm

vector and the motor axis:

$$[\mathbf{J}_v]_{k,:} = \mathbf{r}_{\pi i}^{(k)}, \quad [\mathbf{J}_\theta]_{k,k} = \hat{\mathbf{a}}_k \cdot (\mathbf{r}_{l,a}^{(k)} \times \mathbf{r}_{\pi i}^{(k)}) \quad (2.37)$$

where $\mathbf{r}_{\pi i}^{(k)}$ is the elbow to effector vector and $\hat{\mathbf{a}}_k = \mathbf{R}(\phi_k)(-\hat{\mathbf{x}})$ is the motor axis expressed in the global frame.

Generalized inertia matrix. The inertia tensors obtained from the parametric CAD model are expressed in the local frame of each component, so they are first carried to the global frame through the similarity transform $\mathbf{I}_{\text{global}}^{(k)} = \mathbf{R}_k \mathbf{I}_{\text{CAD}} \mathbf{R}_k^\top$ with $\mathbf{R}_k = \mathbf{R}(\phi_k) \mathbf{R}_x(\theta_k)$. The matrix is then assembled as

$$\mathbf{D} = m_{\text{ef}} \mathbf{J}_g^\top \mathbf{J}_g + \sum_{k=1}^3 \left[(m_{\text{sup}} + m_{\text{ant}}) [\mathbf{J}_{v,l}^{(k)}]^\top \mathbf{J}_{v,l}^{(k)} + [\mathbf{J}_{w,l}^{(k)}]^\top (\mathbf{I}_{\text{sup}}^{(k)} + \mathbf{I}_{\text{ant}}^{(k)}) \mathbf{J}_{w,l}^{(k)} \right] \quad (2.38)$$

where the auxiliary arm Jacobians are

$$[\mathbf{J}_{v,l}^{(k)}]_{:,k} = \mathbf{R}(\phi_k) \begin{pmatrix} 0 \\ -l \cos \theta_k \\ l \sin \theta_k \end{pmatrix}, \quad [\mathbf{J}_{w,l}^{(k)}]_{:,k} = \hat{\mathbf{a}}_k \quad (2.39)$$

Gravity vector. The gravitational torque, obtained by projecting weight contributions through the same Jacobians, is

$$\mathbf{G} = - \left(m_{\text{ef}} \mathbf{J}_g^\top + \sum_{k=1}^3 m_{\text{sup}} [\mathbf{J}_{v,l}^{(k)}]^\top \right) \mathbf{g} \quad (2.40)$$

which combined with (2.38) closes the equation of motion (2.36). The arm weight is projected here through the elbow Jacobian at the full arm length, which is conservative relative to the midpoint lever used in the numerical implementation and slightly increases the sizing margin.

2.3.2.2 Numerical Implementation

Table 2 states the physical data: the masses were measured on the assembled prototype and the inertia tensors were exported from the parametric CAD model of each component.

TABLE 2
Physical data of the delta robot bodies

Body	Mass	Relevant inertia
Arm	$m_{\text{sup}} = 93 \text{ g}$	$I_{zz} = 1.44 \times 10^5 \text{ g} \cdot \text{mm}^2$
Forearm	$m_{\text{ant}} = 33 \text{ g}$	full tensor (see below)
Moving platform	$m_{\text{plat}} = 98 \text{ g}$	n/a
Design payload at the moving platform	$m_{\text{pay}} = 684 \text{ g}$	n/a

The full inertia tensors, converted from $\text{g} \cdot \text{mm}^2$ to $\text{kg} \cdot \text{m}^2$ by dividing by 10^9 , are

$$\mathbf{I}_{\text{sup}} = \begin{pmatrix} 27962 & 0.6 & 4092 \\ 0.6 & 139000 & 0.02 \\ 4092 & 0.02 & 144000 \end{pmatrix} \times 10^{-9} \text{ kg} \cdot \text{m}^2 \quad (2.41)$$

$$\mathbf{I}_{\text{ant}} = \begin{pmatrix} 708000 & -1565 & -825 \\ -1565 & 165000 & -286000 \\ -825 & -286000 & 581000 \end{pmatrix} \times 10^{-9} \text{ kg} \cdot \text{m}^2 \quad (2.42)$$

The moving platform translates as a single body together with the payload and the three forearms, so the effective mass that the Jacobian sees at the effector node is

$$m_{\text{ef}} = m_{\text{plat}} + m_{\text{pay}} + 3 m_{\text{ant}} = 0.098 + 0.684 + 3(0.033) = 0.881 \text{ kg} \quad (2.43)$$

The full motor torque vector $\boldsymbol{\tau}$ is evaluated by sweeping each joint from approximately -5° to 90° , wider than the travel band of the built prototype, over $40^3 = 64\,000$ configurations at the design acceleration $\ddot{\boldsymbol{\theta}} = 10 \text{ rad/s}^2$. At each configuration the Jacobians, the inertia matrix, and the gravity vector are recomputed and the equation

$$\boxed{\boldsymbol{\tau} = \mathbf{D}(\boldsymbol{\theta}) \ddot{\boldsymbol{\theta}} + \mathbf{G}(\boldsymbol{\theta})} \quad (2.44)$$

is solved. The largest joint torque found anywhere in the workspace (the maximum of $\|\boldsymbol{\tau}\|_\infty$) is taken as the worst case, and the actuators are sized against it.

2.3.2.3 Torque Reconciliation

The workspace sweep produces both a static (gravity only, $\ddot{\theta} = 0$) and a dynamic (full $\ddot{\theta} = 10 \text{ rad/s}^2$) peak torque. The dynamic peak decomposes into a gravitational and an inertial contribution:

$$\tau_{\max} = \underbrace{1.306 \text{ N}\cdot\text{m}}_{\text{gravity}} + \underbrace{0.218 \text{ N}\cdot\text{m}}_{\text{inertia}} = 1.524 \text{ N}\cdot\text{m} \quad (2.45)$$

Table 3 reports the two peaks of the sweep; the dynamic entry and the result of Eq. (2.45) are the same quantity, the equation splitting it into the gravitational term computed at zero acceleration and the inertial term contributed by the design acceleration.

TABLE 3
Peak torque from the workspace sweep

Condition	$\tau_{\max} \text{ (N}\cdot\text{m)}$
Static (holding, $\ddot{\theta} = 0$)	1.306
Dynamic ($\ddot{\theta} = 10 \text{ rad/s}^2$)	1.524

Gravity dominates the load. The critical pose occurs when one arm sits nearly horizontal ($\theta \approx 87^\circ$) and the load hangs at the lower workspace boundary for that configuration ($z \approx -319 \text{ mm}$).

2.3.3 Mechanical Structure

2.3.3.1 Frame, Base, Kinematics Chains, moving platform

The mechanical subsystem comprises the laser cut medium density fiberboard frame, three identical kinematic chains at $\phi_k = \{0^\circ, 120^\circ, 240^\circ\}$, and the moving platform; each arm fixes directly to the gearbox output shaft, and each forearm is twin carbon fiber rods with spherical ball joints.

2.3.3.2 CAD Model

The system was modeled in parametric CAD; the model supplies the lengths, masses, and inertia tensors used in the calculations, and generated the laser cut sheet drawings and the STL files for the 3D printed brackets. Figure 10 shows the assemblies.

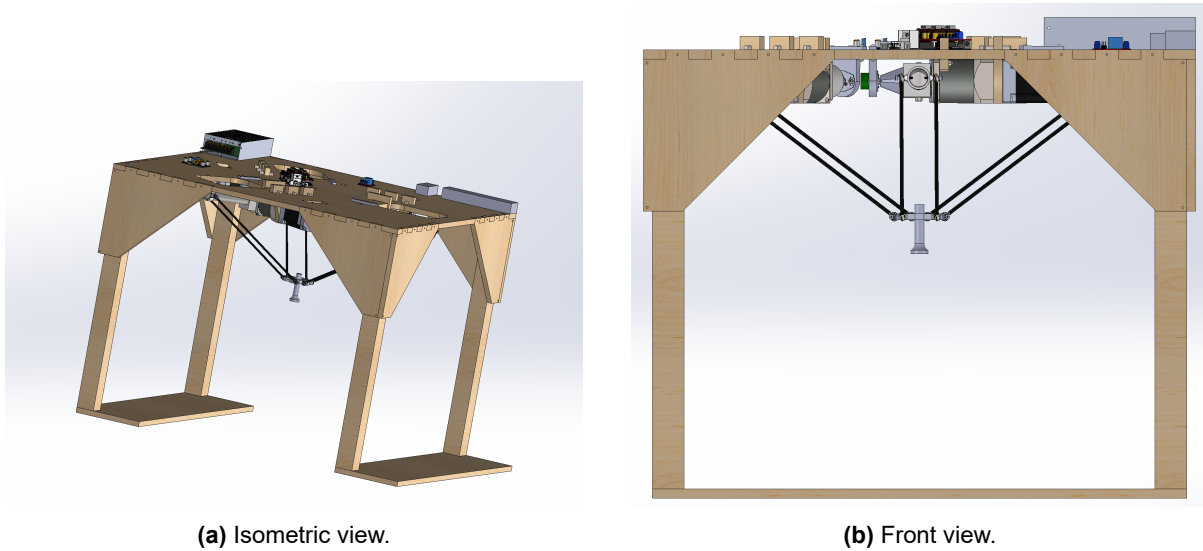


Fig. 10. CAD assembly of the main delta structure.

2.3.4 Actuation

2.3.4.1 Stepper and Planetary Gearbox Selection

The actuator is sized against the dynamic peak torque $\tau_{\max} = 1.524 \text{ N}\cdot\text{m}$. Applying a service factor of $\text{FS} = 5$ gives the design torque at the joint side

$$\tau_{\text{design}} = \tau_{\max} \times \text{FS} = 1.524 \times 5 = 7.62 \text{ N}\cdot\text{m} \quad (2.46)$$

The 1:20 planetary reduction scales the motor shaft torque to $7.62/20 \approx 0.38 \text{ N}\cdot\text{m}$, within a NEMA 23 rating. The stepper, 23HD82003H-35B with an FLF57-LSW 20:1 reducer, delivers $2.2 \text{ N}\cdot\text{m}$ at 4.6 A ; at about 0.85 efficiency the joint torque is about $37 \text{ N}\cdot\text{m}$, a margin near five over the design torque and twenty four over the dynamic peak.

2.3.4.2 Closed Loop Driver Selection

Three drive alternatives were considered for the joint actuators, and the comparison is reported in Table 4.

TABLE 4
Driver comparison for the joint actuators.

Criterion	A4988 DRV8825, loop	or open Brushless servo module, in- tegrated controller	DC MKS SERVO57D, closed loop
Step loss under load	Undetected	Not applicable	Detected and corrected internally
Position feedback	None	Integrated encoder in the module	14 bit magnetic encoder on the motor shaft
Loop closure	Host or none	Internal, in the module controller	Internal cascade at 20 kHz
Current at rest	Full rated holding current	Proportional to load	Regulated to the demanded torque
Interface to the Arduino	Step, Direction, Enable	Serial or pulse commands, protocol specific	Step, Direction, Enable
Cost per axis	Lowest	Highest of the three	Between the two

Each motor is therefore paired with an MKS SERVO57D closed loop driver because the platform must be able to show the user that each joint reached its commanded angle, and an open loop drive cannot support that statement: the driver integrates a 14 bit magnetic encoder and runs a current, velocity, and position cascade internally at 20 kHz, so commanded steps are executed without loss under load, and the independent angular position sensors verify the reached angle after the reduction, where the driver encoder on the motor shaft cannot read. The Step, Direction, and Enable signals from the Arduino reach the three drivers through the CNC Shield.

2.3.5 Sensing

2.3.5.1 Joint Angular Position Sensor Selection

The joint sensor has to report the angle after the reduction, the quantity NFR1 is written against. Table 5 compares three candidates.

TABLE 5
Angular position sensor comparison.

Criterion	Rotary potentiometer	Incremental encoder on the gearbox output	Absolute angular position sensor
Absolute reading at power up	Yes	No, requires an indexing move	Yes
Resolution of the element	Limited by track wear	High	12 bit, about 0.088°
Response time	Immediate	Immediate	About 3 ms, that is about 333 Hz
Wear mechanism	Sliding contact on a resistive track	None	None, no contact
Interface to the Arduino	One analog input	Two interrupt capable digital inputs per axis	One analog input
Inputs required for three joints	3 analog	6 digital, interrupt capable	3 analog

Each joint carries an independent absolute angular position sensor, 12 bit, coupled to the gearbox output. It returns the angle on request and closes the homing loop at start up; no position loop runs on it during motion.

Read on analog inputs A0 to A2, the acquisition resolves about 0.43° per code with the per axis gain of about 1.71, twelve readings averaged per request: better than half of the $\pm 1^\circ$ of NFR1.

The selection turned on the absolute reading at power up and the absence of wear; the post reduction mounting reports the angle the Chapter 3 verification is written against.

2.3.6 Microcontroller Selection

The board must emit three Step and Direction pairs plus a shared Enable, read three analog channels, hold a serial link to the host, and accept the CNC Shield that carries the power trunk to the three drivers.

The drive train demands about 1000 steps per second per axis, 3000 for the three, emitted from software while the same loop parses commands and reads the sensors. Figure 11 compares three candidates against these figures.

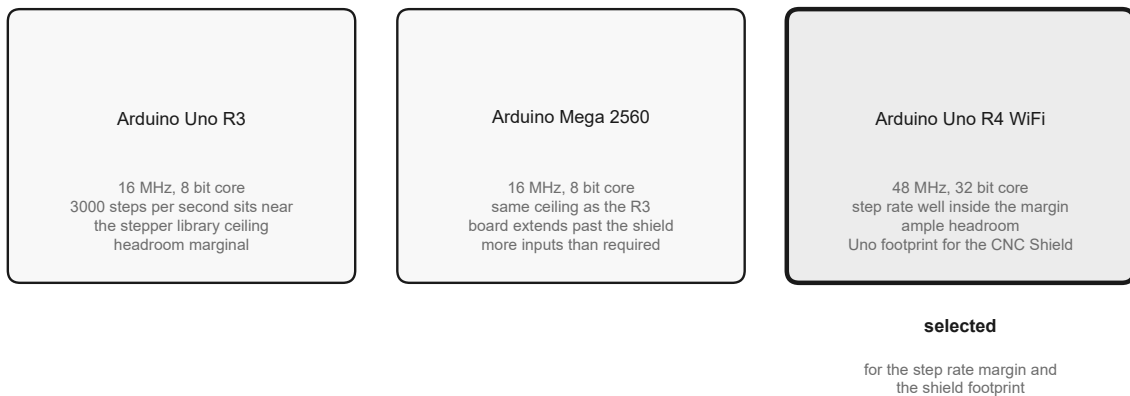


Fig. 11. Microcontroller comparison and selection.

The Uno R4 WiFi is selected: it keeps the Uno footprint the shield requires, and its 48 MHz core leaves margin on the pulse rate where the 16 MHz Uno R3 sits at the ceiling.

2.3.7 Port and Signal Assignment

Figure 12 is the complete map, and it is the same assignment compiled into the firmware.

The assignment leaves three of the six analog channels free, A3, A4 and A5, and five digital lines, D9 to D13.

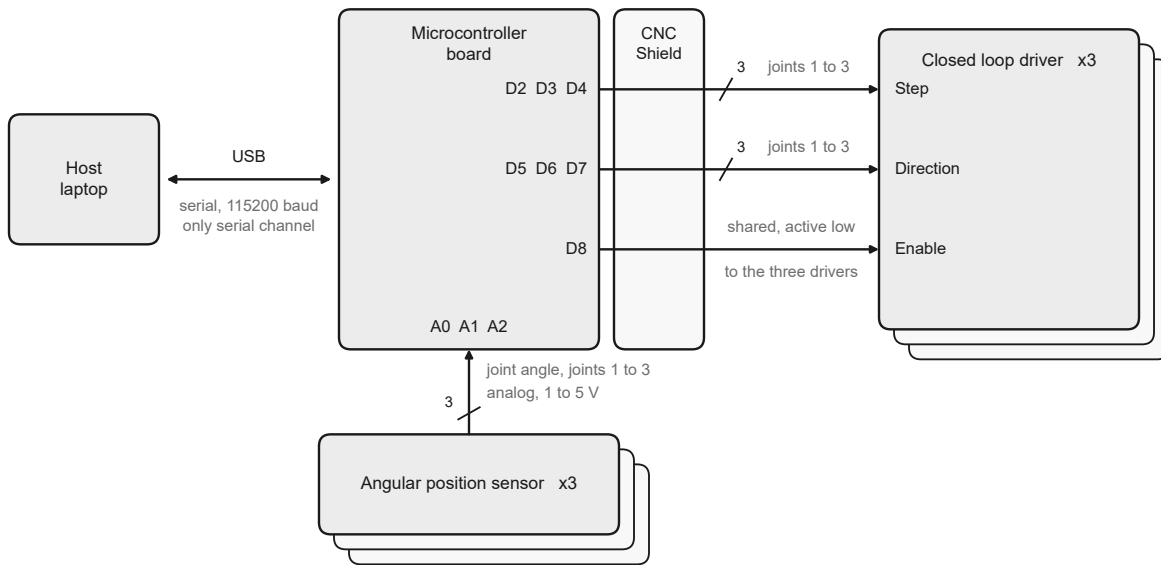


Fig. 12. Port and signal assignment on the Arduino Uno R4 WiFi.

2.3.8 Control Architecture

2.3.8.1 Closed Loop Positioning and Joint Verification

The position loop is closed inside each driver on its own encoder; the board issues Step, Direction and Enable and computes one trapezoidal profile per joint, so motion is coordinated in joint space. Homing is the exception: each joint steps toward zero on the sensor reading until it is inside a one degree band.

2.3.8.2 PID Control Model

The PID control law is modeled on the host and is not part of the hardware control path. The discrete law is

$$u[k] = K_p e[k] + K_i \sum_{j=0}^k e[j] \Delta t + K_d \frac{e[k] - e[k-1]}{\Delta t} \quad (2.47)$$

with $e[k] = \theta_{\text{cmd}}[k] - \theta_{\text{meas}}[k]$. At the default gains, a step from 55° , 62° , and 69° to the 76.5° home settles in 1.02 s with no overshoot. The model is never sent to the robot; it exists to expose the behavior of the loop the driver closes internally.

2.3.8.3 Block Diagram

Figure 13 shows the command and feedback paths: the host sends joint targets, the driver closes the position loop before the reduction, and the post gearbox sensor provides the homing reference and the angle readback used for verification.

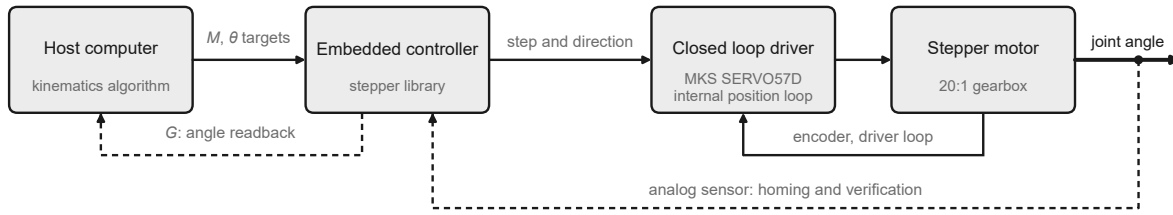


Fig. 13. Control and command architecture; the host side PID and dynamics models are not in the control path.

2.3.9 Educational Interface Design

Each load bearing expression is assembled from symbol blocks in the order the guide states and checked on the server; the same block set serves the five sections.

The closing screen of each section substitutes the constants of the delta robot and evaluates the assembled expressions, and the forward kinematics result is sent to the robot and observed through the webcam. The screens shown here are the final version of the interface, produced from the feedback the twelve participants gave on the version used in their sessions.

2.3.9.1 Assessment Instrument

The same eleven item questionnaire is administered before and after the session: eleven items, four options each, over five concept areas. The measured quantity is the normalized gain, $g = (\text{post} - \text{pre}) / (100 - \text{pre})$. It was administered in Spanish; the items, translated, are in the appendix, Table 7.

2.3.9.2 Interface of the Five Sections

Figure 14 shows the third of the eight forward kinematics screens: figure and legend on the left, equation boxes in the center, the ordered guide on the right.

ÁREA DE TRABAJO

ESTACIÓN A **Cinemática directa** Parte: 0/1

Modo de prueba: Saltar las láminas de esta estación

1 2 3 4 5 6 7 8

3 de 8 **EL CODO: DONDE TERMINA EL BRAZO SUPERIOR**

Dos expresiones ubican el codo: su alcance en horizontal y su caída en vertical.

VISTA LATERAL, PIERNA 1

1 El radio de la base: del centro al pivote del motor (a, dado).

2 Lo que el brazo alcanza en horizontal al girar θ_1 .

3 Lo que el brazo cae en vertical (hacia abajo).

4 El codo: la punta del brazo superior (longitud l).

ECUACIÓN

alcance radial del codo =

seguir la guía: tocar las variables en orden

profundidad del codo =

seguir la guía: tocar las variables en orden

VARIABLES

a 3 p v l tan

sin θ_2 cos θ_3 θ_1 φ_1

+ x - z · 2 (

/) ^ k √ 1

quitar el último limpiar

Comprobar

GUÍA

A Estación A. Cinemática directa 0/1

Lámina 3 de 8 · El codo: donde termina el brazo superior

1. Leer los puntos numerados bajo la figura.
2. Armar en el recuadro ECUACIÓN tocando las variables del recuadro VARIABLES, en este orden:
3. Tocar el botón rojo **alcance radial del codo**.
4. Tocar la variable **a**.
5. Tocar la variable **+**.
6. Tocar la variable **l**.
7. Tocar la variable **·**.
8. Tocar la variable **sin**.
9. Tocar la variable **θ_1** .
10. Tocar el botón rojo **profundidad del codo**.
11. Tocar la variable **-**.
12. Tocar la variable **l**.
13. Tocar la variable **·**.
14. Tocar la variable **cos**.
15. Tocar la variable **θ_1** .
16. Pulsar **Comprobar**.

Fig. 14. Forward kinematics, screen 3 of 8: the elbow expressions assembled from blocks.

Figure 15 shows the closing forward kinematics screen, where the geometric constants of the delta robot are substituted and the assembled kinematics is evaluated.

ÁREA DE TRABAJO

ESTACIÓN A **Cinemática directa** Parte: 0/1

Modo de prueba: Saltar las láminas de esta estación

1 2 3 4 5 6 7 8

8 de 8 **CALCULAR Y ENVIAR**

Tarjeta 2 de 4

2 **DATOS Y CÁLCULO**

DATOS

a (radio de la base)	150 mm
l (brazo superior)	154 mm
v (antebrazo)	320 mm
p (desplazamiento de la plataforma)	25 mm

Calcular la posición del efector

Tarjeta anterior Siguiente tarjeta

Anterior Siguiente

GUÍA

A Estación A. Cinemática directa 0/1

Lámina 8 de 8 · Calcular y enviar

1. En la tarjeta (1), los tres brazos ya vienen puestos en el caso de trabajo: $\theta_1 = 65^\circ$ (brazo 1), $\theta_2 = 35^\circ$ (brazo 2) y $\theta_3 = 50^\circ$ (brazo 3). Arrastrar una figura solo para explorar otros ángulos.
2. Pasar a la tarjeta (2) con **Siguiente tarjeta** y pulsar **Calcular la posición del efector**.
3. Leer el resultado en la tarjeta (3).
4. Con el robot conectado, pulsar **Enviar θ al robot** en la tarjeta (4) y mirar la cámara en Teams.

Fig. 15. Forward kinematics, screen 8 of 8: evaluation of the assembled kinematics.

Figure 16 shows the reachability test: the work target satisfies $|C_1/R_1| \leq 1$, while $(0, 0, -480)$ exceeds unity and no real joint angle reaches it.

ÁREA DE TRABAJO

ESTACIÓN B

Cinemática inversa

Parte: 0/1

Modo de prueba:

Saltar las láminas de esta estación

1 2 3 4 5 6 7

4 de 7

LA PRUEBA DE ALCANZABILIDAD

CORTE X-Z DEL ESPACIO ALCANZABLE ($Y = 0$)

1 El objetivo de trabajo: cae DENTRO de la región, y su razón $|C_t/R_t|$ sale ≤ 1 .

2 El punto $(0, 0, -480)$: cae FUERA, y su razón sale $1.1 > 1$ — ningún ángulo real lo alcanza.

$|C_t/R_t| = 0.178$ ($C_t = 54.497$, $R_t = 306.635$)

La ecuación le pide a una onda de amplitud R_t que alcance el valor $-C_t$; hay solución real solo cuando $|C_t/R_t| \leq 1$. La razón para este objetivo se muestra arriba. ¿Es alcanzable?

☐ Sí: $|C_t/R_t| \leq 1$, existe un θ_i real
 ☐ No: $|C_t/R_t| > 1$, no existe un θ_i real

¿Qué significa físicamente la prueba?

☐ El objetivo queda dentro de la región sobre la que la pierna puede cerrarse: se lo ve dentro del corte del espacio de trabajo
 ☐ Los motores tienen par suficiente para sostener el objetivo
 ☐ La pose evita la singularidad de ángulos iguales

Comprobar

Anterior

Falta completar esta lámina

Siguiente

GUÍA

Estación B. Cinemática inversa

0/1

Lámina 4 de 7 · La prueba de alcanzabilidad

- Mirar la figura y leer los puntos numerados debajo.
- Leer la pregunta y elegir la opción correcta.
- Elegir la razón.
- Pulsar **Comprobar**.

Fig. 16. Inverse kinematics, screen 4 of 7: the reachability test.

Figure 17 shows the gravity term of the forward dynamics section, with the arm mass acting at half length and the grouped mass at the elbow acting at full length.

ÁREA DE TRABAJO

ESTACIÓN C

Dinámica directa

Parte: 0/1

Modo de prueba:

Saltar las láminas de esta estación

1 2 3 4 5 6

3 de 6

EL TÉRMINO DE GRAVEDAD $G_1(\theta)$

Dos masas tiran de la articulación; cada una aporta peso por palanca.

VISTA LATERAL, ARTICULACIÓN 1

1 La masa del brazo (m_u), repartida: su peso actúa en el punto medio, a $l/2$.

2 La masa agrupada del codo (m_{eff}): el antebrazo y la parte de plataforma que carga, actuando en la punta, a l .

3 Cada peso tuerce la articulación con su propia palanca horizontal.

ECUACIÓN

$G_1(\theta_1) =$

seguir la guía: tocar las variables en orden

VARIABLES

g tan sin m_l θ_1

m_ee m_u v m_eff a

l θ_2 + θ_3 · b /

J 2 - (2) √

cos

quitar el último limpiar

Comprobar

Anterior

Falta completar esta lámina

Siguiente

GUÍA

Estación C. Dinámica directa

0/1

Lámina 3 de 6 · El término de gravedad $G_1(\theta)$

- Leer los puntos numerados bajo la figura.
- Armar en el recuadro ECUACIÓN tocando las variables del recuadro VARIABLES, en este orden:
- Tocar la variable **g**.
- Tocar la variable **·**.
- Tocar la variable **sin**.
- Tocar la variable **θ_1** .
- Tocar la variable **·**.
- Tocar la variable **(**.
- Tocar la variable **m_u**.
- Tocar la variable **·**.
- Tocar la variable **l**.
- Tocar la variable **/**.
- Tocar la variable **2**.
- Tocar la variable **+**.
- Tocar la variable **m_eff**.
- Tocar la variable **·**.
- Tocar la variable **l**.
- Tocar la variable **)**.
- Pulsar **Comprobar**.

Fig. 17. Forward dynamics, screen 3 of 6: the gravity term $G_1(\theta_1)$ assembled from blocks.

Figure 18 shows the complete torque equation of the inverse dynamics section, whose three terms accelerate the arm inertia, overcome viscous friction, and hold against gravity.

Fig. 18. Inverse dynamics, screen 2 of 5: the complete torque equation.

Figure 19 shows the opening PID screen, where the user identifies which component closes the motor position loop and which one measures the real arm angle.

Fig. 19. PID control, screen 1 of 6: the two components that close a loop on the physical prototype.

Figure 20 shows the reference case, from 55° , 62° , and 69° towards 76.5° at $K_p = 0.5$, $K_i = 1.6$, and $K_d = 0.05$: the joints settle in about one second without overshoot, the residual error below 0.01° .

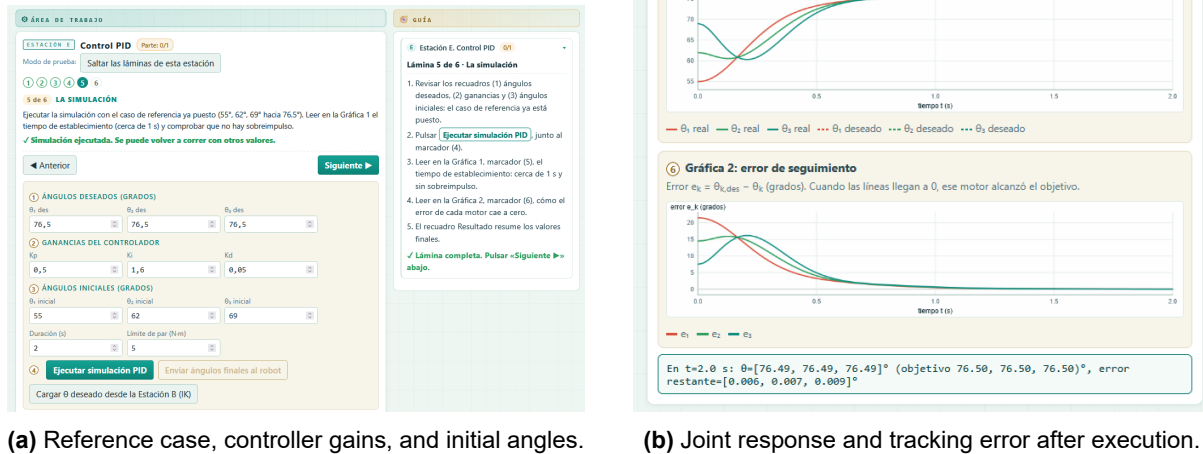


Fig. 20. PID control, screen 5 of 6: simulation of the reference case.

2.4 Risk Management

The principal risks identified at the start of the project, and the mitigation applied in each case, are summarized in Table 6.

TABLE 6
Project risks and mitigation strategies

Risk	Mitigation
Parallel manipulator kinematics and dynamics lie outside both Robotics syllabi.	Self directed literature review; derivation cross checked against an independent numerical implementation.
A sixteen week semester covering mechanical design, fabrication, firmware and host side software.	Weekly milestones on a Gantt chart; early component procurement; contingency activities defined for revalidation.
Failed integration of the host side software despite a working prototype.	Independently testable modules; firmware and serial link validated before the host is connected; degraded fallback retaining joint angle entry.
Joint positioning outside the NFR1 tolerance, or drifting under load.	Driver that closes its own loop and reports step loss; step response characterization per joint; sensor gain calibrated per axis.
Lead times for drivers, gearboxes and angular position sensors delaying integration.	Procurement scheduled in the requirements and conceptual phases; laser cutting and 3D printing used locally for custom structural parts.

2.5 System Integration

2.5.1 Fabrication Processes

The frame panels were laser cut from medium density fiberboard from the CAD sheet drawings, the motor brackets, sensor mounts, and platform fittings were 3D printed from the same model, and the twin forearms were cut from carbon fiber rod with spherical ball joints.

2.5.2 Mechanical Assembly

The motor and gearbox units were mounted to the frame, the arms keyed to the gearbox outputs, the forearms fitted between arms and platform, and the sensors coupled to the gearbox outputs; at home the platform sits on the central axis. Figure 21 shows one joint.



Fig. 21. Integration at a single joint: stepper motor, planetary gearbox, closed loop driver, and analog angular position sensor.

2.5.3 Firmware Integration

The firmware runs homing, the command parser, joint motion, and the scripted demonstration, and carries both kinematic algorithms, so the robot runs from a Cartesian target with no host software. The command set is H to home, G to read the angles, M to move, R for the routine, and IK and FK for the embedded algorithms; unreachable targets are refused, and every motion is clamped to the validated band.

2.5.4 Electronics Integration

The control and power electronics are mounted on the upper frame: the board on its interface shield, the three drivers, the power supply, and the auxiliary rails, wired to the three joints below.

Chapter III

Results

3.1 From the CAD Model to the Physical Prototype

Figure 22 sets the CAD assembly against the built prototype, assembled as modeled, with the electronics of Section 2.5.4 on the top deck.

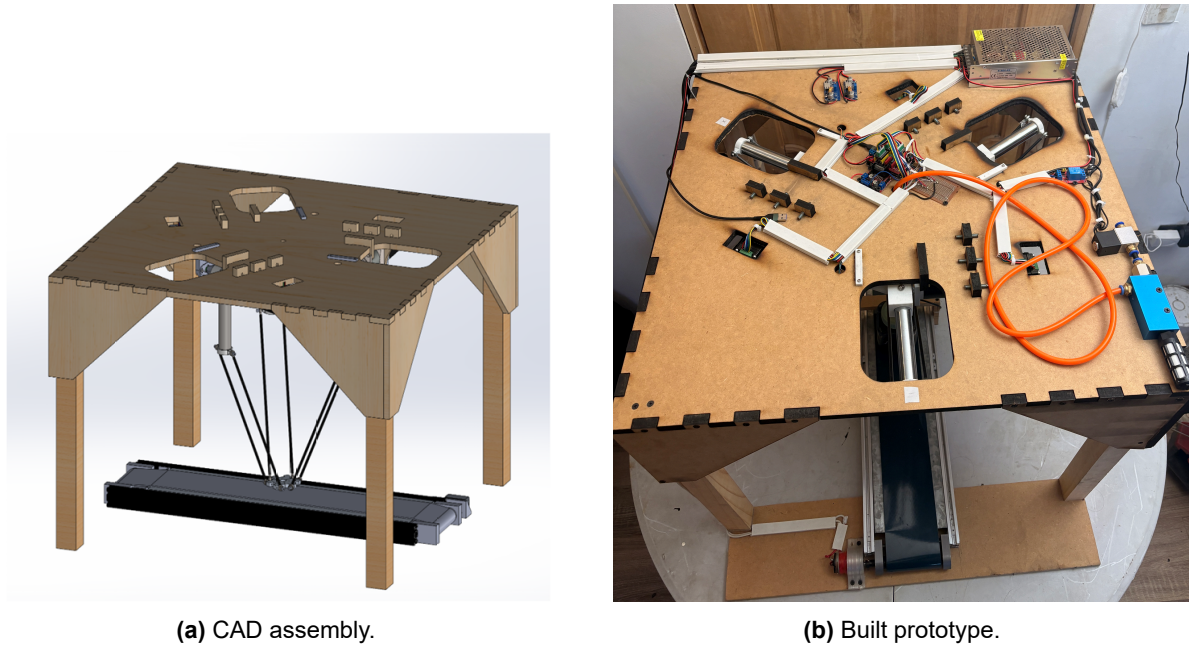


Fig. 22. The CAD model and the built prototype.

3.2 Positioning Tests

Each test commands a Cartesian target through the inverse kinematics algorithm of Section 2.3.1; the reached position is measured with a plumb line over a printed millimeter card, the height with a hand tape, and the joint angles with the angular position sensors. Eight poses at 250 to 350 mm of depth, three repetitions each after homing: twenty four measurements, shown in Figure 23.

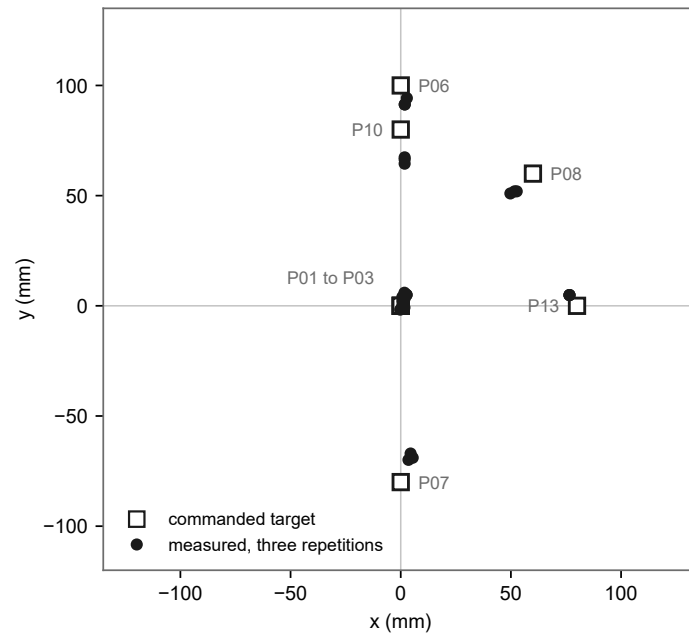


Fig. 23. Commanded and measured positions in the horizontal plane.

The spread of the three repetitions of a pose averages 1.6 mm per horizontal axis; the pose at (80, 0) recorded three identical readings, so that average is slightly optimistic.

The vertical rms of 4.8 mm sits at the 5 mm resolution of the tape, so no finer conclusion is supported; Figure 24 shows the measured against the commanded depth.

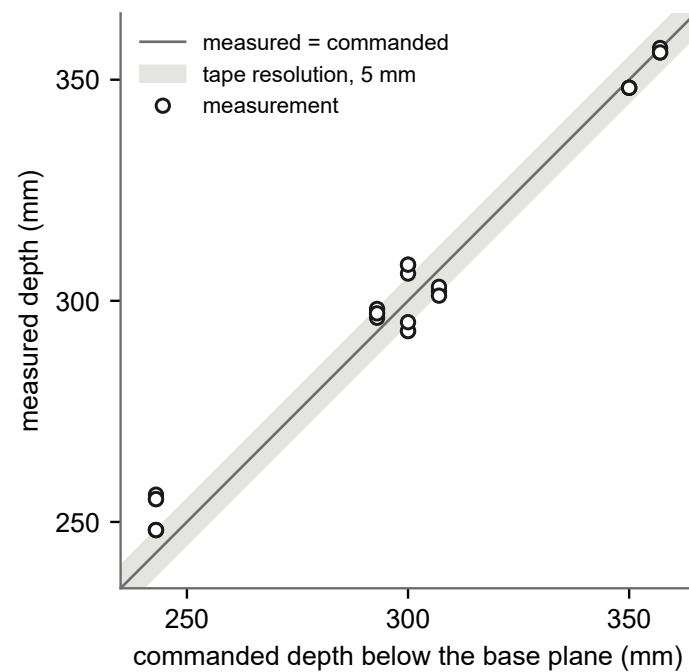


Fig. 24. Measured against commanded depth; the band is the tape resolution.

The sensors as first installed under reported the joint travel; one gain per axis, the 1.71 of Section 2.3.5, cut the worst readback error from 2.94° to 1.03°.

Figure 25 reports the calibrated sensors against NFR1: rms 0.78° from the commanded angle, within the $\pm 1^\circ$ requirement, worst reading 1.57° . One reading was excluded as a transcription slip.

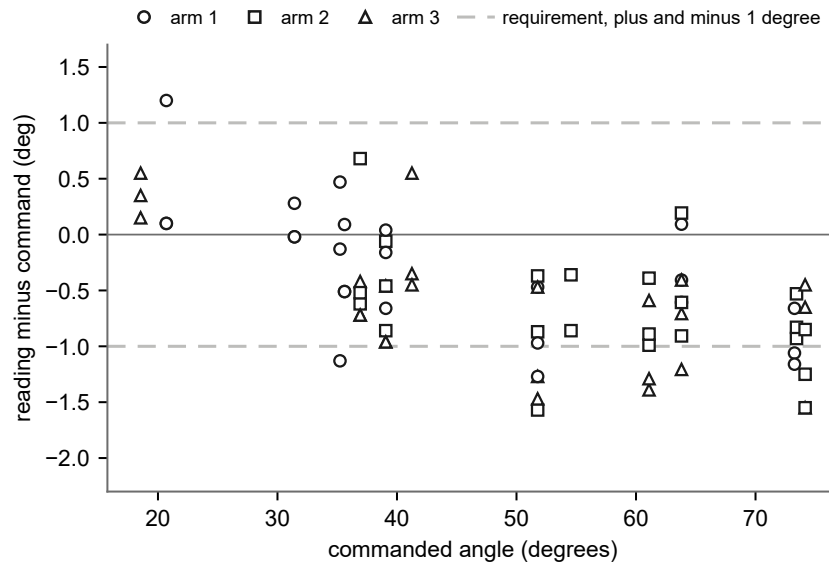


Fig. 25. Angular position sensor reading minus commanded angle for the three arms.

The horizontal accuracy stays open: 9.4 mm with the model as written, or 2.0 mm with the joint zeros offset about 12° , and at these depths the campaign cannot decide between the two. The deciding measurement, the arm angle at home, has not been performed.

3.3 Learning Results

Twelve participants completed the same eleven item questionnaire before and after practice: eight had already taken two robotics courses and four had not yet taken one, the two ends of the audience of people interested in learning parallel robotics. A third planned cohort was not run. One participant answered the initial questionnaire twice after a browser restart; the first attempt was kept.

Scores rose from 53.0% to 70.4%, a mean normalized gain of 0.384, shown in Figure 26.

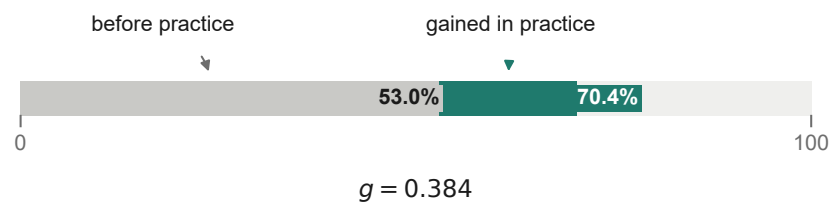


Fig. 26. Scores before and after practice.

Figure 27 shows the five concept areas of the questionnaire, each bar the mean of its items over the twelve participants.

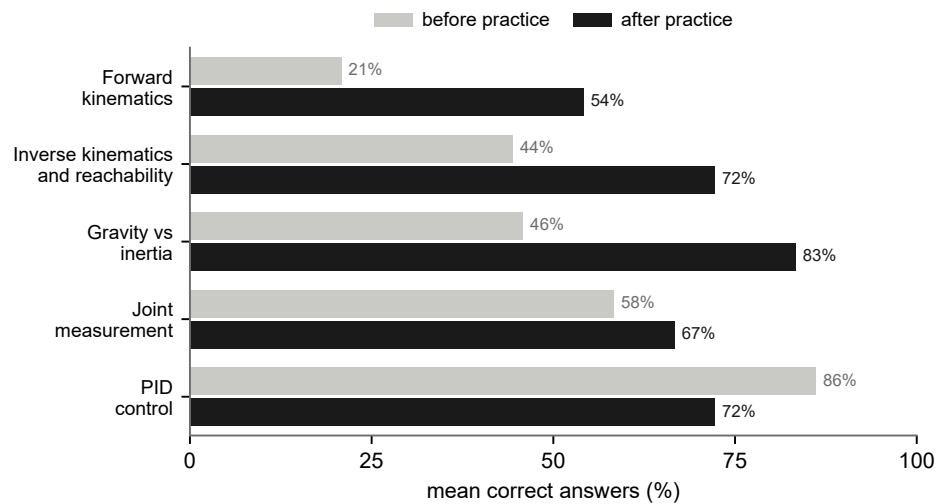


Fig. 27. Mean correct answers by concept area.

The largest gains sit where scores began near chance: forward kinematics 21% to 54% and gravity against inertia 46% to 83%. Inverse kinematics rose from 44% to 72%, joint measurement from 58% to 67%.

The only decline is PID control, 86% to 72%; it was the highest scoring area before practice, so the most probable reading is a ceiling effect, not harm from the practice.

Both ends of the audience moved together: the participants who had already taken two robotics courses rose from 59.1% to 75.0%, gain 0.394, and those who had not yet taken one from 40.9% to 61.4%, gain 0.365.

3.4 Discussion

The principal finding is a mean normalized gain of 0.384 in one practice session, with the largest movements where scores began near chance: forward kinematics, 21% to 54%, and gravity against inertia, 46% to 83%. The movement was shared by both ends of the audience, and the one decline, PID control, started from the highest pre score, a ceiling rather than a harm.

The direction matches the published evidence: educational robots show a moderate positive effect on learning outcomes, $g = 0.57$ across 17 articles and stronger in higher education [7], with consistent gains in achievement and motivation across STEM disciplines [5,6] and in practical environments [1,2]. On Hake's scale the 0.384 sits in the medium band, the range that active methods typically reach over a full course; here it appears after a single session.

The pattern also matches the mechanism those studies propose: platforms that expose joint level control and sensor feedback improve knowledge acquisition [9], and the two areas that moved most here are exactly the ones the robot makes observable, while construction kits without a rigorous kinematic model do not connect the mathematics to the motion [4]. In the reviewed work no platform closes that loop the way this interface does: the user builds the equations block by block, the built result is sent to the robot, and the robot moves it.

What the prototype contributes to that learning is trust: the motion repeats and the readings track the command, so the concepts studied on screen are the ones the robot enacts in front of the user.

For practice, the prototype answers the reported barriers of cost, infrastructure, and complexity [3]: locally fabricated, one laptop, and repeatable motion; the hybrid route of a small physical arm with guided content [8] extends here to a parallel robot. The limits are those of a first study, twelve participants, no control group ruling out other sources of the improvement, and no significance testing, with a gain that speaks for the platform as a whole rather than for any single design feature; within them, the result is a first indication that points in the same direction as the published evidence.

Chapter IV

Conclusions and Recommendations

4.1 Conclusions

- The structure was designed in parametric CAD and built by laser cutting and 3D printing, with carbon fiber forearms. The model was the single geometric source for the kinematics, the torque sizing, and the fabricated parts; the prototype matches it, travels the -23.5° to 76.5° band, and repeats its motion.
- Each joint carries an independent angular position sensor reading the true joint angle, the quantity the $\pm 1^\circ$ requirement is written against. One calibration gain per axis cut the worst readback error from 2.94° to 1.03° ; on the corrected prototype the readings sit at rms 0.78° .
- The interface delivers the five guided sections from one laptop: the user assembles each equation from symbol blocks, every step is checked, a prediction is chosen from two options before each result, and the result runs on the robot. The final version came from the feedback of the twelve participants.
- Based on Hake's g method, the participants learned: scores rose from 53.0% to 70.4%, a mean normalized gain of 0.384. On Hake's scale, below 0.3 is low, 0.3 to 0.7 is medium, and above 0.7 is high; medium is the range of active teaching, where the student learns by doing instead of listening, and this platform teaches exactly that way, its gain landing in that range.

4.2 Recommendations

- Strengthen the learning evidence with a comparison group, a retention questionnaire, and a larger cohort.
- Have every section ask for thinking first: the user answers from the figure and the statement alone before any result is shown.
- Add a new guided section on straight line motion: the user assembles the law and watches the robot follow it, through a Cartesian interpolator on the host.
- Keep the feedback cycle running: a structured feedback round with each new cohort, extending the single participant round that produced the current interface.

References

- [1] P. Zamora, A. Lozada, J. Buele, and F. Avilés-Castillo, "Robotics in higher education and its impact on digital learning," *Front. Comput. Sci.*, vol. 7, 2025.
- [2] H. Wang, N. Luo, T. Zhou, and S. Yang, "Physical robots in education: A systematic review based on the technological pedagogical content knowledge framework," *Sustainability*, vol. 16, no. 16, 2024.
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- [4] E. J. Markvicka *et al.*, "Designing learning experiences with a low-cost robotic arm," in *Proc. ASEE Annu. Conf. Expo.*, 2021.
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- [6] F. Ouyang and W. Xu, "The effects of educational robotics in STEM education: a multilevel meta-analysis," *Int. J. STEM Educ.*, vol. 11, no. 7, 2024.
- [7] K. Wang, G.-Y. Sang, L.-Z. Huang, S.-H. Li, and J.-W. Guo, "The effectiveness of educational robots in improving learning outcomes: A meta-analysis," *Sustainability*, vol. 15, no. 5, p. 4637, 2023.
- [8] F. Gonzalez, "A hybrid physical-virtual educational robotic arm," *Preprints*, 2023.
- [9] L. Č. Zajc, A. Rezelj, and D. Skočaj, "Low-cost open-source robotic platform for education," *IEEE Trans. Learn. Technol.*, vol. 16, no. 1, pp. 18–31, Feb. 2023.

Appendix

Concept Questionnaire

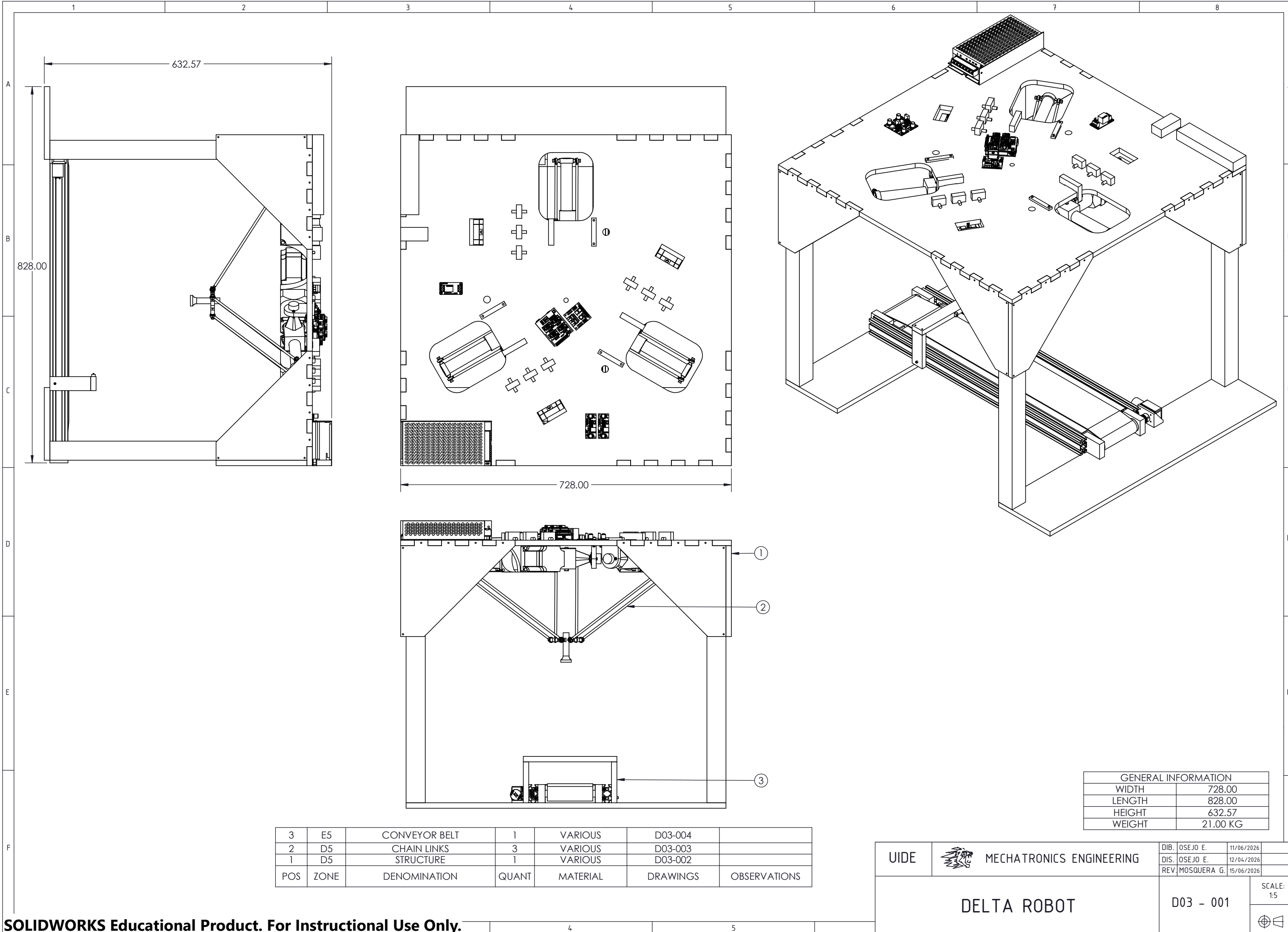
The concept questionnaire was administered in Spanish; the items are given here in translation.

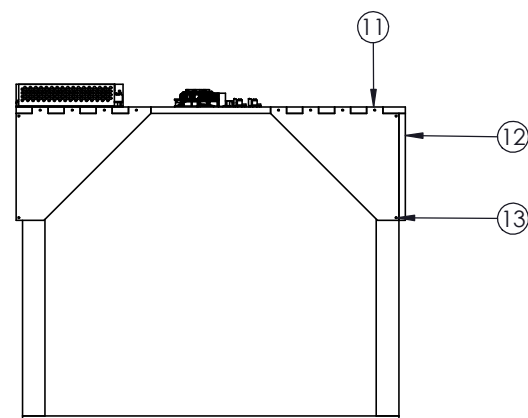
TABLE 7
Concept questionnaire administered before and after the session.

Item	Question	Concept assessed
Q1	Starting from the home pose, if the three joint angles are all made slightly smaller by the same amount, what happens to the end effector?	Coupling between joint angles and end effector motion
Q2	The forward kinematics is solved by intersecting three spheres, which yields a quadratic in z with two roots. Which one does the robot use?	Root selection in forward kinematics
Q3	A target point can have a mathematical inverse kinematics solution and still be refused by the interface before the robot moves. Why?	Workspace limits against mathematical solvability
Q4	How is the inverse kinematics of this delta robot solved?	Structure of the inverse kinematics
Q5	When the inverse kinematics is solved arm by arm, when does an arm run out of solution?	Reachability condition of a single chain
Q6	In the practice pose the arms sit slightly below the home pose, move at moderate speed, and gain speed very gradually. The joint torque has an inertia term, a viscous friction term, and a gravity term. How is that torque distributed?	Relative weight of the dynamic terms
Q7	When the robot is held still in a pose, with neither velocity nor acceleration, the torque required at each joint is	Static gravity torque
Q8	The angular position sensor of each joint is mounted after the reducer. What does this imply?	Sensor placement and the quantity it measures
Q9	On the proportional gain K_p of a PID controller	Role of proportional action
Q10	In this system, which carries a gravity load, what does the integral term K_i contribute?	Role of integral action under a constant load
Q11	What does the derivative term K_d contribute in the PID controller of a joint?	Role of derivative action

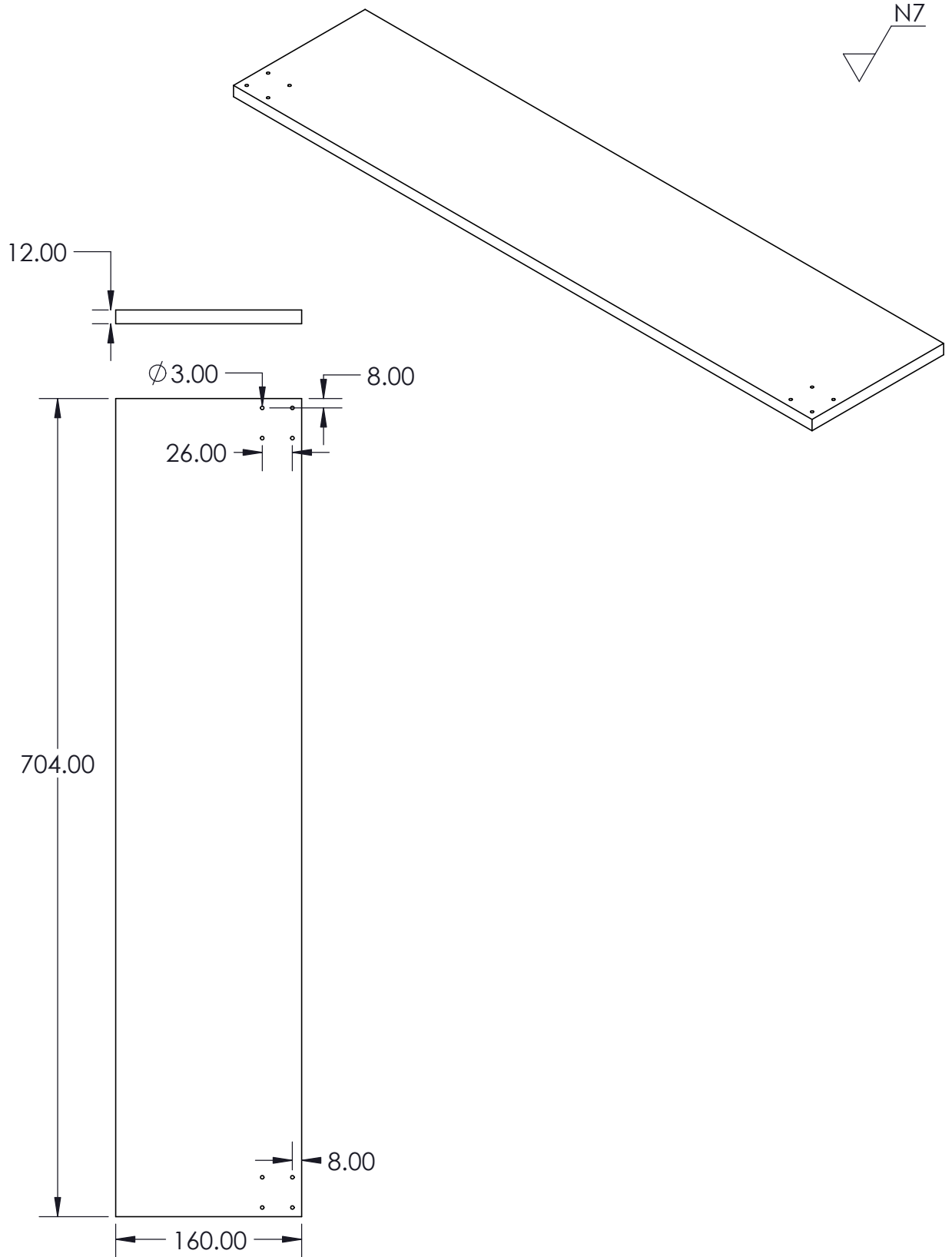
Engineering Drawings

The mechanical drawings of the delta robot follow, in their original A3 and A4 sheet formats.





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			REV.	MOSQUERA G.	15/06/2026	
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MATERIAL:

MDF

TOL.GRAL:
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MECHATRONICS ENGINEERING

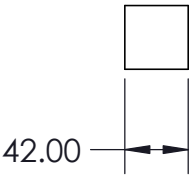
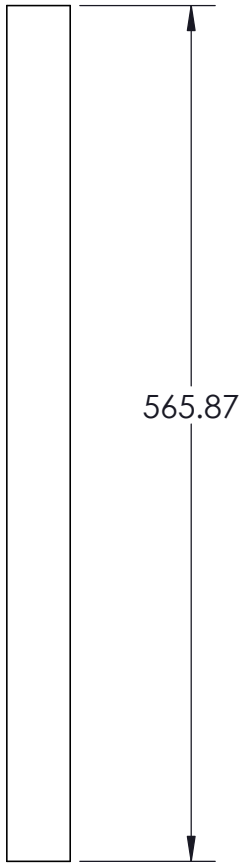
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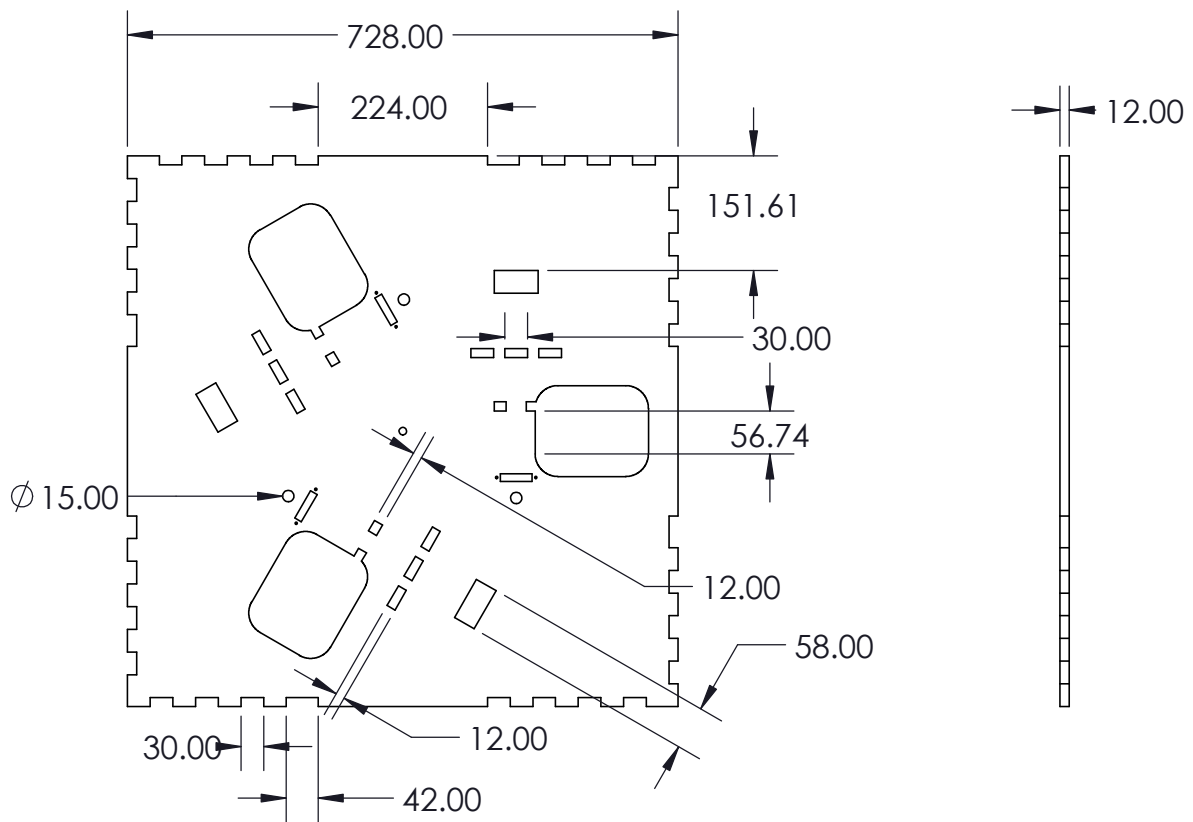
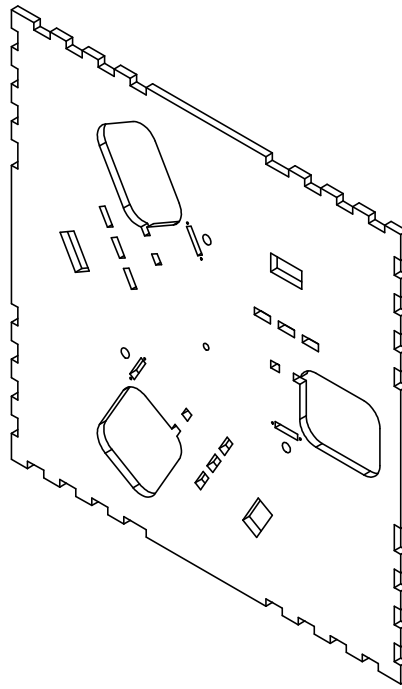
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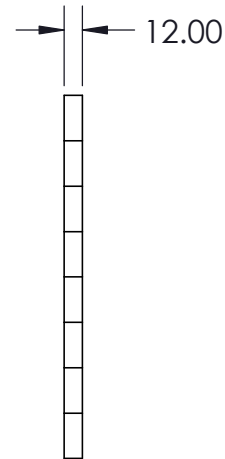
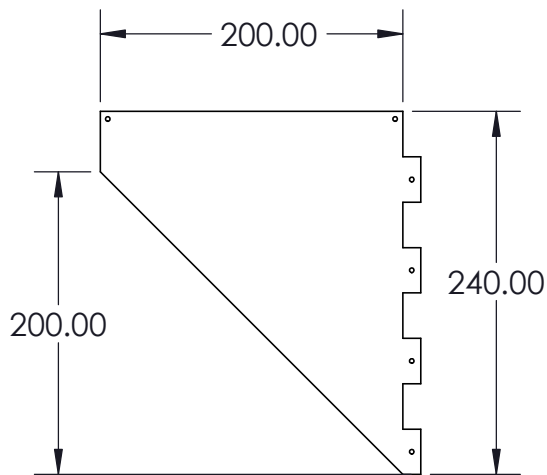
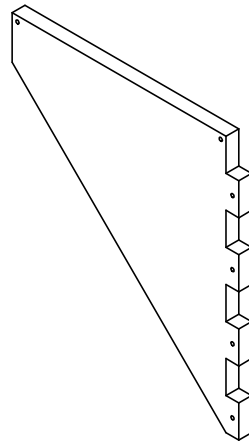




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				REV.	MOSQUERA G.	15/06/2026	
DELTA LEG			D03-202				 



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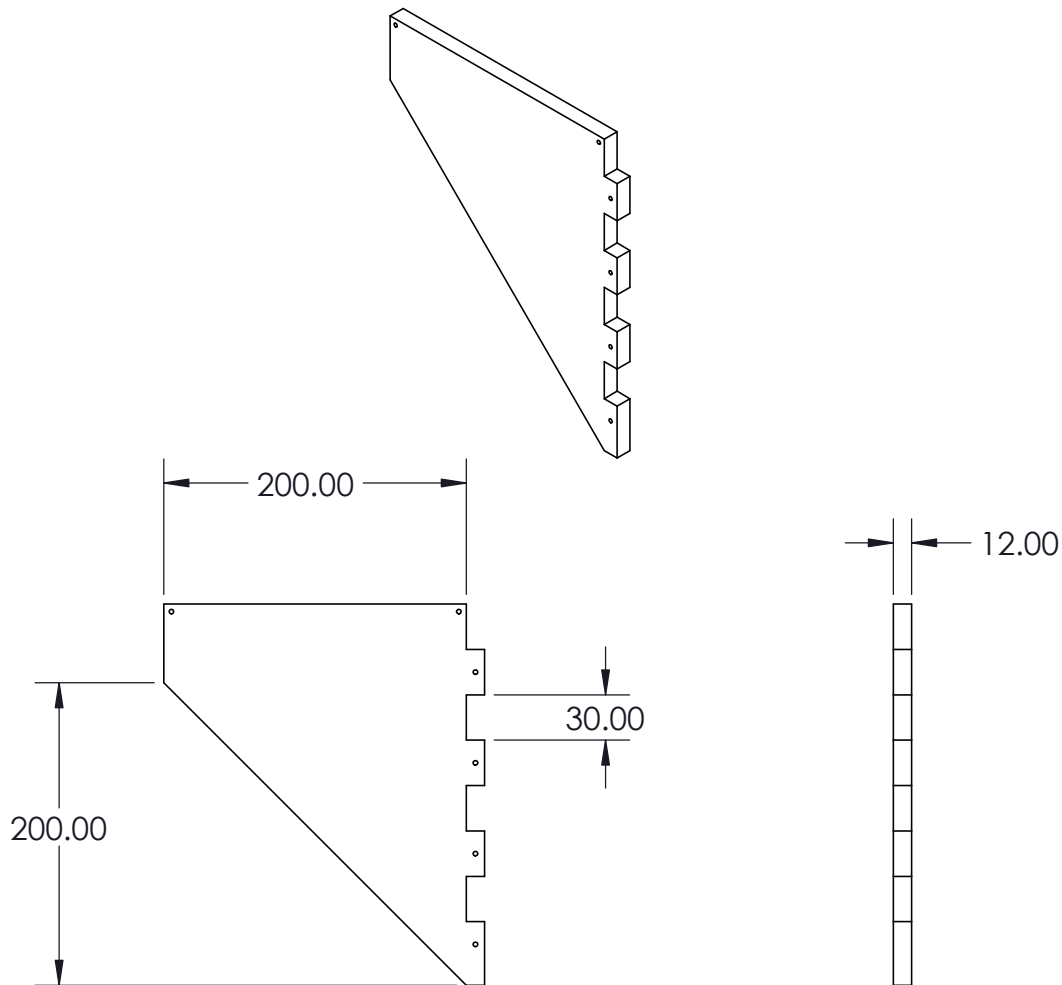
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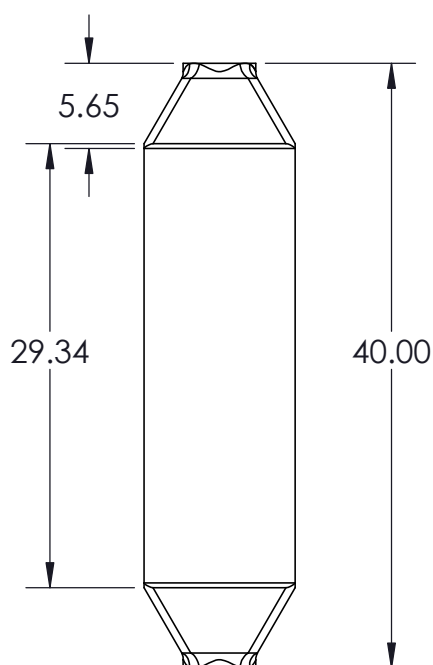
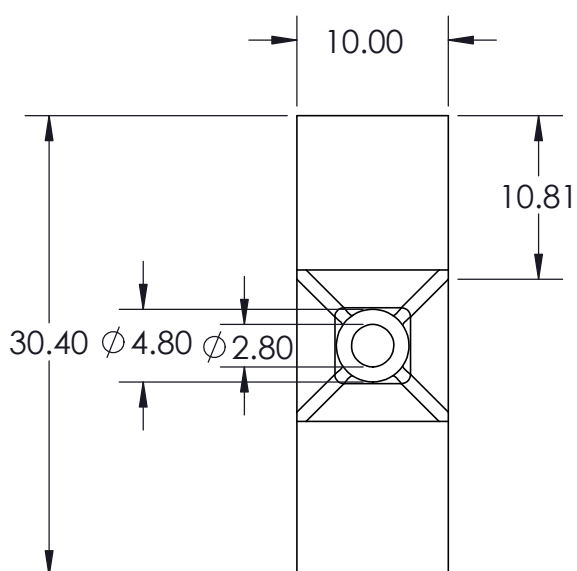
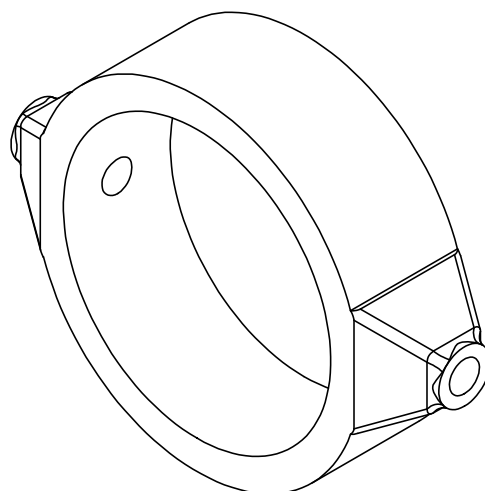
ANGULAR SUPPORT LEGS 2

D03-204



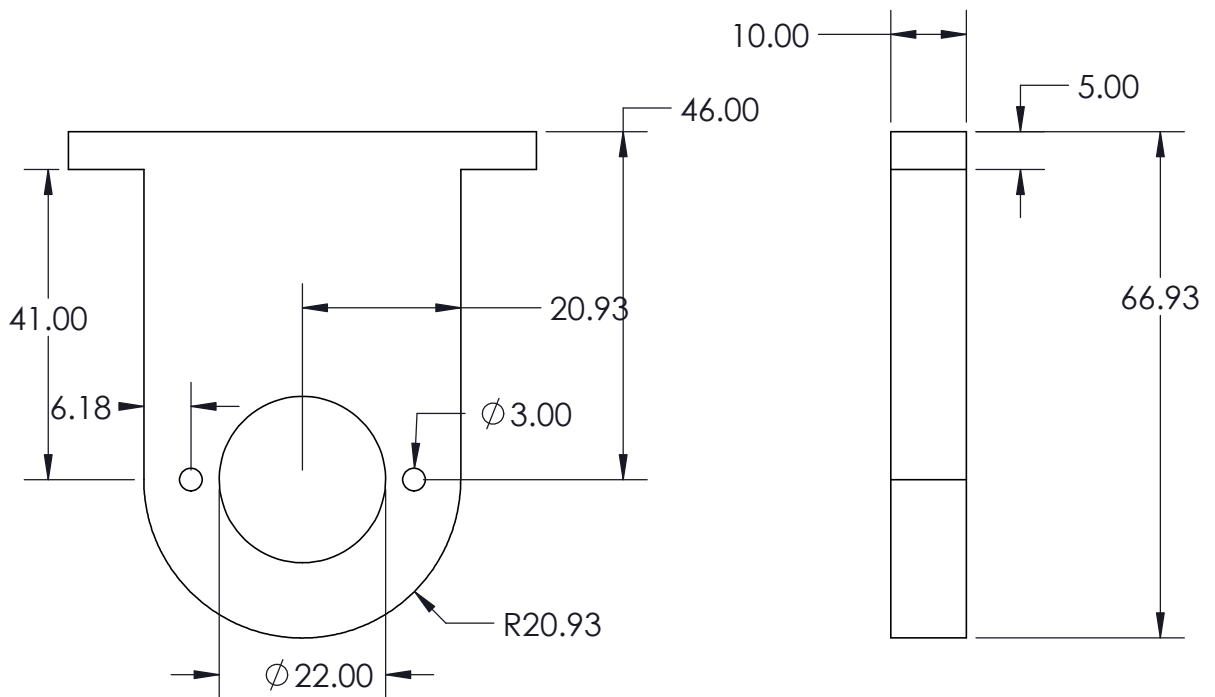
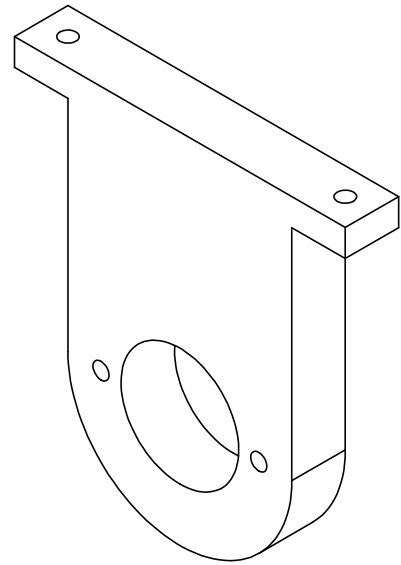


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ANGULAR SUPPORT LEGS			D03-205				



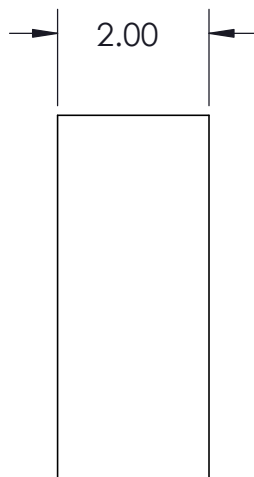
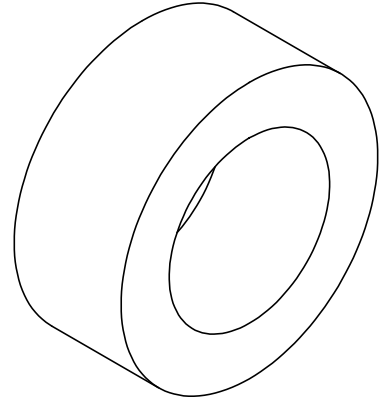
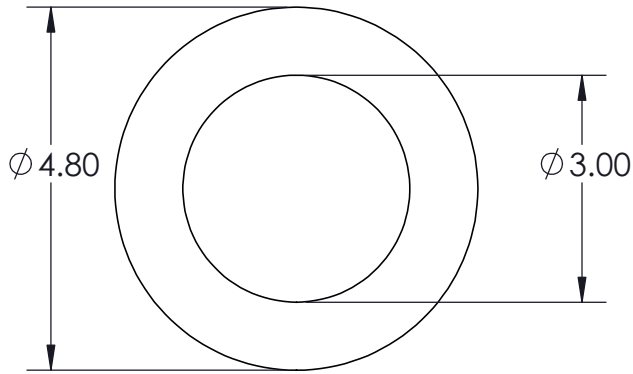
PRINTING SPECIFICATION			
MATERIAL: PETG			
PRINTER: CREALITY ENDER-3 V2			
INFILL TYPE: TRI-HEXAGONAL			
INFILL RATE: 100%			
BED TEMPERATURE: 60°C			
EXTRUSION TEMPERATURE: 200°C			

TREATMENT: NO TREATMENT		UIDE	MECHATRONICS ENGINEERING				
COVERING: NO COVERING							
MATERIAL:	PETG	TOL.GRAL: ±0,1	SCALE: 2:1	DIB.	OSEJO E.	11/06/2026	
				DIS.	OSEJO E.	12/04/2026	
				REV.	MOSQUERA G.	15/06/2026	
LINKS UNION			D03-301				



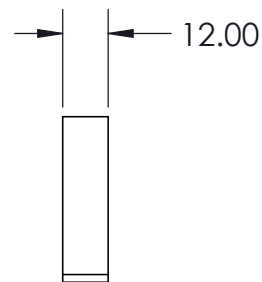
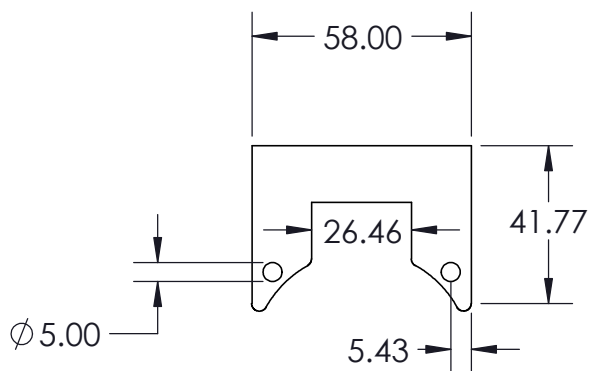
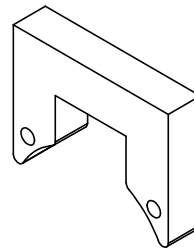
PRINTING SPECIFICATION			
MATERIAL: PETG			
PRINTER: CREALITY ENDER-3 V2			
INFILL TYPE: TRI-HEXAGONAL			
INFILL RATE: 100%			
BED TEMPERATURE: 60°C			
EXTRUSION TEMPERATURE: 200°C			

TREATMENT: NO TREATMENT		UIDE	MECHATRONICS ENGINEERING				
COVERING: NO COVERING							
MATERIAL:	PETG	TOL.GRAL: ±0,1	SCALE: 1:1	DIB.	OSEJO E.	11/06/2026	
				DIS.	OSEJO E.	12/04/2026	
				REV.	MOSQUERA G.	15/06/2026	
SENSOR SUPPORT			D03-302				

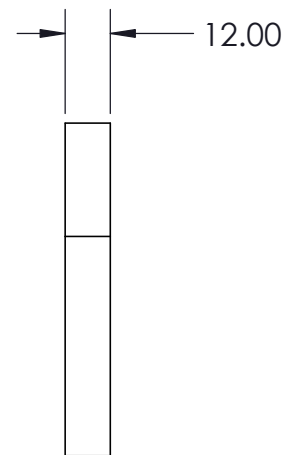
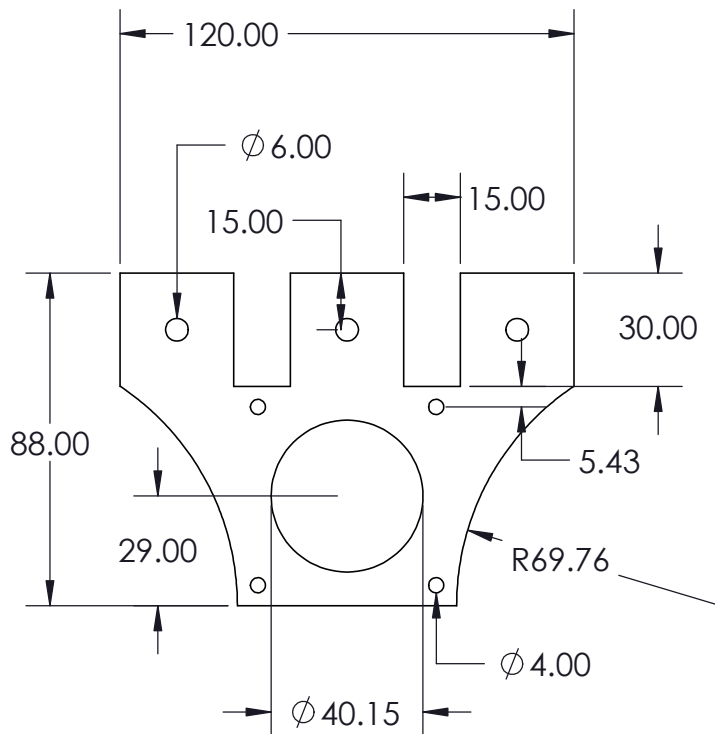
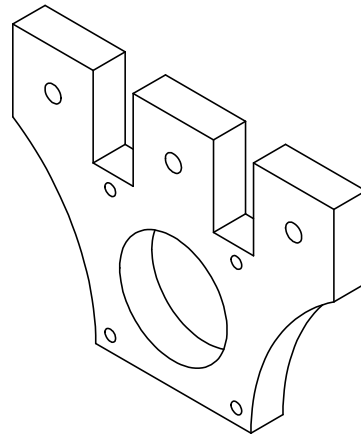


PRINTING SPECIFICATION			
MATERIAL: PETG			
PRINTER: CREALITY ENDER-3 V2			
INFILL TYPE: TRI-HEXAGONAL			
INFILL RATE: 100%			
BED TEMPERATURE: 60°C			
EXTRUSION TEMPERATURE: 200°C			

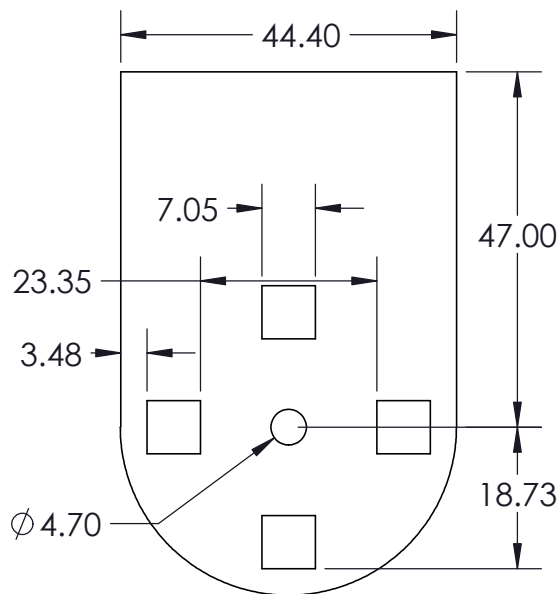
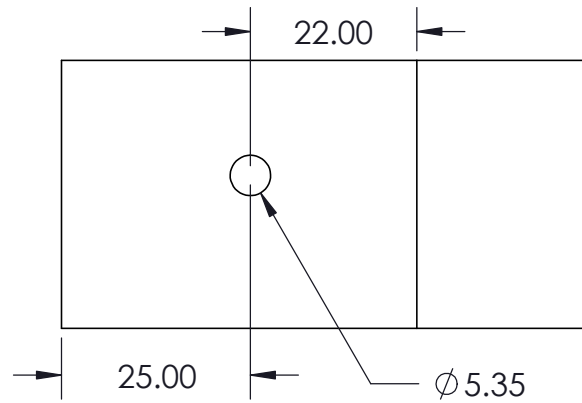
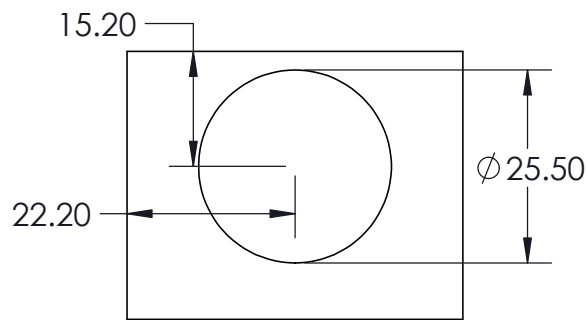
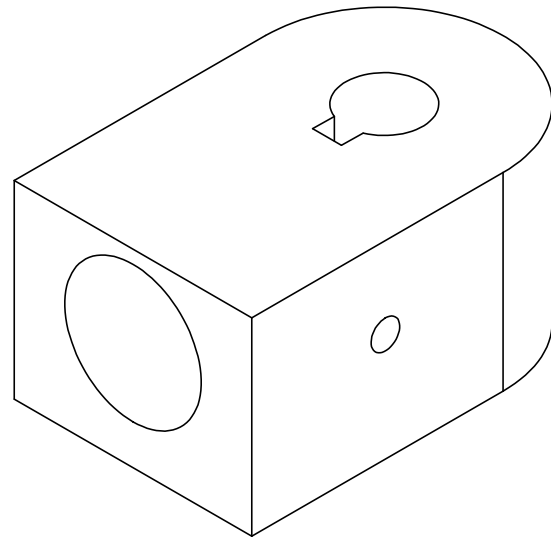
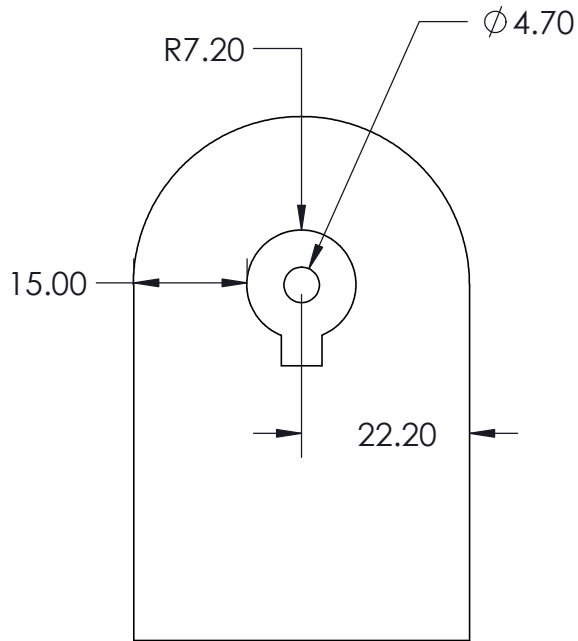
TREATMENT: NO TREATMENT		UIDE	MECHATRONICS ENGINEERING					
COVERING: NO COVERING								
MATERIAL: PETG		TOL.GRAL: ±0,1	SCALE: 10:1	DIB.	OSEJO E.	11/06/2026		
				DIS.	OSEJO E.	12/04/2026		
				REV.	MOSQUERA G.	15/06/2026		
BALL JOINT SEPARATOR			D03-303					



TREATMENT: NO TREATMENT		UIDE	MECHATRONICS ENGINEERING				
COVERING: NO COVERING							
MATERIAL: MDF		TOL.GRAL: ±0,1	SCALE: 1:20	DIB.	OSEJO E.	11/06/2026	
				DIS.	OSEJO E.	12/04/2026	
				REV.	MOSQUERA G.	15/06/2026	
GEARBOX SUPPORT			D03-304				



TREATMENT: NO TREATMENT		UIDE	MECHATRONICS ENGINEERING			
COVERING: NO COVERING						
MATERIAL: MDF	TOL.GRAL: ±0,1	SCALE: 1:20	DIB.	OSEJO E.	11/06/2026	
			DIS.	OSEJO E.	12/04/2026	
			REV.	MOSQUERA G.	15/06/2026	
ENGINE MOUNT		D03-305				



PRINTING SPECIFICATION			
MATERIAL: PETG			
PRINTER: CREALITY ENDER-3 V2			
INFILL TYPE: TRI-HEXAGONAL			
INFILL RATE: 100%			
BED TEMPERATURE: 60°C			
EXTRUSION TEMPERATURE: 200°C			

TREATMENT: NO TREATMENT

COVERING: NO COVERING

MATERIAL:

PETG

TOL.GRAL:
±0,1

UIDE

MECHATRONICS ENGINEERING

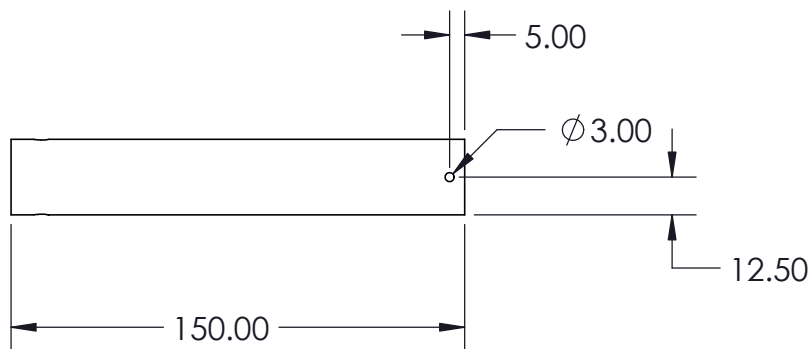
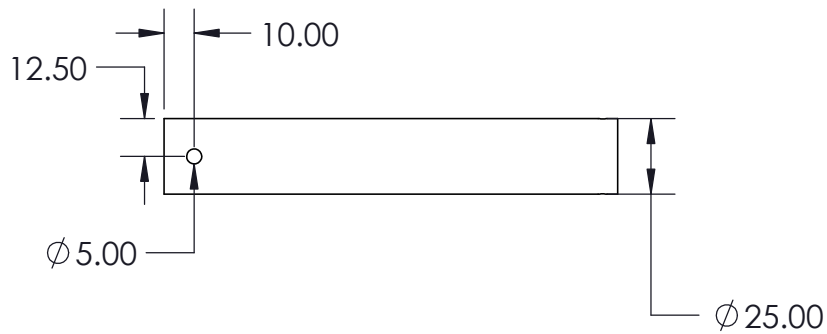
SCALE:
10:1

DIB.	OSEJO E.	11/06/2026	
DIS.	OSEJO E.	12/04/2026	
REV.	MOSQUERA G.	15/06/2026	

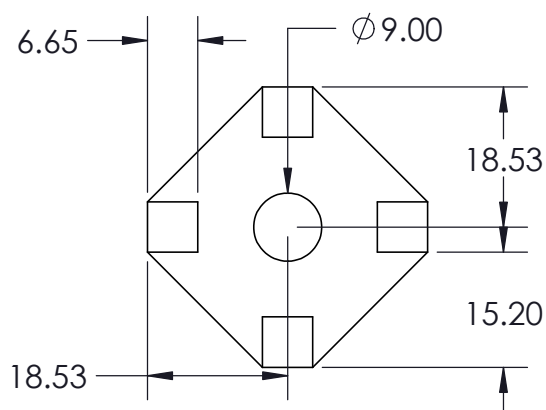
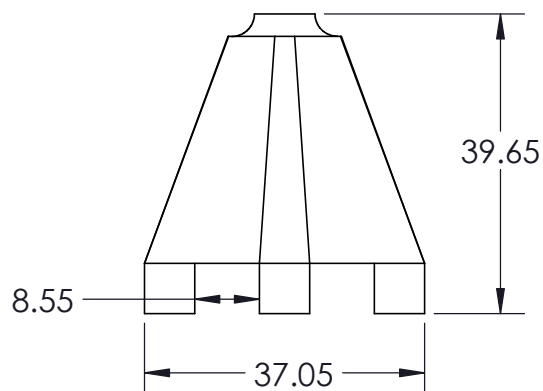
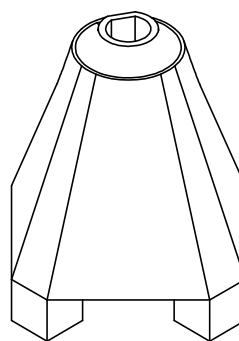
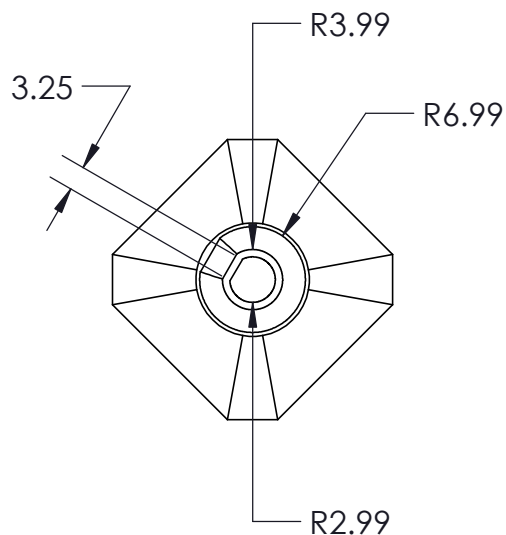
BALL JOINT SEPARATOR

D03-306



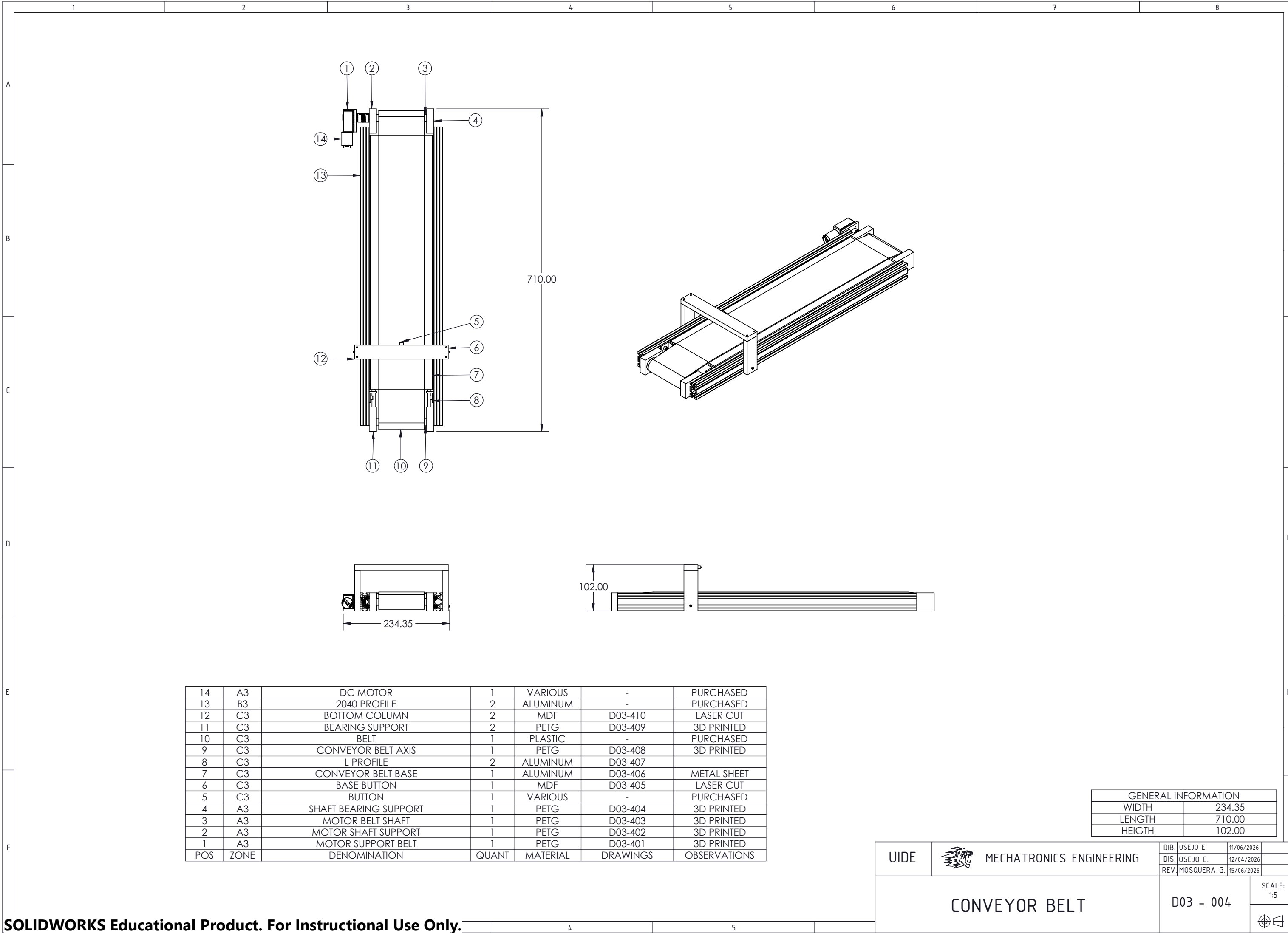


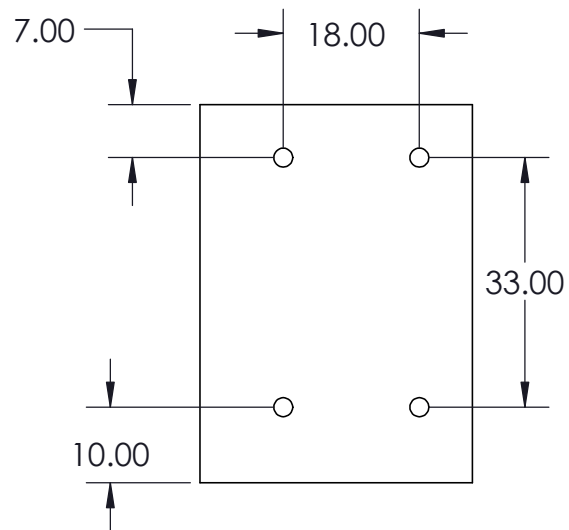
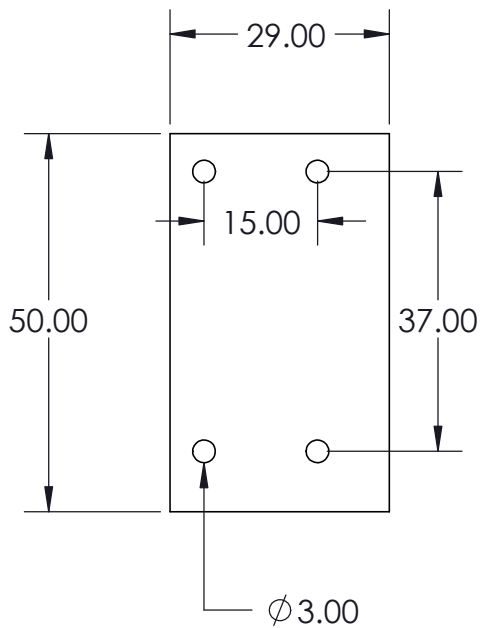
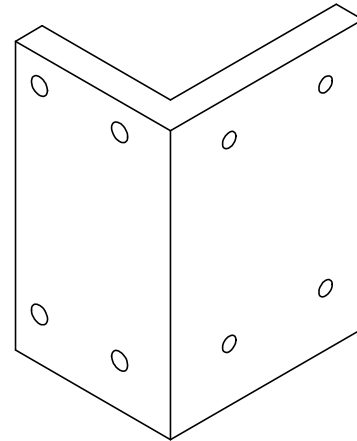
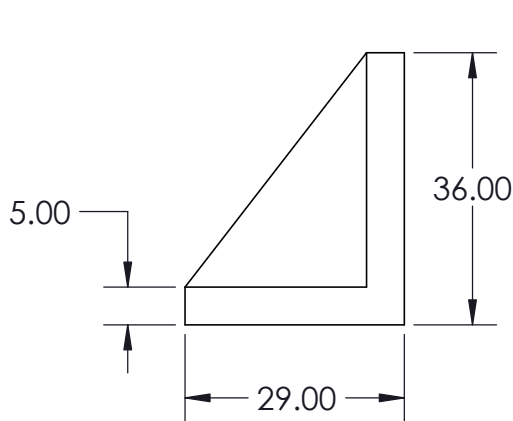
TREATMENT: NO TREATMENT		UIDE	MECHATRONICS ENGINEERING				
COVERING: NO COVERING							
MATERIAL: ALUMINUM		TOL.GRAL: ±0,1	SCALE: 1:2,5	DIB.	OSEJO E.	11/06/2026	
				DIS.	OSEJO E.	12/04/2026	
				REV.	MOSQUERA G.	15/06/2026	
UPPER ARM TUBE			D03-307				
							



PRINTING SPECIFICATION			
MATERIAL: PETG			
PRINTER: CREALITY ENDER-3 V2			
INFILL TYPE: TRI-HEXAGONAL			
INFILL RATE: 100%			
BED TEMPERATURE: 60°C			
EXTRUSION TEMPERATURE: 200°C			

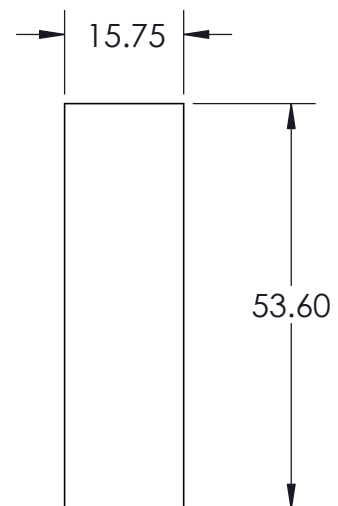
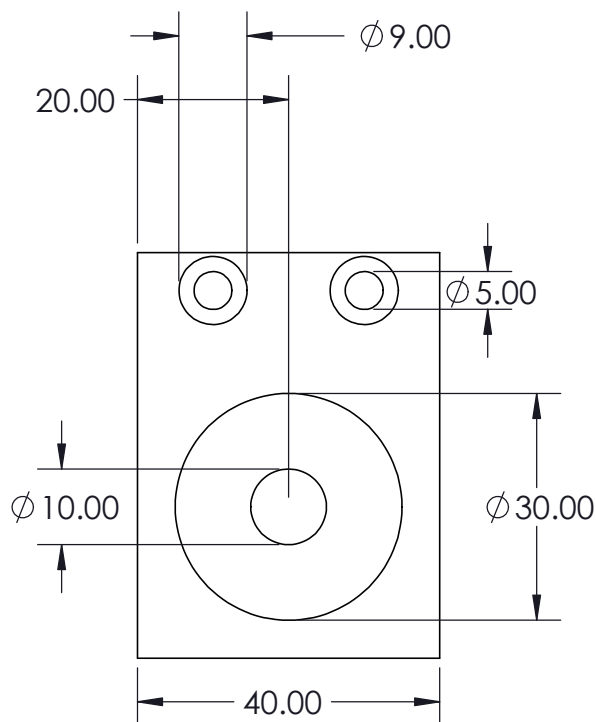
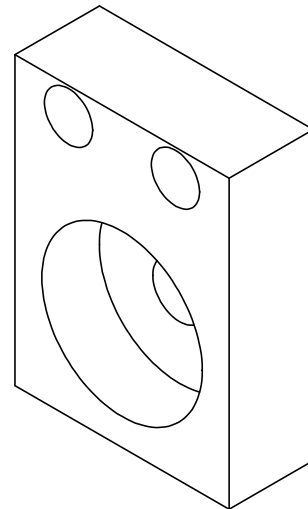
TREATMENT: NO TREATMENT		UIDE	MECHATRONICS ENGINEERING				
COVERING: NO COVERING							
MATERIAL:	PETG	TOL.GRAL: ±0,1	SCALE: 1:1	DIB.	OSEJO E.	11/06/2026	
				DIS.	OSEJO E.	12/04/2026	
				REV.	MOSQUERA G.	15/06/2026	
SENSOR ARM COUPLING			D03-308				





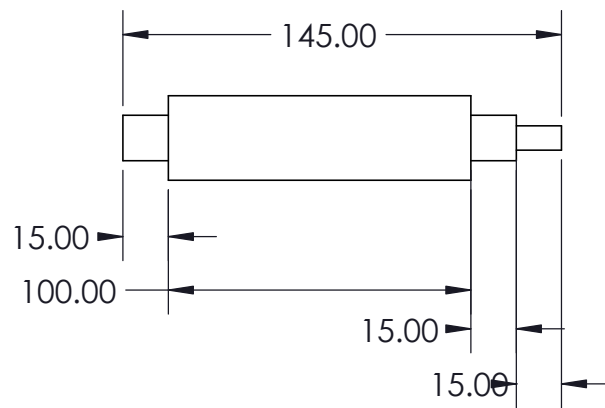
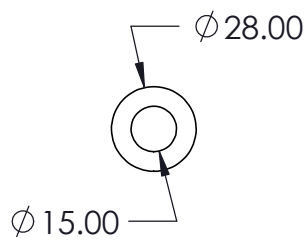
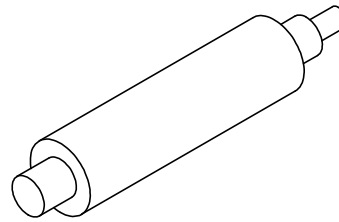
PRINTING SPECIFICATION			
MATERIAL: PETG			
PRINTER: CREALITY ENDER-3 V2			
INFILL TYPE: TRI-HEXAGONAL			
INFILL RATE: 100 %			
BED TEMPERATURE: 60 C°			
EXTRUSION TEMPERATURE: 200 C°			

TREATMENT: NO TREATMENT		UIDE	MECHATRONICS ENGINEERING					
COVERING: NO COVERING								
MATERIAL: PETG		TOL.GRAL: ±0,1	SCALE: 1:1	DIB.	OSEJO E.	11/06/2026		
				DIS.	OSEJO E.	12/04/2026		
				REV.	MOSQUERA G.	15/06/2026		
MOTOR SUPPORT BELT			D03-401					



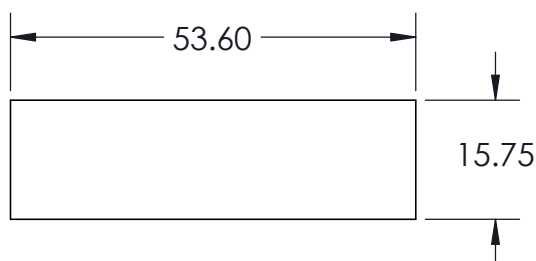
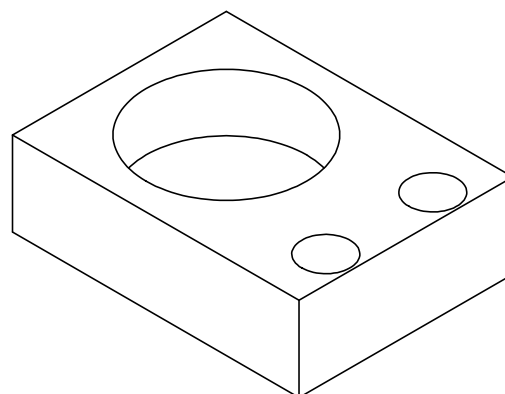
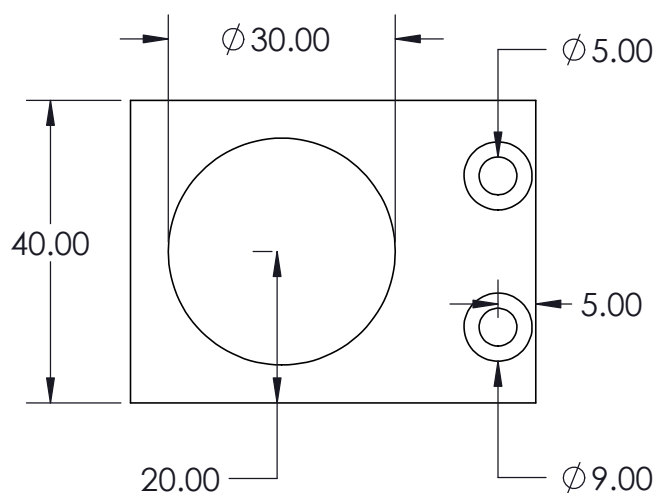
PRINTING SPECIFICATION			
MATERIAL: PETG			
PRINTER: CREALITY ENDER-3 V2			
INFILL TYPE: TRI-HEXAGONAL			
INFILL RATE: 100 %			
BED TEMPERATURE: 60 C°			
EXTRUSION TEMPERATURE: 200 C°			

TREATMENT: NO TREATMENT		UIDE	MECHATRONICS ENGINEERING					
COVERING: NO COVERING								
MATERIAL: PETG		TOL.GRAL: ±0,1	SCALE: 1:1	DIB.	OSEJO E.	11/06/2026		
				DIS.	OSEJO E.	12/04/2026		
				REV.	MOSQUERA G.	15/06/2026		
MOTOR SHAFT SUPPORT			D03-402					



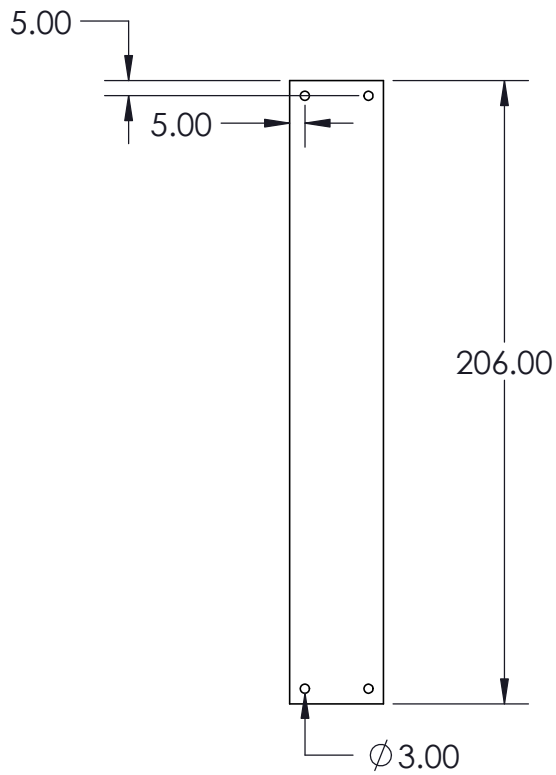
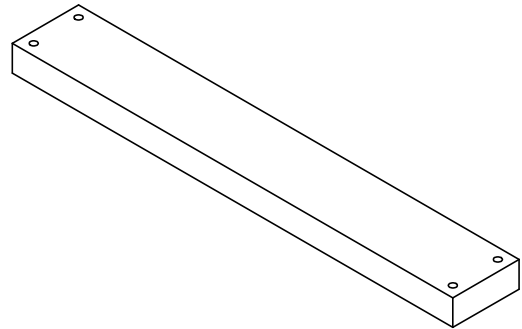
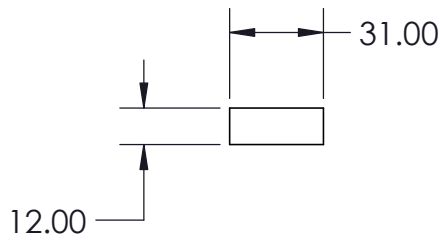
PRINTING SPECIFICATION			
MATERIAL: PETG			
PRINTER: CREALITY ENDER-3 V2			
INFILL TYPE: TRI-HEXAGONAL			
INFILL RATE: 100 %			
BED TEMPERATURE: 60 C°			
EXTRUSION TEMPERATURE: 200 C°			

TREATMENT: NO TREATMENT		UIDE	MECHATRONICS ENGINEERING			
COVERING: NO COVERING						
MATERIAL:		SCALE: 1:2,5	DIB.	OSEJO E.	11/06/2026	
PETG	TOL.GRAL: ±0,1		DIS.	OSEJO E.	12/04/2026	
			REV.	MOSQUERA G.	15/06/2026	
MOTOR BELT SHAFT		D03-403				



PRINTING SPECIFICATION			
MATERIAL: PETG			
PRINTER: CREALITY ENDER-3 V2			
INFILL TYPE: TRI-HEXAGONAL			
INFILL RATE: 100 %			
BED TEMPERATURE: 60 C°			
EXTRUSION TEMPERATURE: 200 C°			

TREATMENT: NO TREATMENT		UIDE	MECHATRONICS ENGINEERING				
COVERING: NO COVERING							
MATERIAL:	PETG	TOL.GRAL: ±0,1	SCALE: 1:1	DIB.	OSEJO E.	11/06/2026	
				DIS.	OSEJO E.	12/04/2026	
				REV.	MOSQUERA G.	15/06/2026	
SHAFT BEARING SUPPORT			D03-404				



TREATMENT: NO TREATMENT

COVERING: NO COVERING

MATERIAL:

MDF

TOL.GRAL:
 $\pm 0,1$

UIDE

MECHATRONICS ENGINEERING

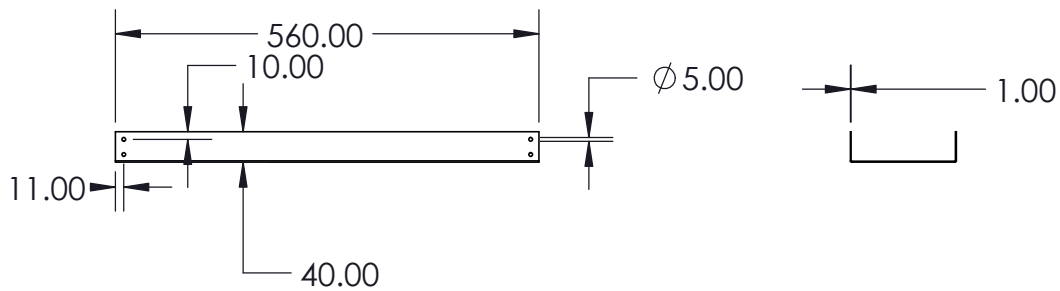
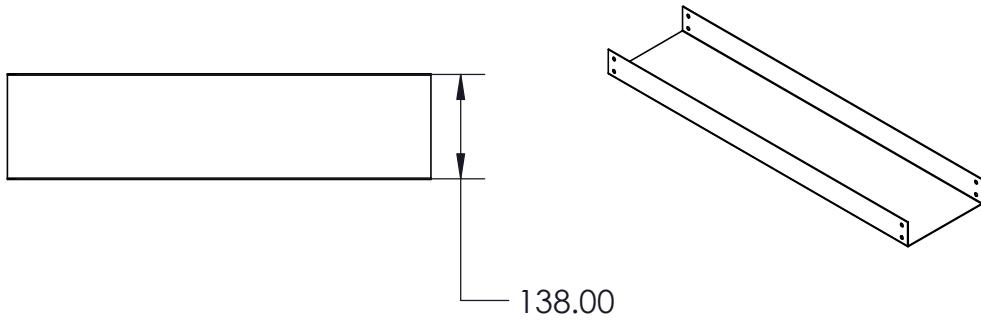
SCALE:
1:2,5

DIB.	OSEJO E.	11/06/2026	
DIS.	OSEJO E.	12/04/2026	
REV.	MOSQUERA G.	15/06/2026	

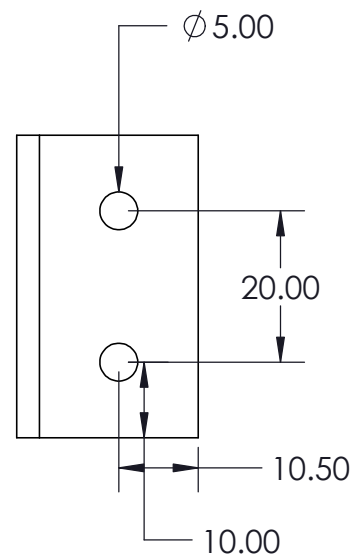
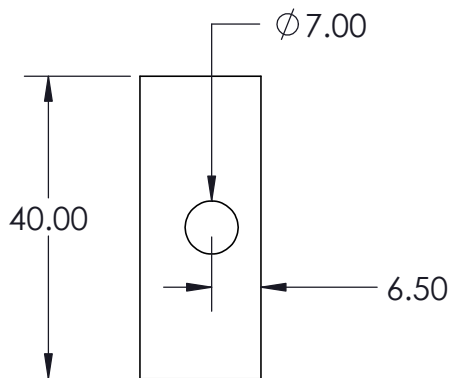
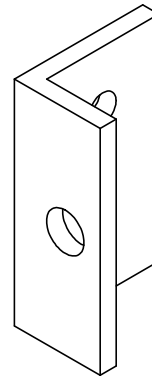
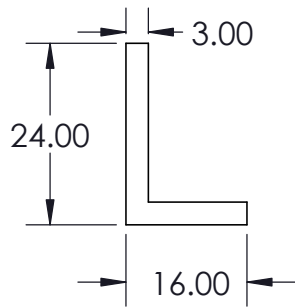
BASE BUTTON

D03-405





TREATMENT: NO TREATMENT		UIDE	MECHATRONICS ENGINEERING			
COVERING: NO COVERING						
MATERIAL:	TOL.GRAL:	SCALE: 1:10	DIB.	OSEJO E.	11/06/2026	
ALUMINUM	±0,1		DIS.	OSEJO E.	12/04/2026	
			REV.	MOSQUERA G.	15/06/2026	
CONVEYOR BELT BASE		D03-406				



TREATMENT: NO TREATMENT

COVERING: NO COVERING

MATERIAL:

ALUMINUM

TOL.GRAL:
±0,1

UIDE

MECHATRONICS ENGINEERING

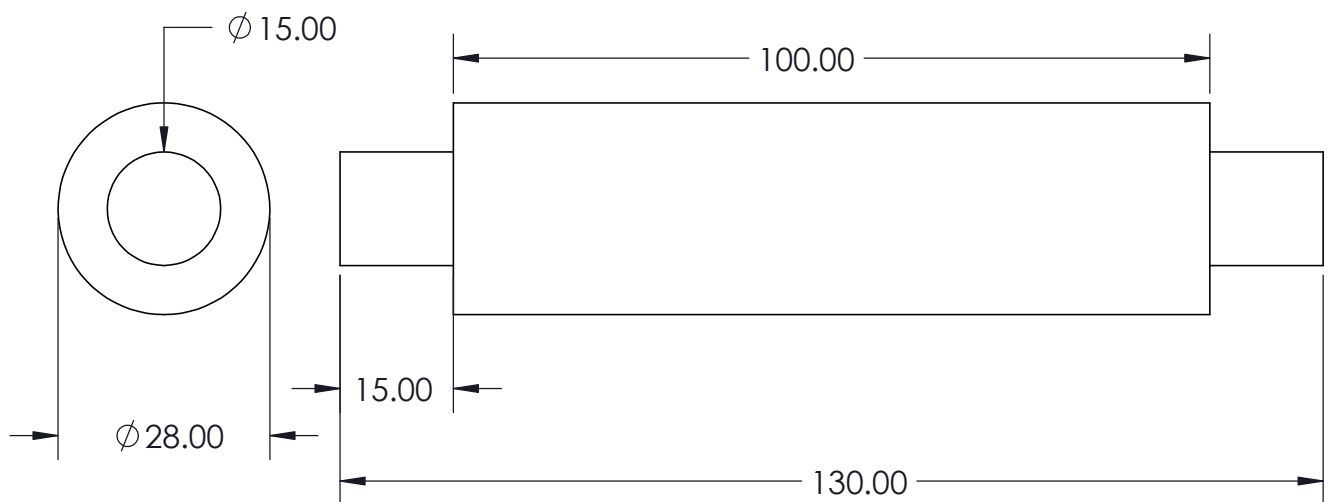
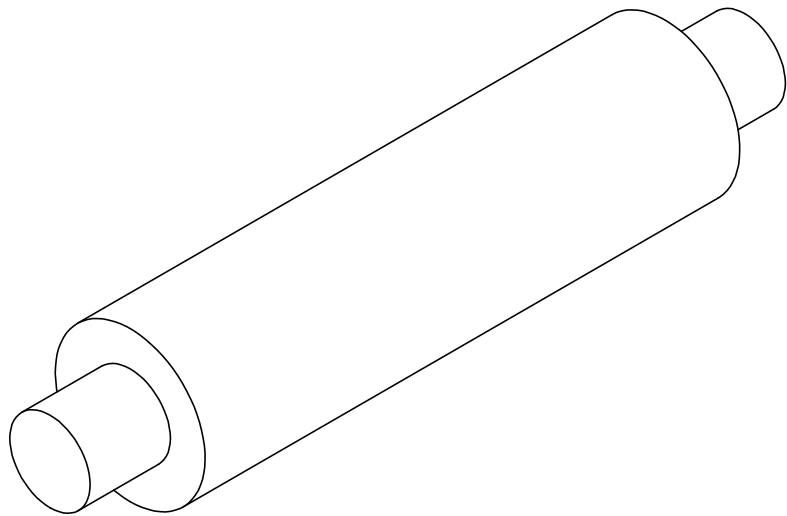
SCALE:
1:1

DIB.	OSEJO E.	11/06/2026
DIS.	OSEJO E.	12/04/2026
REV.	MOSQUERA G.	15/06/2026

L PROFILE

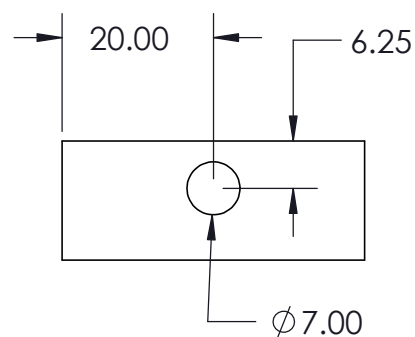
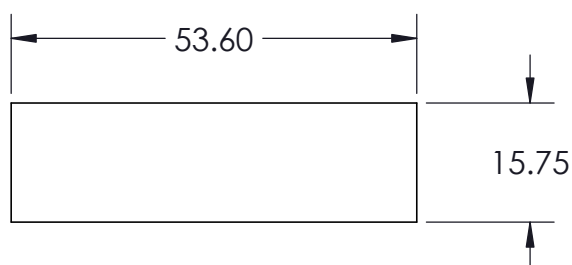
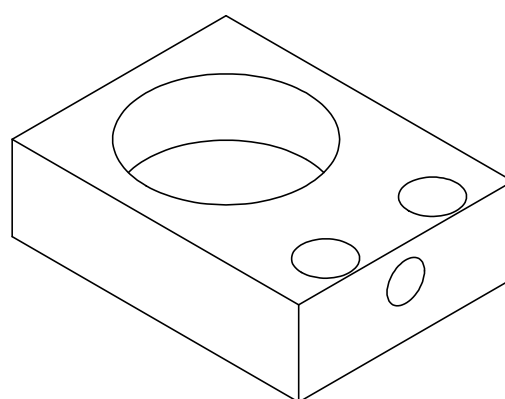
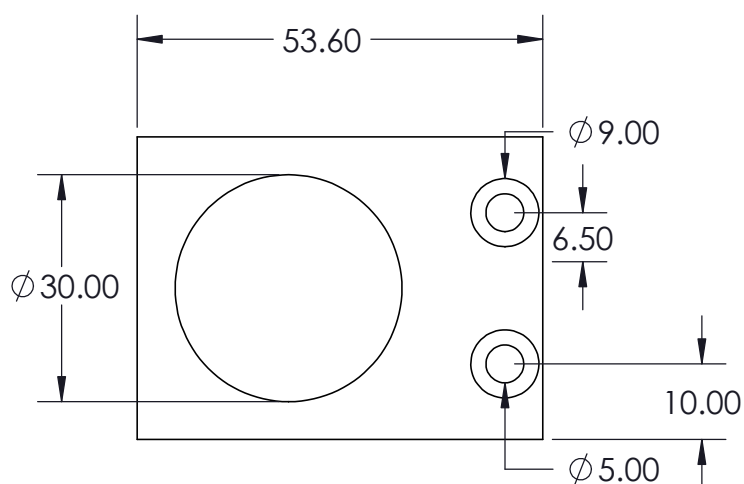
D03-407





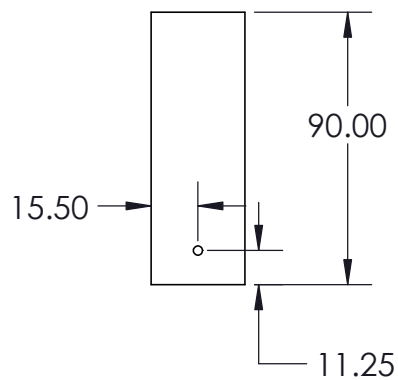
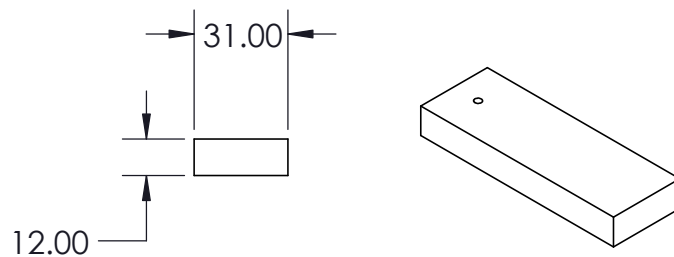
PRINTING SPECIFICATION			
MATERIAL:	PETG		
PRINTER:	CREALITY ENDER-3 V2		
INFILL TYPE:	TRI-HEXAGONAL		
INFILL RATE:	100%		
BED TEMPERATURE:	60°C		
EXTRUSION TEMPERATURE:	200°C		

TREATMENT: NO TREATMENT		UIDE	MECHATRONICS ENGINEERING			
COVERING: NO COVERING						
MATERIAL:		SCALE: 1:1	DIB.	OSEJO E.	11/06/2026	
PETG	TOL.GRAL: ±0,1		DIS.	OSEJO E.	12/04/2026	
			REV.	MOSQUERA G.	15/06/2026	
CONVEYOR BELT AXIS		D03-408				



PRINTING SPECIFICATION			
MATERIAL: PETG			
PRINTER: CREALITY ENDER-3 V2			
INFILL TYPE: TRI-HEXAGONAL			
INFILL RATE: 100%			
BED TEMPERATURE: 60°C			
EXTRUSION TEMPERATURE: 200°C			

TREATMENT: NO TREATMENT		UIDE	MECHATRONICS ENGINEERING				
COVERING: NO COVERING							
MATERIAL:	PETG	TOL.GRAL: ±0,1	SCALE: 1:1	DIB.	OSEJO E.	11/06/2026	
				DIS.	OSEJO E.	12/04/2026	
				REV.	MOSQUERA G.	15/06/2026	
BEARING SUPPORT			D03-409				



TREATMENT: NO TREATMENT		UIDE	MECHATRONICS ENGINEERING			
COVERING: NO COVERING						
MATERIAL:		SCALE: 1:2,5	DIB.	OSEJO E.	11/06/2026	
MDF	TOL.GRAL: ±0,1		DIS.	OSEJO E.	12/04/2026	
			REV.	MOSQUERA G.	15/06/2026	
BOTTOM COLUMN		D03-410				