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Diseño e implementación de un sistema mecatrónico de seguimiento de objetivos en tiempo real basado en visión artificial para la detección y seguimiento automático de intrusos mediante procesamiento de imágenes integrado.

Design and Implementation of a Real-Time Mechatronic Target Tracking System Based on Computer Vision for Automatic Intruder Detection and Tracking via Embedded Image Processing.

Quito - 2026

Aprobación del Tutor del Trabajo de Integración Curricular

Yo, **Ing. Guillermo Alfredo Mosquera Canchingre**, en calidad de tutor del Trabajo de Integración Curricular denominado: *Diseño e implementación de un sistema mecatrónico de seguimiento de objetivos en tiempo real basado en visión artificial para la detección y seguimiento automático de intrusos mediante procesamiento de imágenes integrado*, realizado por el estudiante **Francisco Andrés Hernández Guerra**, certifico que el presente trabajo 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.



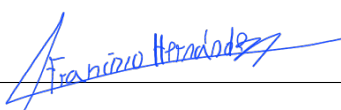
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Dedicatoria

*A mis padres, **Valeria Viviana Guerra Altamirano** y **Francisco Javier Hernández Villamar**.*

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Resumen

Este proyecto de titulación presenta el diseño e implementación de un sistema mecatrónico de seguimiento de objetivos en tiempo real para seguridad residencial. El problema abordado es la naturaleza pasiva de la vigilancia tradicional y la fatiga del operador humano, lo que reduce significativamente la detección de intrusos después de cortos períodos de monitoreo. Mediante una arquitectura distribuida que utiliza una Raspberry Pi 5 con el modelo YOLOv8n para visión por computadora y un microcontrolador ESP32 para control PD, el sistema identifica con éxito siluetas humanas con un nivel de confianza superior al 85% probado hasta un alcance de 5 metros. El alcance físico incluyó la construcción de una plataforma robótica de dos grados de libertad (Pan-Tilt) con una latencia de procesamiento controlada menor a 300 ms. Los resultados demuestran una transición efectiva hacia una respuesta de seguridad activa y autónoma, incorporando un interruptor mecánico de corte además de un sistema de alerta tanto física como virtual mediante notificaciones por Telegram.

Palabras clave: Visión por computadora, Seguimiento de objetivos, Mecatrónica, YOLOv8, Sistemas embebidos, Seguridad activa.

Abstract

This graduation project presents the design and implementation of a real-time mechatronic target tracking system for residential security. The problem addressed is the passive nature of traditional surveillance and fatigue of the human operator, which significantly degrades the detection of intruders after short periods of monitoring. Through a distributed architecture using a Raspberry Pi 5 with the YOLOv8n model for computer vision and an ESP32 microcontroller for PD control, the system successfully identifies human silhouettes with a confidence level that exceeds 85% in a distance less than 5 meters. The physical scope involved the construction of a two-degree-of-freedom (Pan-Tilt) robotic platform with a controlled processing latency of 300 ms. The results demonstrate an effective transition to an active and autonomous security response, incorporating a mechanical kill switch, physical alerts and telegram notifications within indoor environments.

Keywords: Computer vision, Target tracking, Mechatronics, YOLOv8n, Embedded systems, Active security.

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 1.1, 2.3.5
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 1.3, 2.1, 2.2
3. An ability to communicate effectively with a range of audiences.	Analysis	Sections 2.3.1, 4.1
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	Sections 1.3, 2.1.3
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 1.4
6. An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.	Analysis, Comprehension	Sections 3.2.1, 3.2.2
7. An ability to acquire and apply new knowledge as needed, using appropriate learning strategies.	Application, Analysis	Sections 1.2, 2.3.4.2, 2.3.6.2

Chapter I

Introduction

Problem Definition

In the contemporary global landscape, security has transitioned from a localized concern to a complex technological challenge. The rapid urbanization and the increase of high-value assets have required the development of a strong surveillance system. Historically, Closed-Circuit Television (CCTV) served as the primary tool for this task; however, traditional systems are passive which means they function as recording devices that require constant human operation to interpret data and react to threats. Moving further into the era of Industry 4.0, the use of Artificial Intelligence (AI) and Mechatronics systems offers a path to a more active automated security. The motivation for this project relies from the need to aboard gap between image processing and physical response, creating a system that identifies the intruder and pursues it autonomously.

An important limitation of modern surveillance is the Fixed Field of View (FOV). A static camera creates blind spots that moderns intruders can surpass. While Pan-Tilt-Zoom (PTZ) cameras exist, they may also rely on manual control or pre-set patterns that do not adapt to the movement of a target. Furthermore, the human factor is also a weak link in the security chain. Research in industrial psychology identifies a phenomenon known as vigilance decrement, where a human operator's ability to detect moving targets on a screen diminish significantly after only 20 minutes of monitoring [1]. In many cases, especially during late-night shifts, fatigue or distraction leads to surveillance failure. From an economic perspective, employing a full-time security team to monitor multiple camera may require a high cost that many enterprises and residential areas cannot sustain.

State of the Art

The field of automated surveillance has gone to significant transformation, moving from passive recording to smart monitoring systems. This evolution is primarily given due the need to overcome the limitations of human monitoring; as identified by the seminal research from Sandia National Laboratories [4], manual observation is a "low-stimulation" activity where operator attention drops significantly below standards after only 20 minutes. This "human-in-the-loop" vulnerability provides the primary justification for developing the autonomous systems explored

in recent literature.

For instance, B. D. Kaur et al. [5] proposed a sophisticated two-layer AI system that integrates cross-camera tracking to monitor suspicious behavior across multiple nodes, addressing the limitations of single-node surveillance. Building on this need for integrated intelligence, D. Rodriguez Garcia et al. [6] developed a smart security camera platform using an Arducam PTZ setup, achieving over 90% recognition confidence at distances up to 20 feet by integrating person detection, face recognition, and automated logging.

The foundation for low-cost implementation in this field was significantly influenced by W. F. Abaya et al. [7], who used the Raspberry Pi (RPI) and OpenCV to achieve human and smoke detection accuracies of 83.56% and 83.33%, respectively in warehouse environments. As hardware capabilities evolved, the focus moved toward high-performance control and optimization.

Y. L. Melese et al. [8] worked on the physical challenges of target tracking by designing a Fuzzy-PID controller, utilizing a Genetic Algorithm (GA) to find ideal scaling factors that allow the system to handle frequencies up to 100 rad/sec. This mathematical challenge is also complemented by the practical tuning methods demonstrated by Imron et al. [9], who successfully applied the Ziegler-Nichols method to a PID controller for an Arduino-actuated pan-tilt system, ensuring target tracking with minimal oscillation. Furthermore, M. D. Doloiu et al. [10] provided a bridge between vision and mechanics by integrating a camera model with the physical forces of a pan-tilt servo system, creating a foundation for deep learning face tracking.

Hardware optimization remains a critical factor for real-time performance on small devices. S. Pecolt et al. [11] and M. Zamir et al. [12] both explored the implementation of face recognition algorithms—such as Eigenfaces, LBPH, and CNNs—on the Raspberry Pi 4 platform. Their research highlights that while CNNs offer superior accuracy in identifying authorized personnel, they require more resources to maintain low latency.

To guide these hardware choices, D. Greco et al. [13] provided a study for the Raspberry Pi 4, quantifying the trade-offs between inference speed (FPS) and average precision for YOLOv5 and YOLOv8 architectures, proving that YOLOv8-small is currently the most viable option for real-time projects. More performance gains were worked by J. Song et al. [14], who analyzed OpenCV limitations and demonstrated that by implementing OpenCL for GPU acceleration can improve detection up to 86%.

The main intelligence of these systems relies a robust detection and data analysis.

J. Zhou and J. Hoang [15] developed a system using Background Subtraction and a custom Codebook algorithm to classify humans, utilizing color histograms to track individuals across frames. Environmental robustness is further developed by the work of S. Mishra et al. [16], who focused on reducing false positives caused by shadows and light fluctuations for intelligent motion detection.

Moving to a more simple detection, S. Santhi Priya and Sk. Nowshad Ali [17] implemented smart detection by using CNNs to identify aggressive behaviors, such as fighting or unauthorized entry, effectively transitioning surveillance into an automated system. This transition may also need ethical considerations, as explored by Y. Liu et al. [18] in their survey on Privacy-Preserving Video Anomaly Detection (P2VAD), which outlines the importance of implementing an encrypted system for protecting personal information.

Connectivity and infrastructure are equally important for modern emergency response. H. Zhang et al. [19] developed an IoT-based system using MQTT over TLS, achieving alert latencies under 450 ms with a 99.1% success rate. For a bigger scale distributed environments, F. Bashir and S. Arief [20] examined the use of Geospatial Intelligence and Reinforcement Learning to coordinate PTZ cameras across multiple cameras in different areas.

Specialized detection tasks have also gone to a more advance aspect, such as the work by J. D. Muñoz et al. [21], which proved that autonomous zooming on PTZ cameras significantly improves the performance of Faster R-CNN and EfficientDet models for weapon detection. These technical capabilities find applications in diverse fields, including cinematography, where S. Pattanayak et al. [22] showed how AI-driven PTZ movements can automate smooth recording.

However, as these systems become more interconnected, N. M. Allifah and I. A. Zualkernan [23] warn of the security risk by analyzing the consumer IoT devices which revealed high exposure to cloud-based information. To mitigate these risks in local systems, A. K. Arigela and C. Banapuram [24] made use of Node-RED on Raspberry Pi to manage ESP32 edge nodes, providing an easily scaled and more secure systems for home and industrial automation.

Justification

This thesis proposes the development of an Autonomous Mechatronic Target Tracking System. By using a distributed architecture, the system surpasses the heavy computational requirements of Computer Vision (CV) from a high-level processor while maintaining precise, real-time control through a microcontroller. The main focus of the system is an “active vision”

platform. Using a low-cost, ARM-based processing unit as the central computer, the system implements deep learning detection algorithms to identify human presence. Once a target is localized the system calculates required spatial corrections and transmits them to a specialized microcontroller. This controller then controls a 2 Degrees of Freedom mechanical assembly to rotate the camera, ensuring the target remains centered in it.

The importance of this research lies in its compact system low-cost approach. Rather than depending on an external server or an expensive PC, this project explores the efficiency of low-cost, low-power hardware. By optimizing the communication between the processor and the micro controller, the system achieves sufficient performance. This makes smart, automated security a more accessible service for sectors that can not afford the high costs of industrial-grade tracking hardware.

The necessity of this project is highlighted by three critical factors identified in current literature: the failure of human vigilance, the security risks of external cloud systems, and the need for cost-effective hardware. As the “human-in-the-loop” remains as most significant limitation in security systems [4], there is an urgent industrial requirement intelligent systems that can operate without performance downturns.

While commercial smart cameras are widely available, recent evaluations of consumer IoT devices [23] have showed vulnerabilities. This project addresses that limitation by developing a local system. By utilizing a distributed architecture for vision processing and real-time control from a microcontroller this research follows with state-of-the-art for deep learning object detection and closed-loop control optimization [9, 13], providing a high-performance alternative without being too expensive.

In an era where residential and industrial sectors require an active reaction rather than passive monitoring, this mechatronic approach offers a solution that aims to maintain high detection accuracy [6] and low-latency response [19] without compromising data privacy [17, 18].

Objectives

General Objective

To design and implement a mechatronic system capable of real-time target tracking for security purposes, utilizing a distributed architecture and computer vision algorithms to ensure automatic detection and continuous monitoring of intruders.

Specific Objectives

- Design a 2-degree-of-freedom (2-DOF) robotic platform, including a 180° continuous rotation base and a vertical tilt mechanism, utilizing 3D printing and mechanical transmission components.
- Integrate a pre-trained convolutional neural network model into an embedded vision pipeline using specialized libraries to achieve real-time identification and localization of human targets.
- Implement a communication protocol to transmit tracking coordinates and a control algorithm to synchronize camera movement with the target.
- Integrate a non-blocking notification and alert system capable of executing local and remote indicators upon target confirmation without interrupting the primary tracking loop.
- Evaluate the operational efficiency of the integrated system by analyzing performance metrics—including detection confidence, processing latency, and processor core temperature—under varying model inference resolutions and target distances.

Chapter II

Methodology and Design

This project applies the VDI 2206 methodology to the development of a real-time mechatronic target tracking system by integrating mechanical, electronic, and software domains through a flexible V-shaped macro-model and recursive micro-level cycles. The process begins with a requirements phase that establishes key functional detection goals and essential hardware, economic, and privacy constraints. In the conceptual design phase and specific architecture was selected as the optimal alternative due to its mechanical advantage and structural stability. Finally, the specific design details the hierarchical integration of an embedded single-board computer with a lightweight deep learning model for computer vision and processing, a dedicated real-time microcontroller for bridge communication, and precision actuators alongside a vision sensor and gear transmission to achieve a high-performance-to-cost ratio for autonomous surveillance.

The VDI 2206 methodology [25] is a specialized engineering guideline that provides a structured framework for the design and development of mechatronic systems. It integrates the domains of mechanics, electronics, and information technology into a synergetic workflow. The methodology is designed to manage two primary challenges: complexity and heterogeneity.

This method consists of two main working levels:

1. **The Micro-Level:** Is an action oriented cycle made for addressing specific technical challenges encountered during the design process. Rather than a linear path, it is a continuous loop that ensures every aspect is validated.
2. **The Macro-Level (The V-Model Procedure):** The macro-level provides the strategy for the entire project's life cycle. It ensures that the various engineering domains (mechanical, electrical, and software) are joined through a structured "V" shape.

Requirements

The stakeholders' needs were translated into specific and technical requirements that are the bases of software design, mechanical dimensioning, and concurrency loops of the mechatronic prototype.

Functional Requirements (FR)

- **FR-01:** The system shall identify human shapes within the video stream using real-time computer vision algorithms, distinguishing them from pets or inanimate objects based on geometric proportions.
- **FR-02:** The system shall adjust its field of view to maintain a detected human subject within the central frame.
- **FR-03:** The system shall execute a dual-layer alert routine upon multi-frame human confirmation, activating local physical indicators and capturing a photographic record to be transmitted asynchronously to a remote mobile interface.

Non-Functional Requirements (NFR)

- **NFR-01:** To mitigate vigilance decrement and operator fatigue, the system shall function independently, executing tracking routines automatically upon detection.
- **NFR-02:** The total latency of the tracking loop—from image acquisition to control signal—shall not exceed 300 ms to ensure fluid tracking of moving targets.
- **NFR-03:** The detection algorithm must reach a confidence score of 0.85 or higher to initiate tracking protocols and concurrent alert routines.

Restrictions (RE)

- **RE-01:** The software architecture must be optimized for embedded processing units with limited RAM and CPU resources.
- **RE-02:** The system is restricted to indoor environments with controlled lighting, excluding physical active deterrents to focus exclusively on non-blocking tracking and informational alerts.
- **RE-03:** The mechanical range of motion for the tracking base (Pan axis) is restricted to 180 degrees to prevent cable stress and structural failure.
- **RE-04:** The hardware must include a pause button to disable the camera's vision model when needed.

Conceptual Design

In this stage, two distinct mechanical designs were proposed to accomplish the tracking requirements. Both models use a Pan-Tilt system configuration but are different in their transmission methods and structural load distribution.

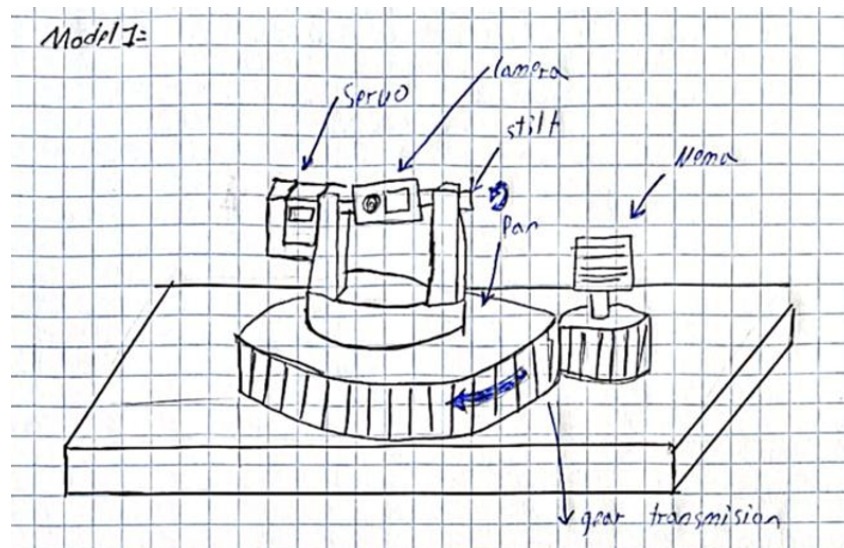


Fig. 1. Gear-Reduced Pan and Servo Tilt Architecture.

Alternative 1: Gear-Reduced Pan and Servo Tilt

This model functions as an indirect drive system for the horizontal axis. A Nema stepper motor transmits motion to the main base by using a gear reduction system. The vertical axis (Tilt) is controlled by a servo motor placed on a vertical support ("stilt").

- **Mechanical Logic:** By implementing a gear ratio, the system increases the motion's angular resolution. This setup establishes the camera's weight from the motor's drive shaft, providing higher stability.
- **Advantages:** Higher precision for each step, reduced vibration during quick stops, and a stronger center of gravity. It also allows an easy disassemble of the motors for repairs or replacement.

Alternative 2: Direct Drive Pan and Geared Tilt

This alternative consists on a direct drive for the Pan axis, where the camera assembly is being moved directly by the Nema motor. The Tilt axis utilizes a gear segmentation system driven by a secondary motor.

- **Mechanical Logic:** This design was designed to minimize the size of the device by integrating the tilt mechanism directly with the pan motor .
- **Disadvantages:** The motor shaft must move the entire axial load and must resist bending moments of the camera and tilt components. This may result on a backlash disadvantage, making the system more loose and compromising the stability of the camera system. Also motor reparation or replacement becomes more difficult.

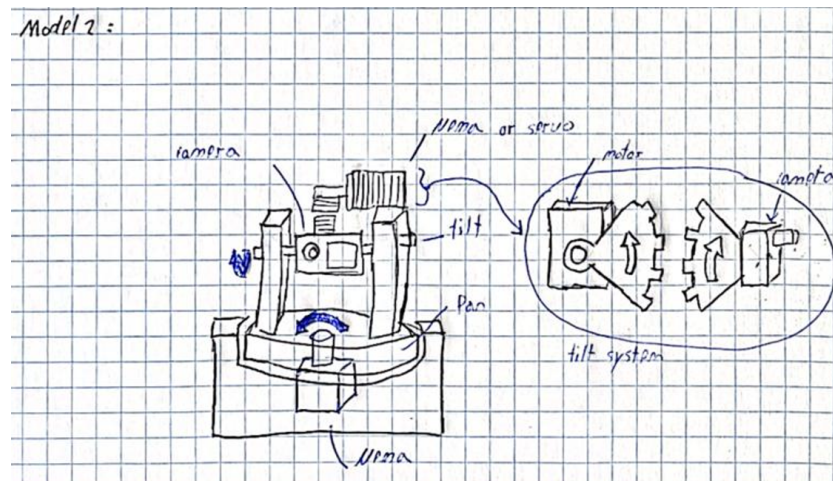


Fig. 2. Direct Drive Pan and Geared Tilt Architecture.

Alternatives Evaluation

To compare both mechanical architectures, a decision matrix was implemented based on the key mechanical and operational plus and cons identified during the conceptual phase.

TABLE I
Decision Matrix for Conceptual Alternatives

Evaluation Criteria	Alternative 1: Gear-Reduced Pan	Alternative 2: Direct Drive Pan
Mechanical Stability	High: Camera weight is decoupled from the motor's drive shaft.	Low: Motor shaft bears the entire axial load and bending moments.
Precision & Vibration	High: Gear ratio multiplies torque and increases angular resolution.	Low: Prone to mechanical "play" and backlash.
Control System Viability	Optimal: Robust center of gravity prevents oscillations.	Compromised: Mechanical looseness can destabilize the control loop.
Maintenance	Easy: Allows straightforward disassembly for motor repairs.	Difficult: Complex head assembly hinders motor replacement.
Device Footprint	Moderate: Requires external gear assembly and vertical stilt.	Minimized: Tilt mechanism is compactly integrated into the head.

Detailed Design

Following the selected conceptual design, the requirements define the system through three hierarchical levels: logical, functional, and physical. The understanding of each integration ensures the a proper synchronization of software, electronics, and mechanical components.

System Architectures

Logical Architecture. This architecture defines the system in depending of data and information flow, establishing the relationships between logical processes, data storage, and structures. It focuses on how data flows through the system to make the functional requirements take place, without detailing the physical components that would be used.

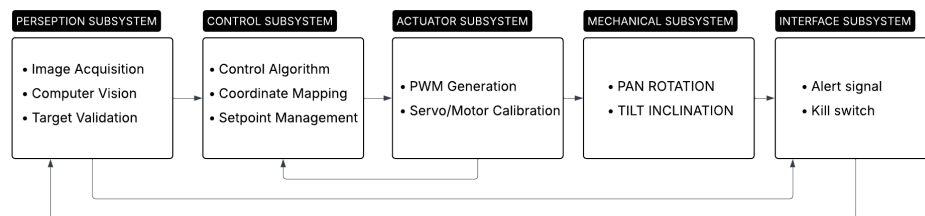


Fig. 3. System logical architecture detailing the information and data flow.

Functional Architecture. The functional architecture decomposes the overall system task into fundamental, manageable sub-functions and defines their hierarchical interconnections. It maps the technical operations derived from the requirements specification to a functional structure that identifies the core operational blocks required for autonomous surveillance and tracking.

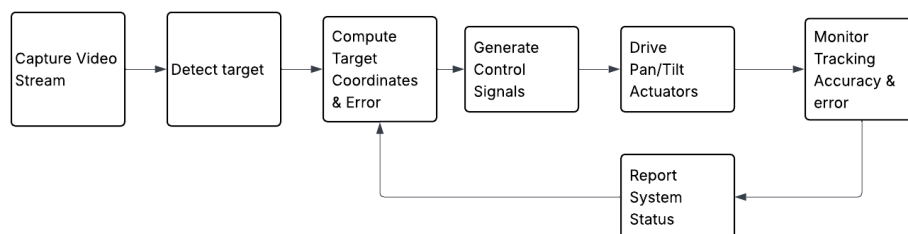


Fig. 4. Functional decomposition and interconnection architecture.

Physical Architecture. The physical architecture translates the functional requirements and logical flows into tangible mechanical and electronic components. It details the precise spatial arrangement, integration points, and physical interconnections of all hardware elements, including the sensor mounts, gear mechanisms, and control electronics, according to the selected concept.

Selected Design and Justification

After a comparative analysis, Alternative 1 was selected as the final design for the prototype development. The decision is justified by the following criteria:

- **Mechanical Advantage:** The gear transmission in the Pan axis allows the Nema motor

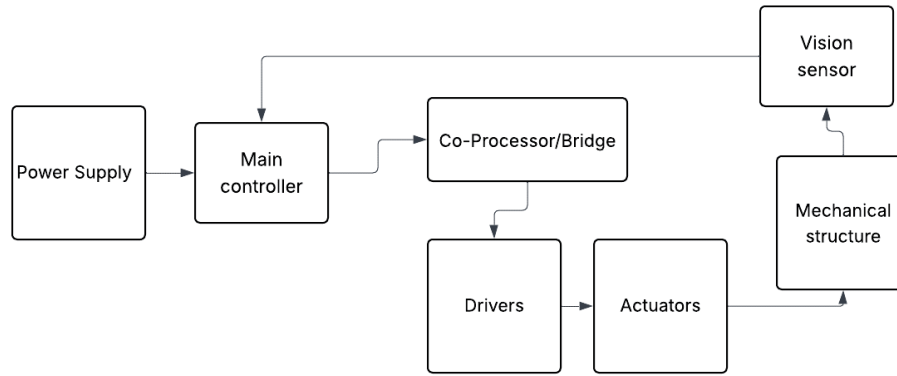


Fig. 5. System physical architecture and component integration diagram.

to operate in an optimal efficiency range. It also prevents the motor from suffer under the inertia of the camera assembly, ensuring good performance during continuous operation.

- **Structural Integrity:** Unlike Alternative 2, where the motor shaft is a critical point of failure due to direct loading, Alternative 1 distributes the weight across a bigger base. This ensures that the alignment remains precise over time, preventing shaky movements.
- **Control Simplicity:** The use of a servo for the Tilt axis simplifies the control logic. Since the web camera is a lightweight load for the Pan axis, this combination approach (Stepper + Servo) offers balance between torque and ease of implementation for an embedded system.

Specific Design Subsystems

The system is organized into 3 hierarchical subsystems:

- **Vision and Intelligence Layer (Master):** This layer is centered on a embedded processing unit which primary functions for image acquisition from the optical sensor, real-time human detection using neural network inference, and the calculation of target error co-ordinates. By isolating the heavy computational load in this area, the system can have enough computational resources for less latency and better performance.
- **Control and Communication Layer (Bridge):** A selected microcontroller functions as the interface between the processor and the physical hardware. It is responsible for reading serial data from the master unit, executing the control algorithms and generating the pulse signals for controlling the motor's movements.
- **Actuation Layer:** In this it is located the mechanical drive system and its corresponding power electronics. It utilizes a 2 degree of freedom system consisting of a stepper motor for the horizontal (Pan) axis providing a holding torque and resolution. A servo motor was

used for the vertical (Tilt) axis.

Component Selection and Technical Justification

To implement the hierarchical architecture described above, the following components were selected:

Main Processor. For the selection of the main processor of the project, it is important to make a comparing of the available commercial models of Raspberry Pi.

TABLE II
Compare contrast Raspberry Pi models [1]

Feature	Raspberry Pi 3 B+	Raspberry Pi 4	Raspberry Pi 5	Project Impact
CPU Architecture	Cortex-A53	Cortex-A72	Cortex-A76	The A72 and A76 provide good performance for video processing.
Clock Speed	1.4 GHz	1.5 GHz	2.4 GHz	Higher frequency ensures the system stays within the 300 ms latency requirement.
RAM Technology	LPDDR2	LPDDR4	LPDDR4X	LPDDR4 is the minimum standard required for high-speed tensor operations in Computer Vision.
RAM Capacity	1 GB	4 GB	4 GB / 8 GB	4 GB allows stable multi-threading (AI + Motors + Stream) without memory bottlenecks.
USB Ports	2.0	3.0	3.0	USB 3.0 is critical to prevent data lag between the camera and the processor.
Selection Status	Insufficient	Optimal	Optimal	The RPi 4 and RPi5 are the ideal processors for real-time tracking.

The Raspberry Pi 5 (4GB RAM) was selected as the primary processing unit to achieve the best balance between performance and real-time processing capabilities. Compared to previous generations, the Raspberry Pi 5 uses a more powerful Cortex-A76 processor operating at 2.4 GHz, which significantly improves the computational performance.

Although this platform requires higher power consumption and active cooling, these limitations are justified by the big improvement in processing speed and system reaction. While both the Raspberry Pi 4 and Raspberry Pi 5 are capable of supporting vision models, the increased performance of the Raspberry Pi 5 provides a more reliable efficiency for achieving

the 300 ms latency constraint. Also, its 4GB of LPDDR4X RAM and improved architecture enable efficient multi-threading and faster response to tasks such as real-time object detection, tracking, and local network streaming, making it a more robust solution for the automated surveillance system. [1].

Computer Vision Model Selection. A wide variety of computer vision models are available in the current market; however, because of the limited computational resources common in embedded systems, a filtering process is necessary to select the most efficient architecture for the Raspberry Pi 5. The primary objective is to identify a model that minimizes resource consumption without compromising the detection accuracy. Among the evaluated alternatives, models from the YOLO (You Only Look Once) family developed by Ultralytics, were selected due of it's real-time performance and efficient single-stage detection.

Additionally, Ultralytics YOLO models like the YOLOv5 and YOLOv8 offer lightweight variants specifically designed for low resource devices, achieving a strong balance between accuracy and computational cost. They also provide advantages such as straightforward deployment, support for multiple export formats (like NCNN), and a well-maintained ecosystem with extensive documentation and community support. These features make them more flexible and easier to integrate than alternatives like MobileNet-SSD or EfficientDet-Lite, which are adaptable which may offer a lower performance [2].

TABLE III
Comparison of different YOLO versions [2]

Model	Type	Accuracy (mAP)	Inference Speed	Resource Consumption
YOLOv8n	Detection	Medium-High	Very High	Low
YOLOv5n	Detection	Medium	Very High	Very Low
YOLOv5x	Detection	High	High	Medium-Low
YOLOv8x	Detection	Medium	High	Medium

Since the system requires high precision to meet the minimum 0.85 confidence requirement and simultaneously operating at the maximum possible speed the YOLOv8n (Nano) was selected.

- **YOLOv8n (Nano):** This model presents a common detection vision model on edge devices. Its "nano" architecture was specifically designed for embedded processing, providing the necessary accuracy to reach a 0.85 confidence score without compromising the frame rate required for fluid tracking. This choice is fundamental to ensure the system of

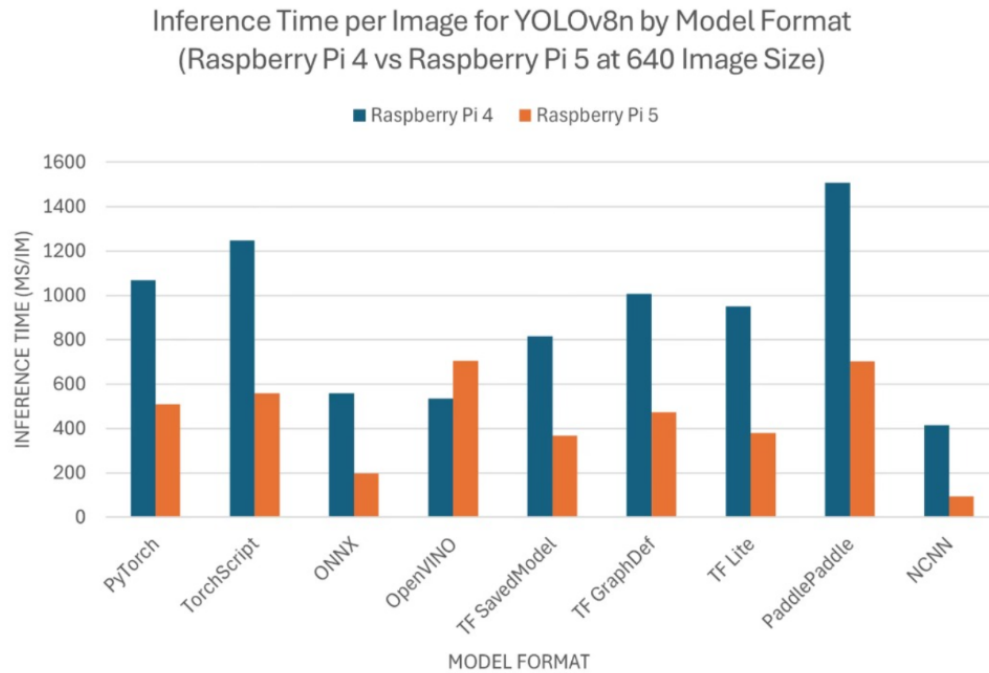


Fig. 6. Inference time per image YOLOv8n by Model Format (Raspberry Pi 4 vs Raspberry Pi 5 at 640 image size) [3].

maintaining its operation below the 300 ms total latency margin, allowing faster reaction.

To achieve this performance on the Raspberry Pi 5, the model is deployed using the NCNN format. As showed in the graphic, NCNN is the most efficient format for this hardware, reducing inference time to almost 100 ms per image. This is really optimized compared to standard formats like PyTorch (510 ms) or even TF Lite (380 ms). By using NCNN, the system will have free two-thirds of the 300 ms latency budget that can be used for image pre-processing and mechanical actuation. [3].

Hardware Components. Bridge Microcontroller. ESP32-WROOM-32: The ESP32 handles all low-level hardware timing. By offloading the PWM and stepper pulse generation to this dedicated dual-core controller, the system avoids the "jitter" or mechanical lag that occurs when a general-purpose OS (like Raspberry Pi OS) is under high CPU load.

Image Sensor. Logitech C920 Pro HD: This camera provides high-definition video with a wide dynamic range, which is crucial for the requirement of distinguishing human geometric proportions in indoor environments with varying light.

Pan Axis Actuator. NEMA Stepper Motor: A NEMA stepper motor is the best choice for the pan system as it provides the high precision and holding torque necessary to ensure stable and accurate angular positioning of the camera assembly during real-time tracking operations. This motor requires the use of the DRV8825 driver, which is configured at 1/16 mi-

crostepping to improve motion smoothness, and handles a peak current of 2 A.

Tilt Axis Actuator. High-Torque Servo: For the vertical axis, a servo motor shall be employed. Given that it is responsible for supporting the 300 g camera payload, the servo must be capable of handling this load while providing sufficiently rapid movement.

Other Generic Components: Additional components include LED and BUZZER (for physical alerts) and a 12V 3 A DC power supply to power both the servo and the NEMA motor.

Sizing Calculations

Pan Mechanism Bearing (Axial Load). First, in the pan mechanism, whose function is to rotate the entire camera system (with an approximate weight of 500 grams), the rotation occurs about a vertical axis. The bearing is positioned beneath the rotating structure to reduce friction. Since the load acts along the axis of rotation, it is considered primarily **axial**, and therefore a bearing specialized in supporting axial loads was selected.

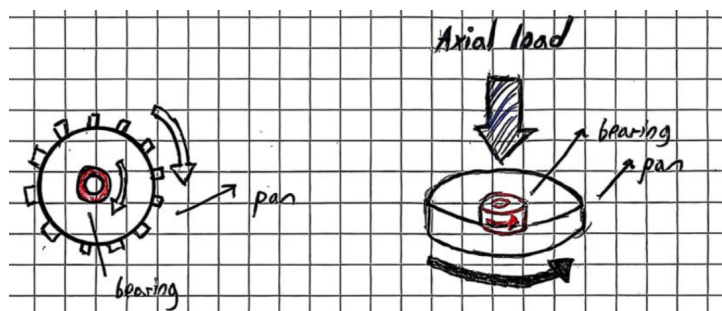


Fig. 7. Axial load distribution diagram for the pan mechanism.

Given that the applied load is extremely small (approximately 4.9 N), any thrust bearing would be significantly oversized for this application. For instance, one of the smallest available thrust bearings, the F6-12M with a 6 mm inner diameter, is capable of supporting dynamic loads of 360 lbf and static loads of 282 lbf at speeds up to 5000 rpm. This clearly exceeds the system requirements by a large margin.

As a result, the selection criterion was not based on load capacity but rather on **mechanical stability**. A bigger inner diameter allows the prototype to have a greater contact surface between the rotating base and the bearing, improving the structural stability of the pan mechanism. Based on this criterion, the selected bearing was the F10-18M, which has an inner diameter of 10 mm and an outer diameter of 18 mm, and is capable of supporting dynamic loads of 502 lbf and static loads of 612 lbf at 2500 rpm [26].

Tilt Mechanism Bearing (Radial Load). The bearing selection for the tilt mechanism can now be dimensioned. This bearing is responsible for supporting a **radial** load which corresponds to

the camera's weight, approximately 300 grams (≈ 2.94 N). Similar to the previous case, this load is extremely small, and all standard bearings are capable of supporting it without difficulty.

Therefore, the selection criterion was based on **availability and cost-effectiveness**, opting for one of the most common and economical solutions available: the 608 deep groove ball bearing. This bearing has a dynamic load capacity of approximately 3.45 kN and a static load capacity of 1.37 kN, with a maximum operating speed of up to 75,000 rpm. Additionally, it features an inner diameter of 8 mm and an outer diameter of 22 mm, making it compact perfect for the tilt mechanism. [27].

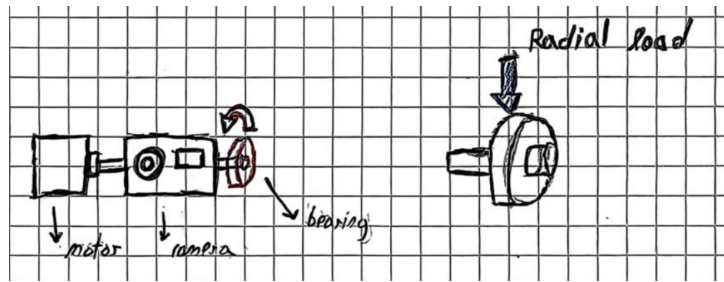


Fig. 8. Radial load distribution diagram for the tilt mechanism.

Sizing Calculations for Motors: Pan Axis (NEMA). The pan axis is responsible for supporting the main loads of the system. A 2:1 gear transmission is used to rotate the entire tilt assembly, which includes the webcam, servomotor, 3D-printed structures, and bearings, resulting in a total mass of 0.5 kg.

To calculate the torque required to drive the pan mechanism, two main components must be considered. First, the dynamic torque, which is defined as the product of the moment of inertia and the angular acceleration. For simplification, the system mass (0.5 kg) is modeled as a solid disk. The moment of inertia is calculated based on it, and an angular acceleration of 20 rad/s^2 is selected as a minimum design value.

Dynamic Torque:

$$T = J \cdot \alpha \quad (2.1)$$

Moment of Inertia (solid disk):

$$J = \frac{1}{2}mr^2 \quad (2.2)$$

In addition to the dynamic component, it is important to consider the friction torque generated by the bearing. Although rolling bearings provide low friction, it is not non-existent.

This friction can be approximated using the basic Coulomb friction model:

$$T_f = \mu \cdot F \cdot r \quad (2.3)$$

where μ is the bearing friction coefficient (assumed as 0.01), F is the applied load (0.5 kg $\approx$ 4.9 N), and r is the effective radius of the bearing (9 mm for the selected bearing).

Finally, the sum of the dynamic torque and friction torque determines the **minimum required torque** that must be provided by the motor. A safety factor of 2 is applied to ensure reliable and robust system operation.

Substituting the design values into the previously defined equations, the specific torque components are calculated for the pan axis:

Inertial Torque (T_a):

$$\begin{aligned} T_a &= \frac{1}{2} m \cdot r^2 \cdot \alpha \\ T_a &= \frac{1}{2} (0.5 \text{ kg}) \cdot (0.05 \text{ m})^2 \cdot (20 \text{ rad/s}^2) \\ T_a &= 0.0125 \text{ Nm} \end{aligned} \quad (2.4)$$

Friction Torque (T_f):

$$\begin{aligned} T_f &= \mu \cdot F_a \cdot r_{\text{bearing}} \\ T_f &= (0.01) \cdot (4.9 \text{ N}) \cdot (0.009 \text{ m}) \\ T_f &= 0.000441 \text{ Nm} \end{aligned} \quad (2.5)$$

Total Required Torque:

$$\begin{aligned} T_{\text{total}} &= T_a + T_f \\ T_{\text{total}} &= 0.0125 \text{ Nm} + 0.000441 \text{ Nm} \\ T_{\text{total}} &= 0.0129 \text{ Nm} \end{aligned} \quad (2.6)$$

The calculated minimum torque required for the pan system is 0.0258 Nm (applying the safety factor of 2 to the base total). A safety factor of 2 has been established for the project giving a required torque of 0.0516 Nm. While a NEMA 14 motor, offering a holding torque of 0.052 Nm (7.5 oz-in), would be the most appropriate option, its limited availability in the

Ecuadorian market makes the NEMA 17 the most viable selection for this project.

In conclusion, the implementation of a NEMA 17 stepper motor is an optimal choice for the pan system due to its high step resolution and available torque of 0.45 Nm. This additional torque may provide smooth motion and prevention of loss of steps during high-demand, real-time tracking operations.

Sizing Calculations for Motors: Tilt Axis (Servo). The tilt system is only responsible for handling the inclination of the camera over the pan axis. The weight of the camera is approximately 300 grams, and its center of mass is located 5 cm from the pivot.

For this torque calculation, the formula for gravitational torque was used, which is defined as the load (camera mass $\times$ gravity) multiplied by the distance from the center of mass of the camera to the pivot of the servo.

Gravitational Torque (T_s):

$$T_s = m \cdot g \cdot d$$

$$T_s = (0.3 \text{ kg}) \cdot (9.81 \text{ m/s}^2) \cdot (0.05 \text{ m})$$

$$T_s = 0.14715 \text{ Nm} \approx 1.5 \text{ kg} \cdot \text{cm} \quad (2.7)$$

The minimum required torque is 1.5 kg·cm. With a safety factor of 2 applied, the required torque increases to 3 kg·cm. There is a great variety of servos that can fulfill the required torque, like the HS-311 motor, which provides exactly the 3 kg·cm torque required at 4.8 V. However, due to availability, the MG996R servo was selected.

Available Torque (Servo MG996R):

- Stall Torque at 4.8 V: 8.5 kgf · cm (Safety factor = 5.6)
- Stall Torque at 6 V: 10 kgf · cm (Safety factor = 6.6)

The Servo MG996R is a suitable choice for the tilt mechanism, as it provides a stall torque of 8.5 kgf · cm at 4.8 V and 10 kgf · cm at 6 V, along with an operating speed of 6 rad/s, which is sufficient to meet the inclination speed requirements.

Electrical Power Sizing and Distribution. To ensure stable operation across all subsystems, the power distribution network was dimensioned to handle the peak loads of both the high-torque actuators and the logic components.

- **Main Power Supply:** The system is powered by a 12V, 3A DC power supply. This capacity is sufficient to drive the entire mechatronic architecture simultaneously.

- **Stepper Motor Circuit:** The 12V line is connected directly to the DRV8825 stepper driver. The driver's potentiometer was calibrated to limit the NEMA 17 current draw to a maximum of 1A. This prevents the motor from overheating while still providing enough torque.
- **Servo Motor Circuit (Voltage Step-Down):** Because the MG996R servo motor cannot operate directly from a 12V source, an XL4005 Buck Converter was integrated into the circuit. This converter steps down the 12V supply to a stable 5V. The XL4005 can handle up to 5A of continuous current, which gives a margin to supply the stall current required by the MG996R.

To validate the selection of the main power supply, the total maximum power consumption of the actuators is calculated:

$$\begin{aligned}
 P_{\text{total}} &= P_{\text{stepper}} + P_{\text{servo}} \\
 P_{\text{total}} &= (12\text{V} \cdot 1\text{A}) + (5\text{V} \cdot \sim 2.5\text{A}) \\
 P_{\text{total}} &\approx 12\text{W} + 12.5\text{W} = 24.5\text{W}
 \end{aligned} \tag{2.8}$$

Since the 12V 3A power supply provides up to 36W, the power source is perfectly sized to handle the maximum simultaneous mechanical load with a 30% safety margin.

Gear Transmission Dimensioning. To implement the 2:1 gear transmission on the Pan axis, the gears were specifically designed.

A gear module of 1.5 was selected. The transmitter gear (pinion attached to the NEMA 17) was designed with 50 teeth, and the driven gear (integrated into the Pan base) was designed with 100 teeth. This results pitch diameters of 75 mm and 150 mm, respectively.

The module of 1.5 was chosen due to 3D printing (FDM) tolerances. A smaller module would result in teeth too thin for a 0.4 mm 3D printer nozzle to reproduce accurately, leading to weak profiles and mechanical binding. The 1.5 module ensures the teeth have sufficient structural thickness to prevent shearing under load while maintaining print fidelity.

Using a high tooth count (50T/100T) significantly increases the angular resolution of the NEMA 17 stepper motor. While the motor provides 1.8° per step, the 2:1 reduction decreases the final pan rotation to 0.9° per step at the camera base, allowing for highly precise adjustments. Furthermore, having a larger number of teeth ensures smoother movement, as more teeth are in contact simultaneously. This reduces mechanical looseness, which is critical for

maintaining the detected human subject within the central frame as fluently as possible

Risk Management

In mechatronic systems, risk management must address hazards that compromise both user safety and component integrity. The integration of high-performance processing units, high-torque actuators, and custom additive manufacturing elements can cause operational risks such as thermal dissipation limits, electrical overcurrent, and mechanical pinching points.

To ensure a safe operating environment during maintenance and continuous surveillance, each physical and thermal failure mode must be identified and mitigated in the design phase. Table IV details the primary technical risks associated with user integrity and hardware protection, along with their respective mitigation strategies.

TABLE IV
User Safety and Component Integrity Risks

Risk	Mitigation Strategy
Thermal Damage and Fire Hazard	Integrate an active cooling system to reduce the CPU temperature and use lower inference resolutions to minimize computational stress on the Raspberry Pi.
Mechanical Pinching Hazards	Install a physical pause button to interrupt communication between the Raspberry Pi and the ESP32, ensuring the actuators come to an immediate halt.
Electrical Overcurrent and Shorts	Properly calibrate the motor drivers and buck converter, and ensure adequate ventilation within the electronics enclosure to maximize heat dissipation.
Actuator Burnout and Overloading	Align the camera's center of mass with the pivot axis to eliminate holding torque, and integrate appropriate bearings to reduce mechanical friction.
Structural Shear and Component Drop	Apply specific 3D printing techniques for each component based on its mechanical function and structural importance.

System Evolution and 3D Modeling

System Block Diagram. The following block diagram shows the electrical connections and data flow between the main components of the prototype

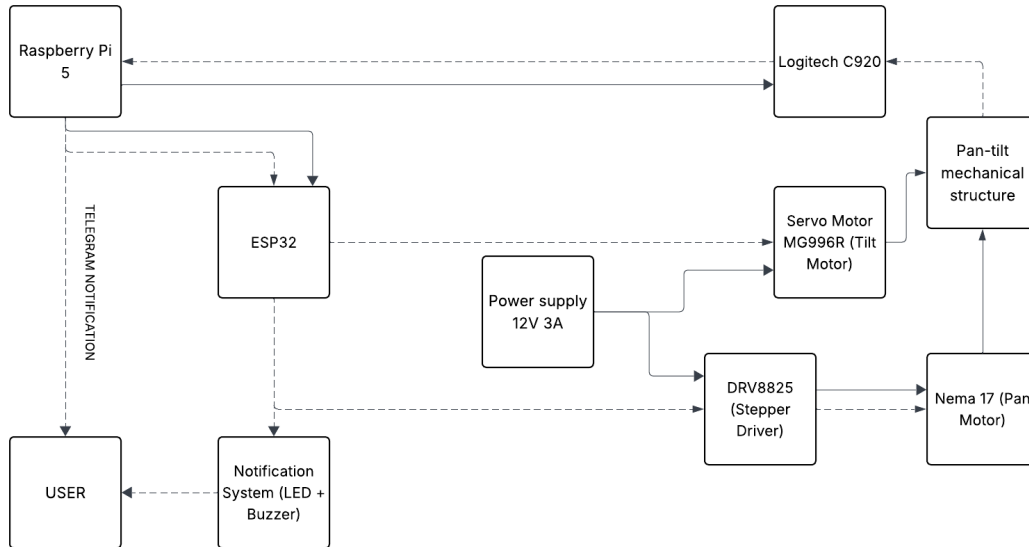


Fig. 9. System block diagram

Preliminary Designs and System Evolution. Before achieving the final mechanical and software architecture, preliminary versions of both the hardware and software were developed and tested. This section details the initial implementations, the technical challenges encountered during physical testing, and the decisions that led to the final design.

The initial software architecture was tested using the YOLOv8n model implemented on the Raspberry Pi via the NCNN framework. The first iteration was configured at an inference resolution of 640 pixels. While the system successfully achieved an acceptable rate of 12 FPS, it presented critical thermal management issues. Operating under this continuous computational load, the Raspberry Pi's CPU temperature went to 80°C in less than one minute. This excessive heat created a significant risk of thermal throttling and potential damage to the processor in time.

Optimizations for the Final Design: To mitigate the thermal bottleneck, the computational load was reduced by lowering the inference resolution to 320 pixels and implementing a frame-skip parameter of 2. This adjustment stabilized the CPU temperature at 65°C. Additionally, this optimization also reduced latency, allowing the inference speed to reach 30 FPS. However, to maintain stability and synchronize with the micro-controller's data reading, the software framerate was regulated and limited using the same frame skip parameter of 2.

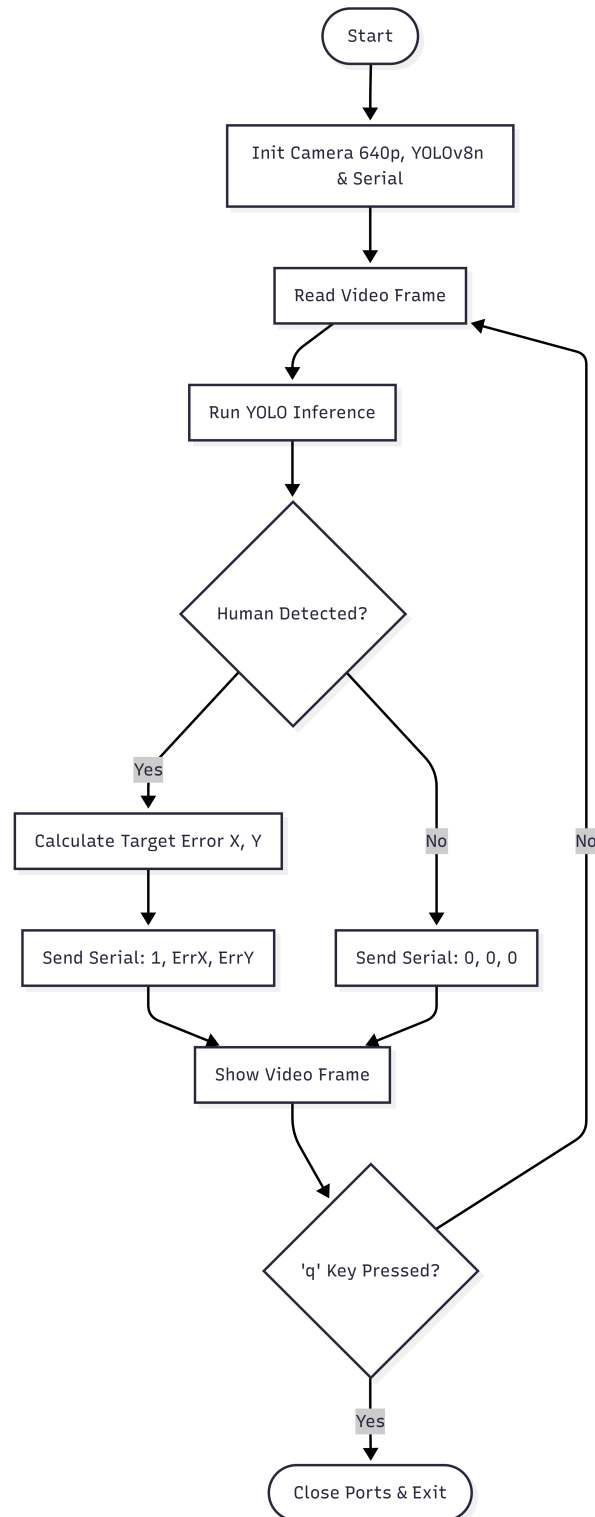


Fig. 10. Flowchart of the preliminary Raspberry Pi script.

During the tracking tests, another software challenge emerged: the prototype experienced severe oscillation when trying to center the target. This was caused by the system when attempting to reach an exact pixel coordinate, a really difficult task for the Tilt axis since the servo motor lacks fractional-degree resolution.

To resolve this, two control strategies were implemented in the final version: a Proportional-Derivative (PD) controller was introduced to improve the motor response, and a dead-zone tolerance range was established (configured to 20 pixels for the X-axis). This prevents the system from doing micro adjustments when the target is already in an acceptable central frame, entirely eliminating the jitter.

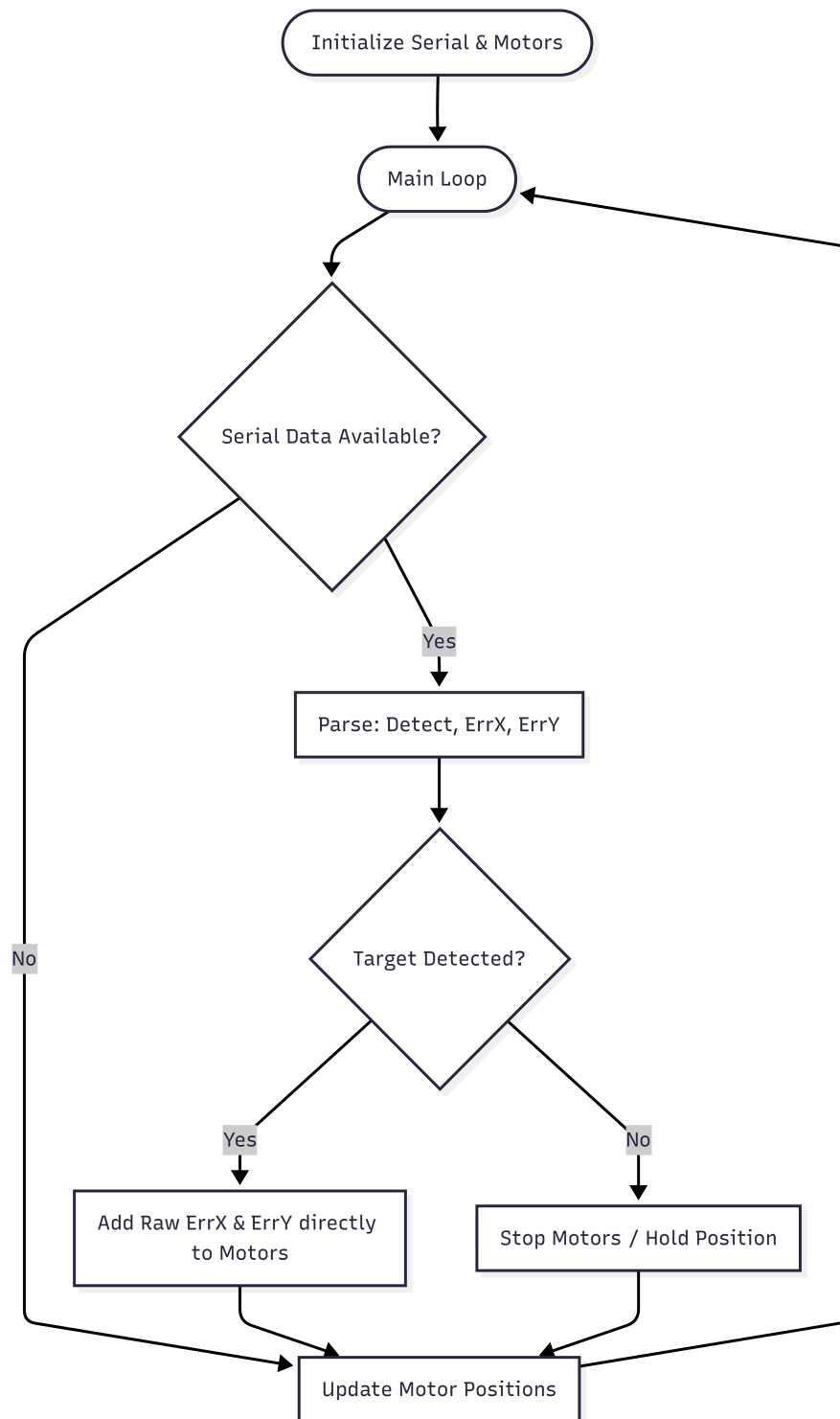


Fig. 11. Flowchart of the preliminary unsynchronized ESP32 control loop.

In the early mechanical prototypes, the Pan-Tilt mechanism functioned properly in virtual simulation, but in the physical assembly it was revealed some issues regarding mechanical tolerances and structural balance.

The primary problem was the inherent looseness in the rotational axis of the Pan base. Because the upper assembly's weight was not well distributed—with the Tilt servo motor shifting the center of gravity to one side—the Pan base tended to lean toward the heavier side. This incorrect inclination caused the teeth of the driven gear to separate from the NEMA pinion, resulting in poor gear connection, skipping teeth, and loss of mechanical transmission.

Optimizations for the Final Design: To solve the alignment issue without drastically increasing the system's weight or footprint, the drive gear on the NEMA was redesigned. Mechanical alignment guides were integrated directly into the 3D-printed gear structure. These guides restricted the base from tilting under the pan's load, forcing the pan axis to maintain a strictly horizontal posture. This modification ensured an optimal gear engagement between the stepper motor and the tracking platform at all times.

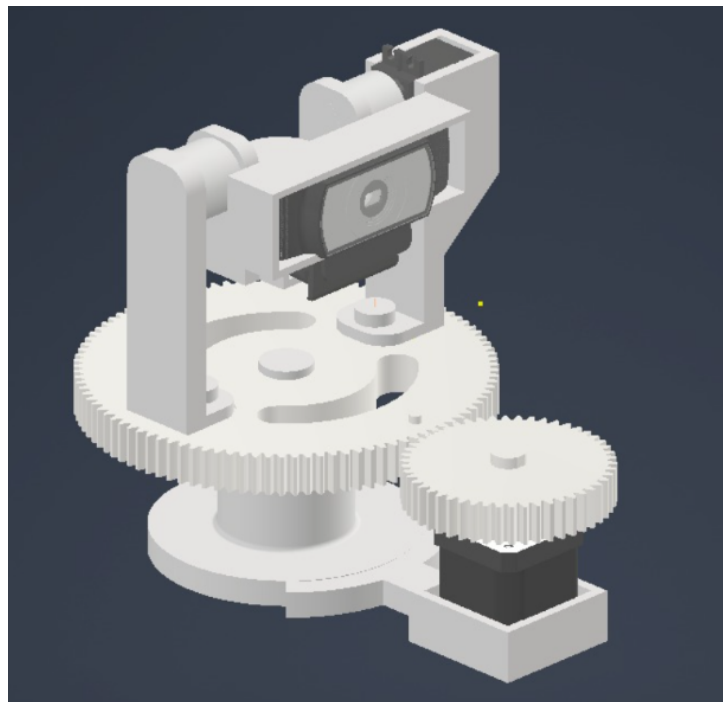


Fig. 12. Preliminary design without alignment guides.

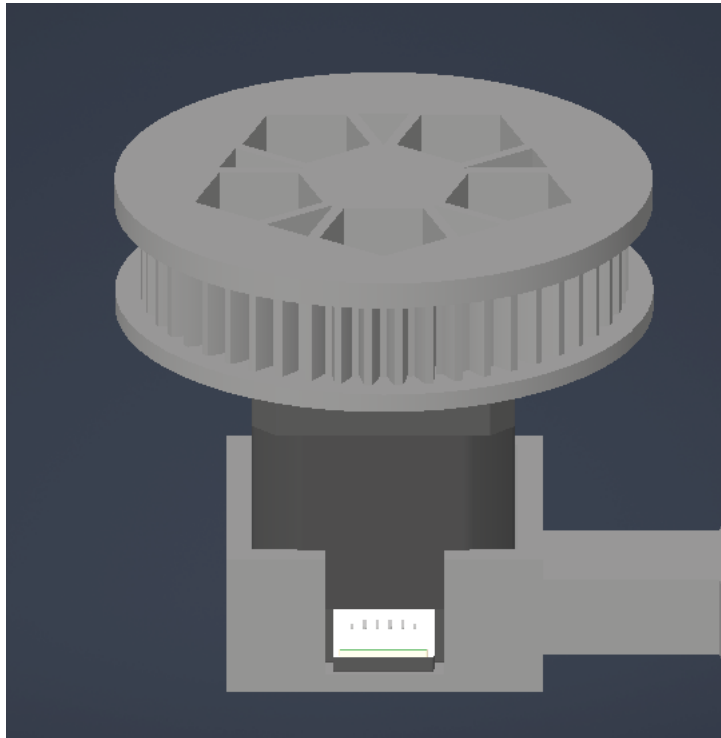


Fig. 13. Optimized driven gear featuring integrated alignment guides.

Final 3D Modeling. To validate the physical viability of the selected "Gear-Reduced Pan-Tilt" architecture, a complete 3D CAD assembly was developed. The model demonstrates the main distribution between the electronic components, actuators, and structural elements.

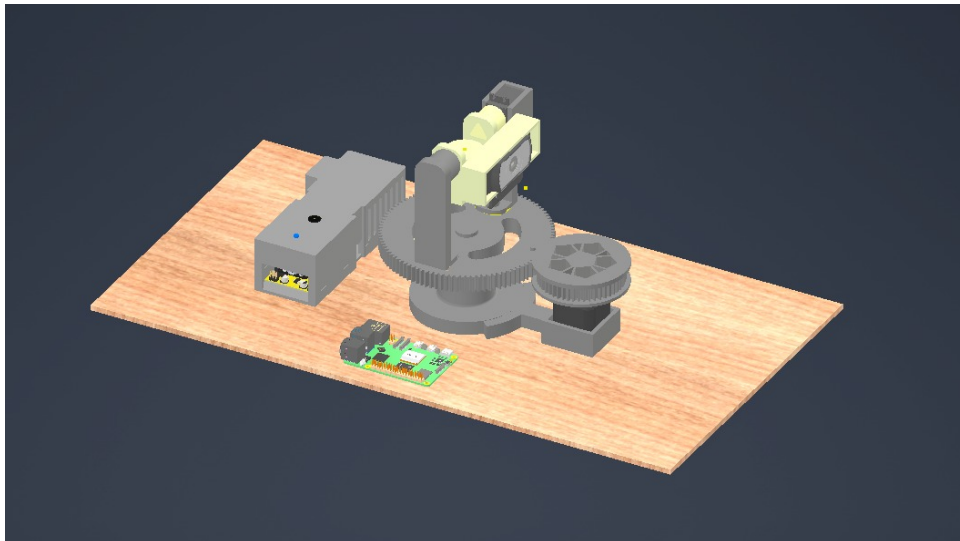


Fig. 14. Complete 3D CAD assembly of the Gear-Reduced Pan-Tilt system.

Pan Tilt Axis Interface: The functioning of the assembly consists of a unified bottom plate that securely mounts the NEMA 17 stepper motor alongside a the pan base. The mechanical interface of the Pan axis is driven by the gear system. The drive pinion is attached to

the NEMA 17 shaft and meshes directly with the main driven gear. This main gear functions as a rotary platform and is located over the central pillar. The F10-18M thrust bearing is located internally between the central pillar and the main gear absorbing the entire axial load (the weight of the upper assembly) and protecting the stepper motor shaft from undesired forces.

Tilt Axis and Camera Housing Interface: Mounted securely on top of the main driven gear are two vertical supports that form a U-shaped form.

- **Right Support:** Features a mounting extrusion dimensioned to house the MG996R servo motor. The servo's shaft connects directly to the right side of the camera bracket, providing direct-drive tilt actuation.
- **Left Support:** Contains a housing for the 608 deep groove ball bearing, which provides a low-friction pivot point that supports the radial load of the camera assembly.
- **Camera Cradle:** It is an enclosure that tightly grips the Logitech C920 webcam. It's center of mass is aligned with the pivot axis.

Control Electronics Enclosure: In addition to the pan-tilt mechanism is the control area, which contains all the electronic components required for actuation and logic processing. This integrated enclosure contains the DRV8825 driver calibrated for the NEMA 17 stepper motor, and the buck converter utilized to step down the voltage to a stable 5V for the servo motor. Finally, the enclosure also includes the ESP32 microcontroller, which handles the low-level processing and directly controls the movement of both actuators.

Software Architecture and Logic Design

The software architecture is distributed between two processing units: a Raspberry Pi acting as the Master Vision processor and an ESP32 functioning as the Bridge Controller.

Master Vision Logic (Raspberry Pi). The primary control loop located on the Raspberry Pi is designed to prioritize real-time processing and minimal latency. The system logic, illustrated in Fig. 15, integrates computer vision inference, filtering, and asynchronous network communications.

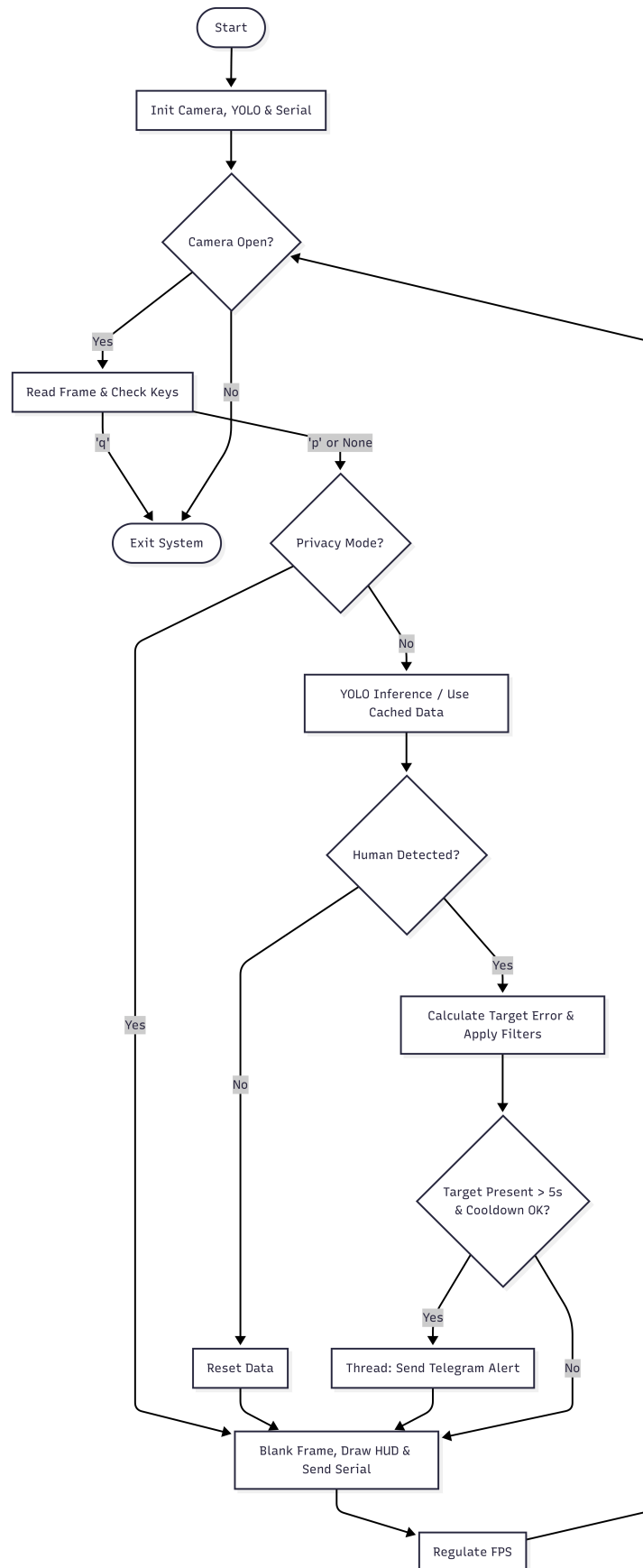


Fig. 15. Flowchart detailing the main execution loop, temporal filtering, and asynchronous tasks of the Raspberry Pi script.

The execution sequence begins with the initialization of the YOLOv8n model, the UART serial communication, and the video capture pipeline. During the main loop, a frame-skipping algorithm optimizes CPU usage by performing full tensor inferences only on designated frames, while maintaining previous error coordinates during skipped cycles.

When a human target is detected, the algorithm calculates the spatial error between the image center and the target's upper torso. To prevent mechanical oscillation and hardware jitter, a deadzone filter is applied to the error data before they are transmitted via Serial to the ESP32.

To manage security alerts without compromising the mechanical tracking loop, a multi-threading strategy was used. If a target maintains presence in the frame for more than 5 seconds, a secondary thread is called to capture the current frame and transmit it via the Telegram API. This architectural decision ensures that the network latency involved in uploading an image does not affect the main computer vision and serial communication loop.

Bridge Controller Logic (ESP32). The ESP32 acts as the low-level Bridge Controller, responsible for translating the spatial error coordinates received from the Raspberry Pi into the motor movements. By isolating this task on the microcontroller with real-time operating capabilities, the system avoids mechanical jitter and ensures smooth motor actuation. The logic implemented in the ESP32 is detailed in Fig. 16.

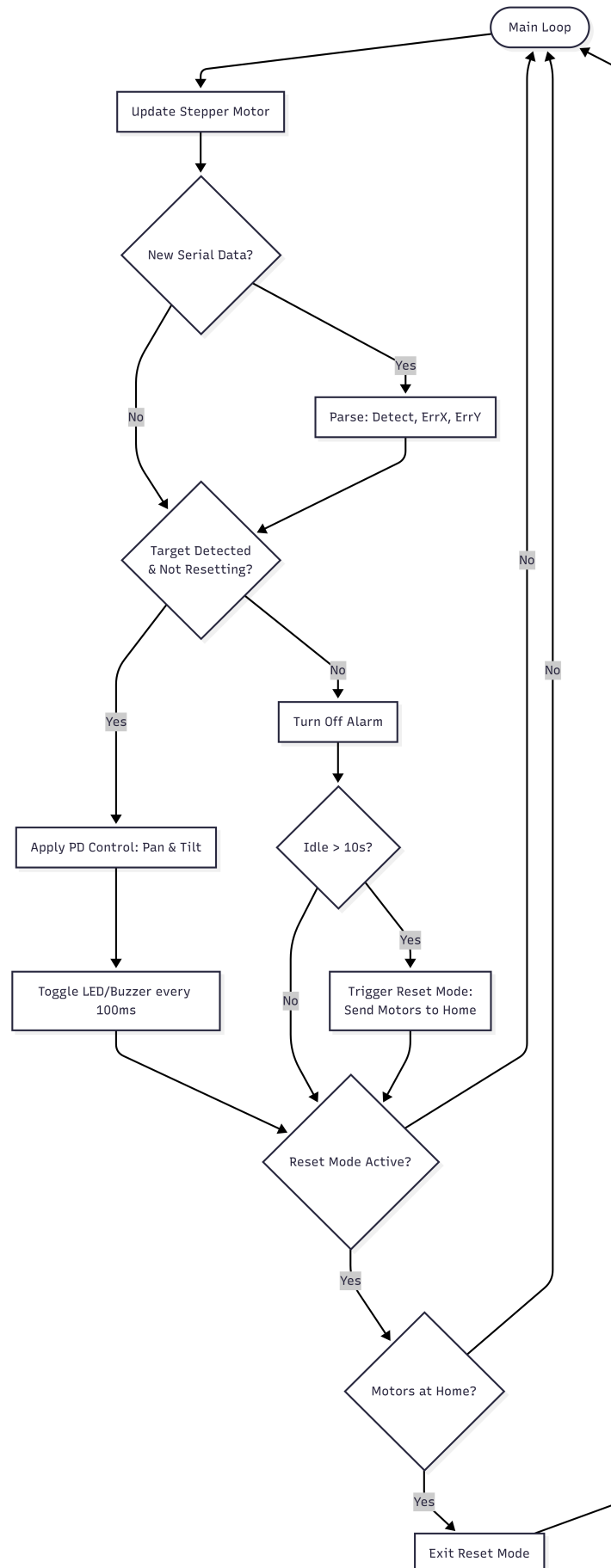


Fig. 16. Flowchart of the ESP32 main control loop, detailing serial parsing, PD control execution, and the idle homing sequence.

The core of the ESP32 firmware relies on a non-blocking execution architecture. The main loop begins by continuously updating the stepper motor state, ensuring that the high-frequency pulses required by the DRV8825 driver are generated without interruption.

Subsequently, the microcontroller checks the UART serial buffer for incoming data. If a new frame is available, it extracts the boolean detection status and the raw spatial errors (*ErrX* and *ErrY*). The control flow then evaluates the system's state:

- **Active Tracking Mode:** If a target is currently detected and the system is not in a resetting state, the ESP32 applies a Proportional-Derivative (PD) control algorithm to both the Pan (Stepper) and Tilt (Servo) axes. This controller minimizes the position error dynamically.
- **Idle and Homing Routine:** If no target is detected, to maintain an monitoring field of view, the system includes an timeout mechanism. If the tracking loop remains inactive for more than 10 seconds, a "Reset Mode" is activated. This routine commands both motors to return to their designated default coordinates. Once the home position is reached, the system exits the reset mode and returns to its standard monitoring loop, awaiting new serial data.

Chapter III

Results

System Integration

The physical prototype was manufactured using 3D printing with PLA filament. The printing parameters were optimized based on the structural and mechanical requirements of each individual component:

- **General Structural Components:** Printed with a 15% infill density to optimize manufacturing time and material consumption without compromising structural integrity.
- **High-Stress Mechanical Elements:** Components such as structural joints, mechanical couplings, and screws were printed with a 30% infill density to surpass operational mechanical stresses.
- **Transmission Gears:** To ensure high torsional strength and prevent tooth shearing during power transmission, the gears were sliced with 3 outer wall perimeters, providing a more resistant structure.
- **Electronics Enclosure:** The protective housing for the electronic subsystems secures the ESP32 microcontroller, stepper motor driver, and buck regulator module—was printed with a 10% infill density and 2 outer wall perimeters, as its primary function aesthetic and protecting from dust.

Following the manufacturing process, all mechanical and electronic components were assembled and secured in flat surface to ensure balance stability.



Fig. 17. Physical implementation and final assembly of the mechatronic tracking system.

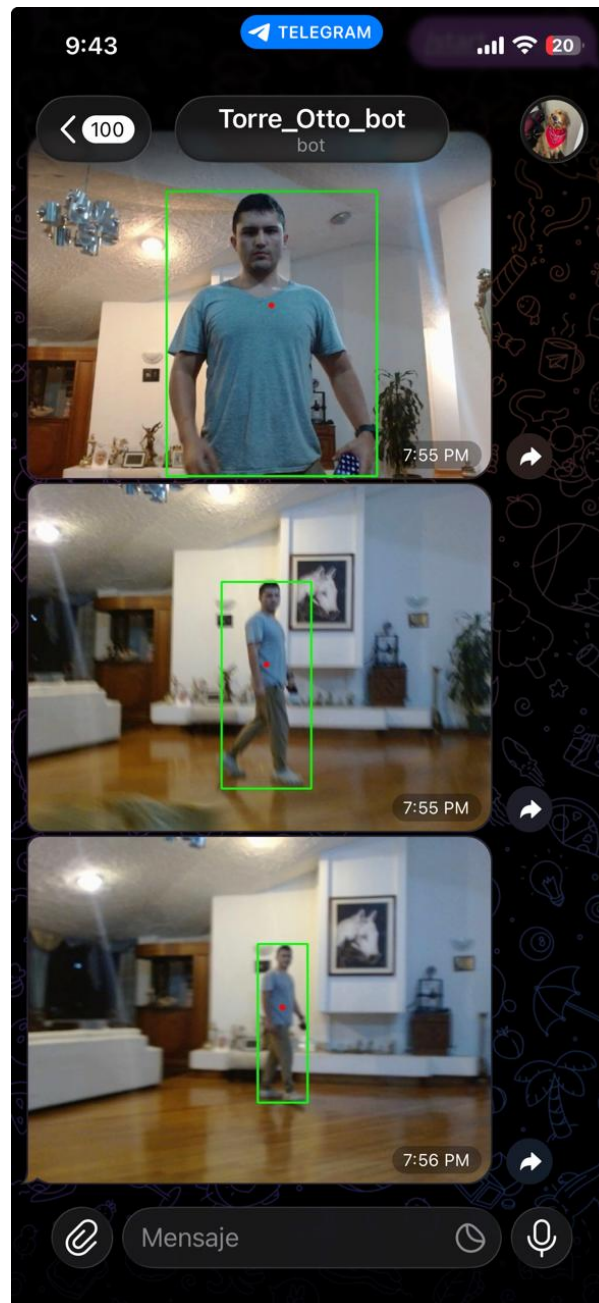


Fig. 18. Telegram bot digital notification system.

Subject Discrimination Testing

To validate the reliability of the system in residential environments and prevent false alarms, experimental tests were conducted to verify the algorithm's ability to distinguish between an actual human presence and a domestic animal.

The evaluation was performed by introducing a dog and a human subject into the camera's field of view along 3 specific distances and analyzing the algorithm's behavior.

- **Scenario A: Pet Only:** Across all tested distances (1m, 3m, and 5m), the vision algorithm successfully ignored the dog. No valid human bounding boxes were generated.

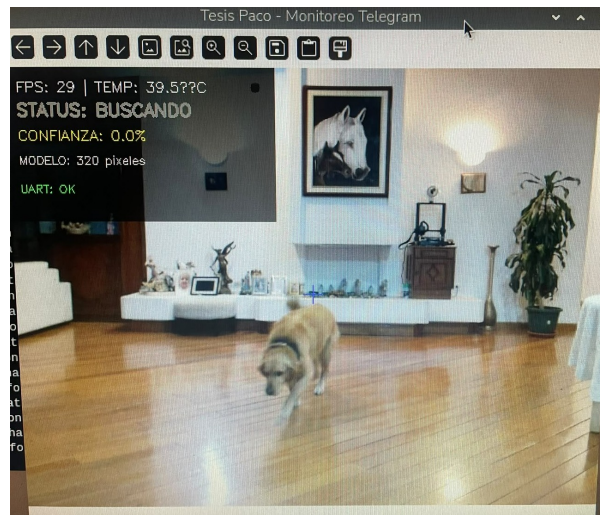


Fig. 19. Prototype test on domestic animal

- **Scenario B: Human and Pet Presence:** The algorithm maintained focus only on the human target ignoring completely the animal.

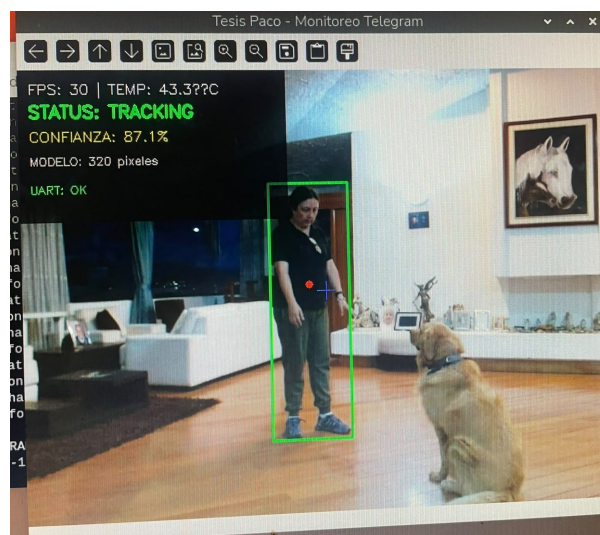


Fig. 20. Prototype test on domestic animal and human

TABLE V

Discrimination Test Results across Target Distances

Distance (m)	Subject in Frame	Detection Status	Mechanical Response
1 m	Dog Only	Ignored	Idle / Home Position
1 m	Human + Dog	Human Detected	Active Tracking
3 m	Dog Only	Ignored	Idle / Home Position
3 m	Human + Dog	Human Detected	Active Tracking
5 m	Dog Only	Ignored	Idle / Home Position
5 m	Human + Dog	Human Detected	Active Tracking

System Behavior under Multiple Human Targets

The primary scope of the mechatronic platform was strictly dimensioned for single-target residential tracking. As a consequence, the control algorithm was not optimized to handle various intruders present in the camera's field of view.

During the evaluation with two human objectives, the YOLOv8n vision model identified both individuals but inconsistently alternated its target selection between them across the frames. As a result the ESP32 received different error positions in each frame. This continuous switching caused the mechanical response to become oscillatory, as the microcontroller continuously moved the mechanism from side to side in an attempt to center two different physical positions.

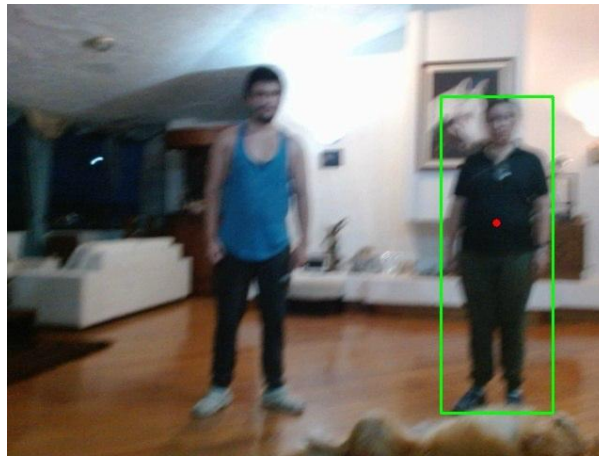


Fig. 21. Prototype test on multiple targets

Property Verification

To evaluate the performance, operational limits, and efficiency of the tracking prototype, a series of experimental tests were conducted by controlling two primary independent variables:

1. **Model Inference Resolution:** Evaluated at 640, 480, and 320 pixels to analyze the computational scaling effects of the vision framework.
2. **Target Distance:** Tested at intervals of 1 m, 3 m, and 5 m from the camera assembly to determine the effective detection range.

The experimental characterization was carried out in a controlled indoor environment under stable illumination and in a open viewing area minimizing external noise and isolating the performance of the computer vision model.

The core performance metrics measured to evaluate the system's operational efficiency include:



Fig. 22. Experimental testing environment under controlled artificial lighting conditions.

- **Effective Inference Rate (FPS):** The real-time frame processing frequency of the vision pipeline.
- **Inference Latency (ms):** The total elapsed time required for the model to execute a single forward pass.
- **Model Confidence (%):** The statistical probability accuracy rating assigned by the neural network to the detected target.
- **CPU Temperature (°C):** The thermal state of the primary processor during continuous operation.

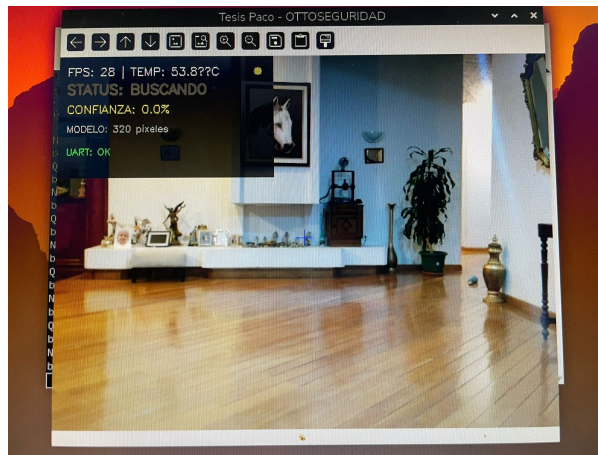


Fig. 23. Raspberry Pi real-time telemetry and system monitoring interface.

Experimental Results

To evaluate the system's performance, physical tests were conducted varying the neural network's input resolution (320x320, 480x480, and 640x640 pixels) and the target distance (1m, 3m, and 5m). The metrics obtained during these tests are summarized in Table VI.

TABLE VI

Experimental Performance Metrics of YOLOv8n across varying Resolutions and Target Distances.

Input Resolution	Target Distance (m)	Global Video Speed (FPS)	Effective Inference Rate (FPS)	Inference Latency (ms)	Model Confidence (%)	CPU Temp. (°C)
320 × 320	1	28	9.3	107.1	90.0	65.1
320 × 320	3	30	10.0	100.0	89.8	65.5
320 × 320	5	29	9.7	103.4	88.3	65.3
480 × 480	1	24	8.0	125.0	92.4	72.8
480 × 480	3	22	7.3	136.4	91.5	73.2
480 × 480	5	24	8.0	125.0	90.6	73.5
640 × 640	1	18	6.0	166.7	94.3	78.4
640 × 640	3	20	6.7	150.0	93.2	79.7
640 × 640	5	18	6.0	166.7	92.1	81.1

Discussion and Analysis

The experimental data reveals a clear relationship between optical accuracy and embedded computational efficiency. The analysis of these results justifies the architectural decisions made during the system's development.

Thermal Management and Stability: As observed in the experimental data, operating the YOLOv8n model at a 640x640 resolution causes severe thermal stress on the processing unit, with temperatures peaking at 81.1 °C. This validates the preliminary hardware observations, as continuous operation above 80 °C risks thermal throttling and hardware degradation. On the other hand, the 320x320 resolution maintains a stable thermal footprint, peaking at a safe 65.5 °C even at maximum computational load, ensuring continuous and secure long-term operation without requiring active cooling systems.

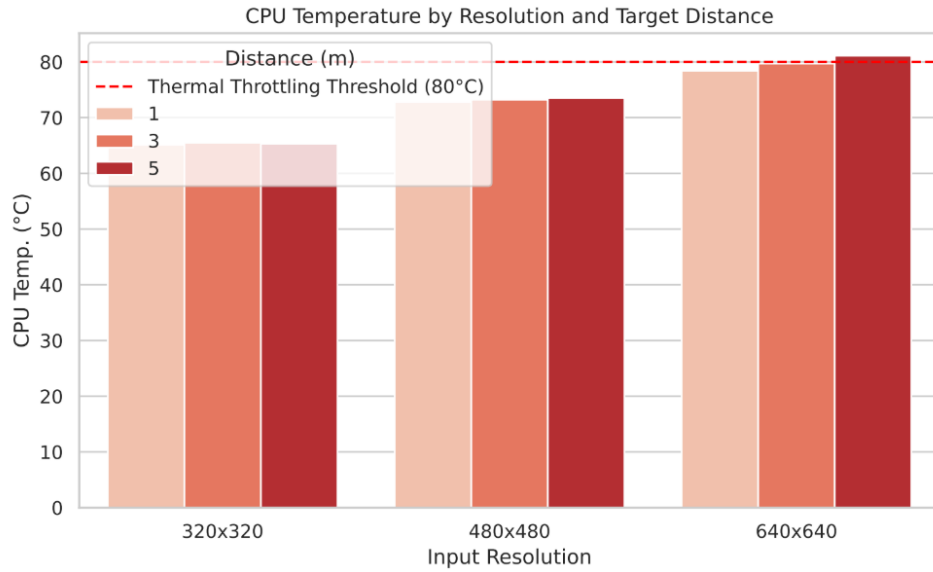


Fig. 24. CPU Temperature behavior as a function of Inference Resolution and Target Distance.

Latency Budget and Actuation Speed: The primary functional requirement requested a latency budget of 300 ms to guarantee an immediate and fluid response. At 640x640, the inference latency consumes up to 166.7 ms, leaving an low margin for image pre-processing, serial communication, and stepper motor actuation. The 320x320 configuration, however, limits the inference latency to an average of 103.5 ms. This efficiency preserves nearly two-thirds of the 300 ms budget, allowing the ESP32 and actuators to perform smooth tracking without lagging.

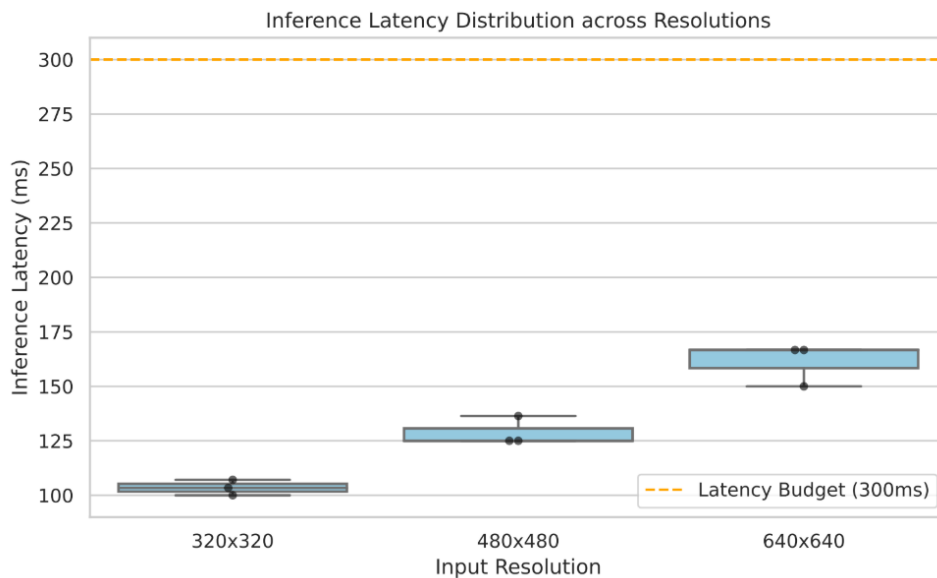


Fig. 25. Inference Latency across different optical resolutions compared to the system budget.

Accuracy vs. Distance: While the 640x640 resolution provided the highest detection

confidence (up to 94.3%), the critical requirement for the vision system was to maintain a minimum operational confidence of 85% (0.85). The experimental results demonstrated that even at the lowest evaluated resolution (320x320) and the maximum tested distance (5 meters), the system successfully registers a confidence of 88.3%. This proves that the loss in inference resolution does not act as a critical factor security environments.

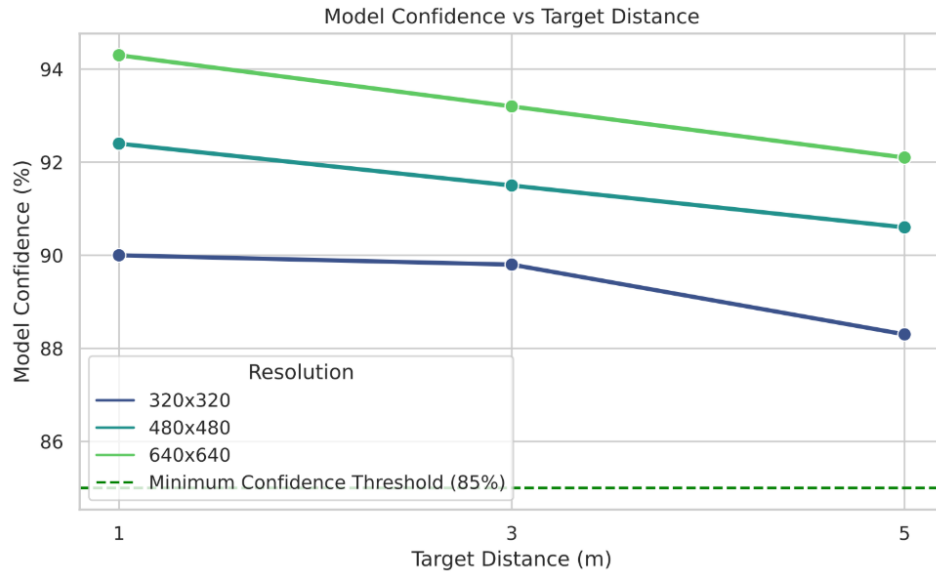


Fig. 26. Model Confidence degradation over distance by input resolution.

In conclusion, configuring the vision pipeline at 320x320 pixels is the best operational point. It fulfills the 85% accuracy while avoiding the 80 °C thermal danger zone, and satisfies the 300 ms real-time latency budget required for mechatronic actuation.

Chapter IV

Conclusions and Recommendations

Conclusions

The implementation of a distributed Master-Bridge control architecture successfully decoupled high-level neural network processing from low-level motor actuation, fulfilling the design restriction to optimize the software for embedded units with limited computational resources. By offloading the stepper and servo pulse generation to the ESP32, the system eliminated mechanical jitter and ensured the intelligent security camera operated comfortably within the non-functional requirement of a 300 ms maximum latency budget. Furthermore, experimental validation demonstrated that executing the YOLOv8n model at a 320x320 resolution via the NCNN framework represents the optimal operational point for the Raspberry Pi 5. This configuration successfully achieves the functional requirement of identifying human shapes based on geometric proportions and consistently maintains a detection confidence above the 85% minimum non-functional threshold up to 5 meters. This performance is fully maintained within the strict restriction to indoor environments, while successfully preventing the CPU from crossing the critical 80 °C thermal throttling limit. Mechanically, the system's stability was improved by moving from a direct-drive setup to a 2:1 gear-reduced Pan transmission with structural alignment guides. Complementing this hardware upgrade with a 20-pixel dead-zone filter on the X-Y-axis completely eradicated steady-state oscillations during active tracking, allowing the system to smoothly adjust its field of view to maintain the subject within the central frame as a core functional requirement. To prevent false positives, the system successfully employed a temporal filtering non-functional requirement, requiring continuous target presence before confirming a detection.

Finally, utilizing existing local network restrictions via Wi-Fi, the integration of an asynchronous Telegram bot along with physical LED and buzzer alerts generates digital and physical notifications upon final human confirmation, satisfying the system's requirements. This complete setup allows the system to function independently to avoid operator fatigue, requiring human intervention only during confirmed alerts. To complete the safety constraints, the hardware successfully incorporated a pause button to disconnect the camera's detection and movement when needed.

Recommendations

To expand the system's capabilities and robustness in future similar projects, some hardware and software upgrades are recommended.

To achieve high-resolution inference (e.g., 640x640) at elevated frame rates without encountering thermal limitations, future development should explore integrating dedicated Edge AI hardware accelerators, such as a Google Coral TPU, or moving into from the vision pipeline to a specialized embedded platform like the NVIDIA Jetson series. This hardware scaling would provide the an extra computational upgrade to run more complex vision model algorithms in a lower latency.

The optical system's operational flexibility could also be improved by replacing the fixed-focus webcam with a motorized optical zoom lens coupled with an automated PID-based autofocus control loop. This would allow the system to capture a more detailed visual data and maintain tracking accuracy at distances farther the current 5-meter tested range. Additionally, incorporating an Infrared (IR) or a thermal camera module would enable continuous 24/7 security monitoring, ensuring target detection in zero-light environments or through visual obstructions.

On the software architecture area, future work should focus on implementing secondary biometric or facial recognition models. This would allow the system to differentiate between authorized individuals and potential intruders. This can drastically reduce false-positive tracking targets. In addition, integrating a multi-object tracking algorithm (such as DeepSORT) is recommended to help the camera maintain focus on a primary target in crowded scenes, preventing the actuators to fail when multiple humans enter the frame.

Mechanically, while the current tracking platform was successfully restricted to a 180-degree range of freedom to prevent wiring stress, changing the component distribution would allow continuous 360-degree rotation eliminating most blind spots in open-area security areas. Finally, upgrading actuators with the addition of encoders on the pan is also highly recommended. This integration would provide real-time positional feedback to the ESP32 ensuring that the camera's physical position perfectly matches the coordinate system generated by the computer vision model, even during high-speed target movements.

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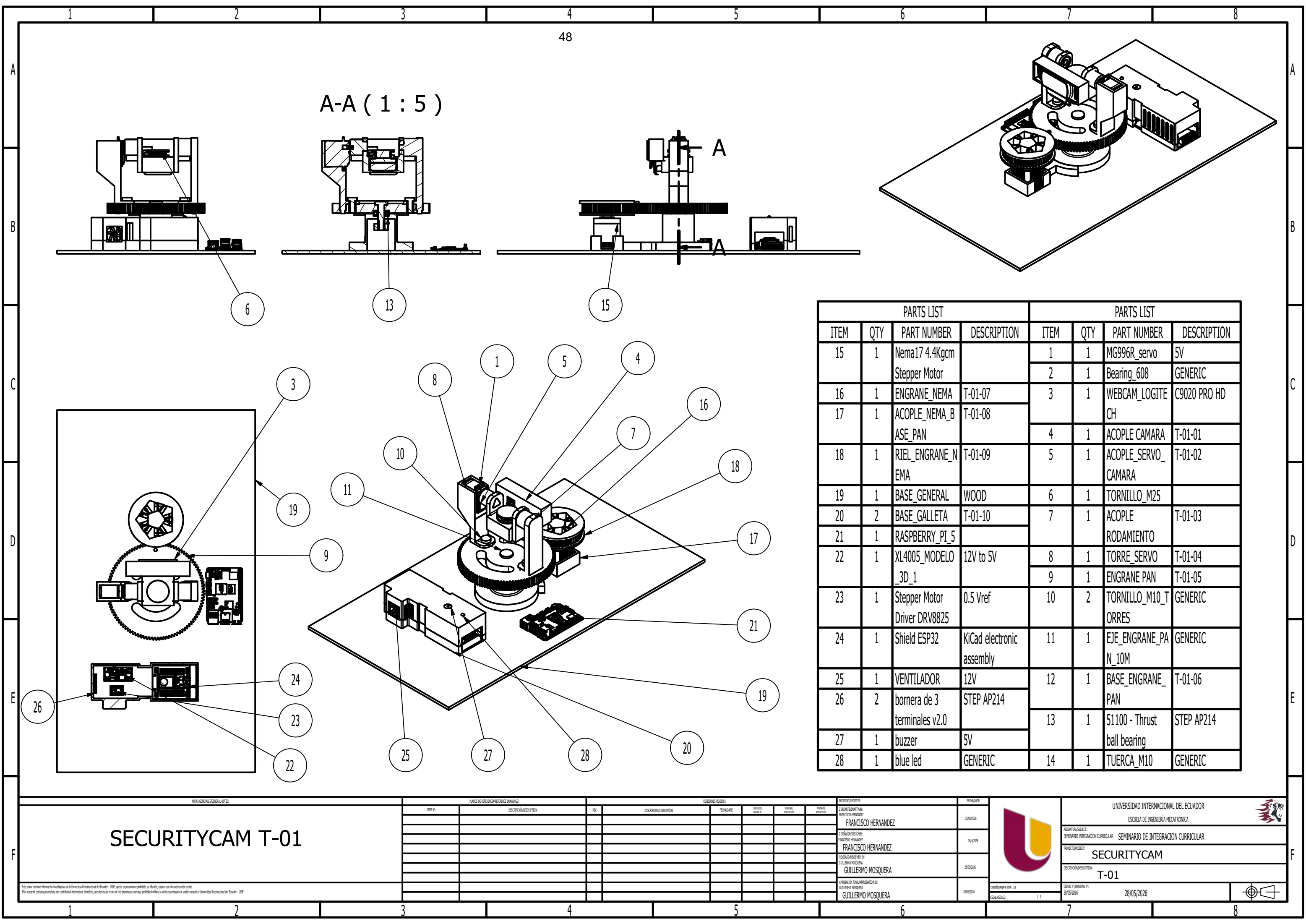
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Appendix

Plan Formats

The following technical drawings detail the mechanical dimensions, assembly instructions, and component specifications for the Pan-Tilt mechatronic tracking system.



PARTS LIST				PARTS LIST			
ITEM	QTY	PART NUMBER	DESCRIPTION	ITEM	QTY	PART NUMBER	DESCRIPTION
15	1	Nema17 4.4Kgcm Stepper Motor		1	1	MG996R_servo	5V
16	1	ENGRANE_NEMA	T-01-07	2	1	Bearing_608	GENERIC
17	1	ACOPLE_NEMA_BASE_PAN	T-01-08	3	1	WEBCAM_LOGITECH	C9020 PRO HD
18	1	RIEL_ENGRANE_NEMA	T-01-09	4	1	ACOPLE_CAMARA	T-01-01
19	1	BASE_GENERAL	WOOD	5	1	ACOPLE_SERVO_CAMARA	T-01-02
20	2	BASE_GALLETA	T-01-10	6	1	TORNILLO_M25	
21	1	RASPBERRY_PI_5		7	1	ACOPLE RODAMIENTO	T-01-03
22	1	XL4005_MODELO_3D_1	12V to 5V	8	1	TORRE_SERVO	T-01-04
23	1	Stepper Motor Driver DRV8825	0.5 Vref	9	1	ENGRANE PAN	T-01-05
24	1	Shield ESP32	KiCad electronic assembly	10	2	TORNILLO_M10_TORRES	GENERIC
25	1	VENTILADOR	12V	11	1	EJE_ENGRANE_PAN_10M	GENERIC
26	2	bornera de 3 terminales v2.0	STEP AP214	12	1	BASE_ENGRANE_PAN	T-01-06
27	1	buzzer	5V	13	1	51100 - Thrust ball bearing	STEP AP214
28	1	blue led	GENERIC	14	1	TUERCA_M10	GENERIC

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SECURITYCAM T-01

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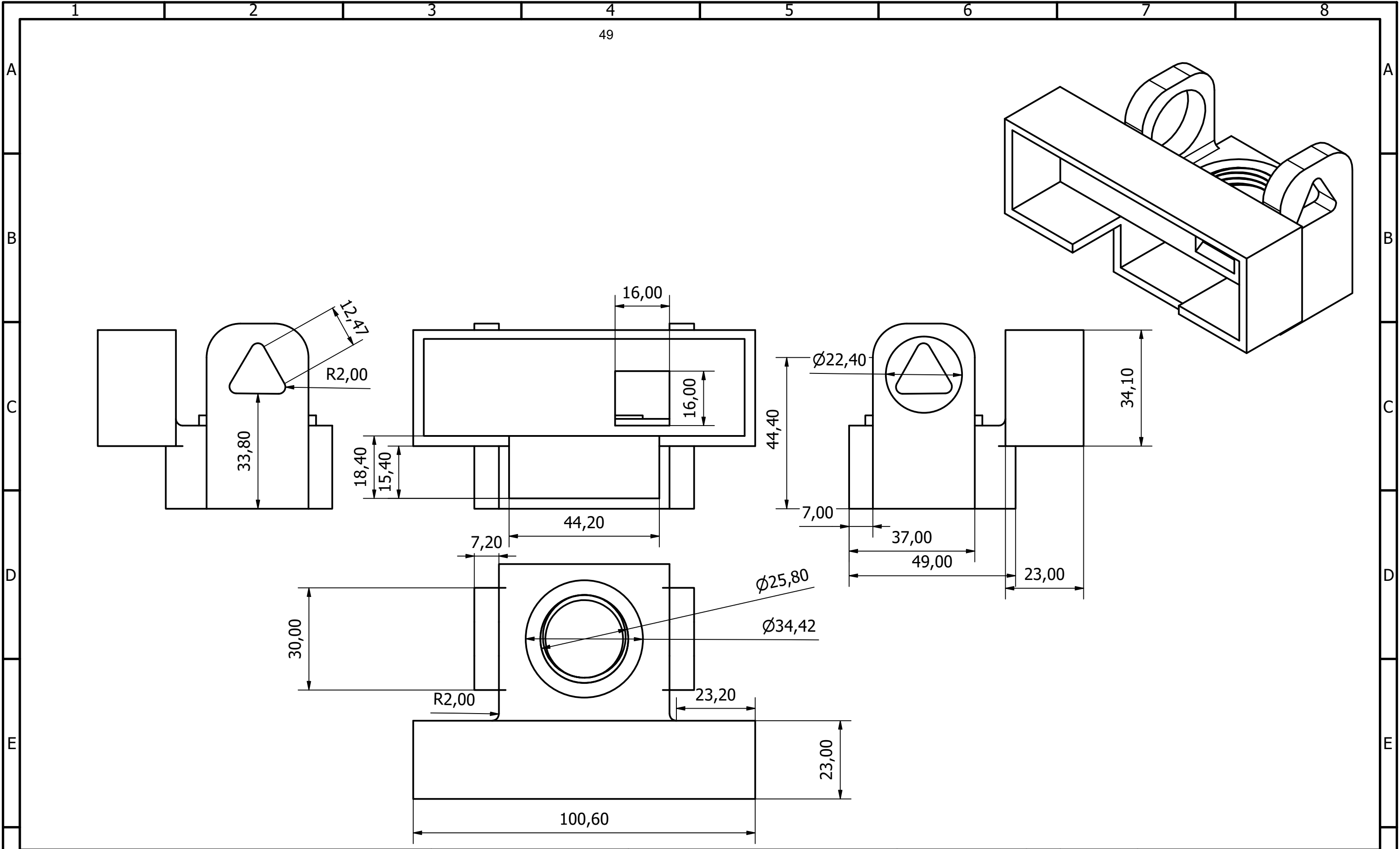
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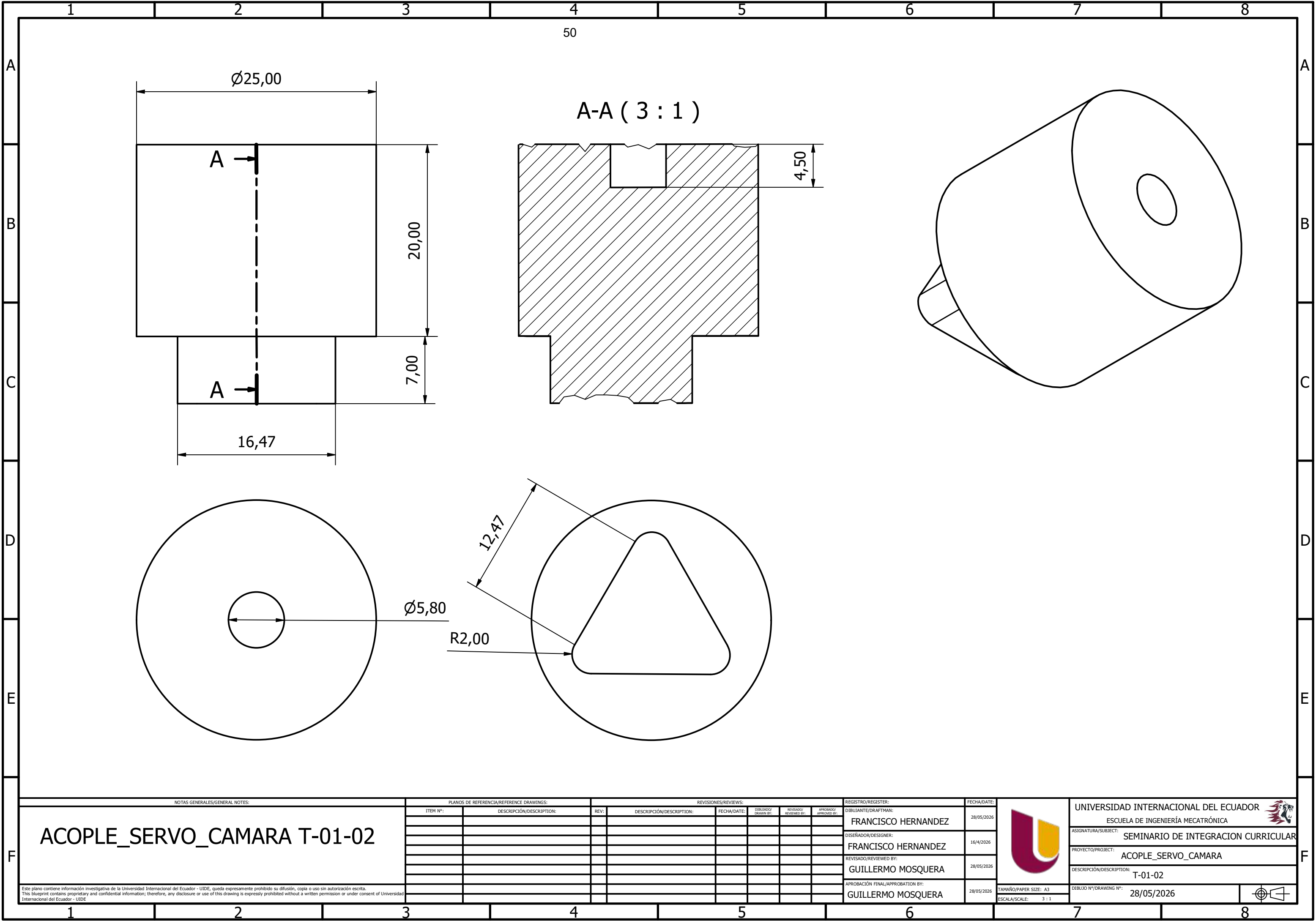
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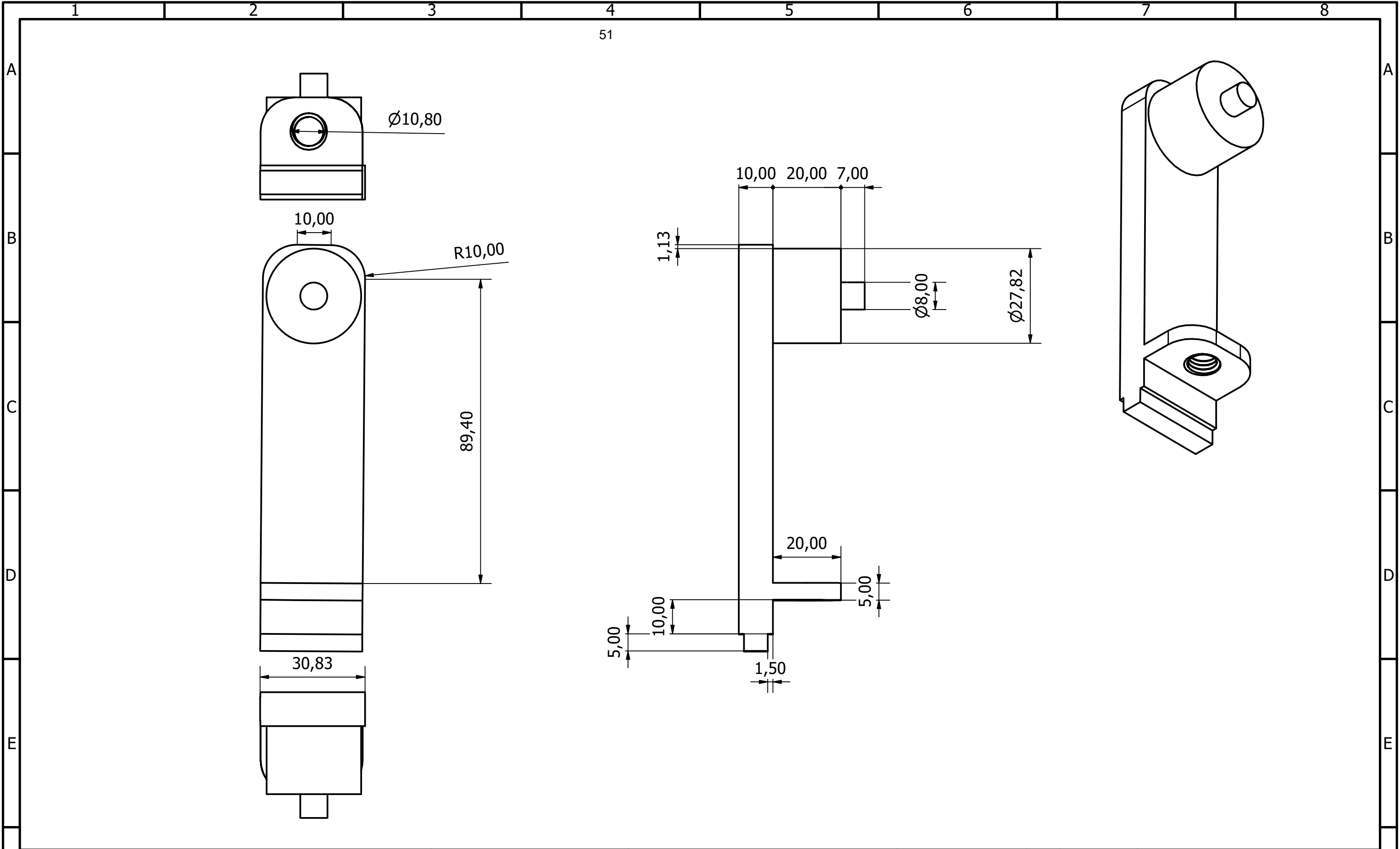
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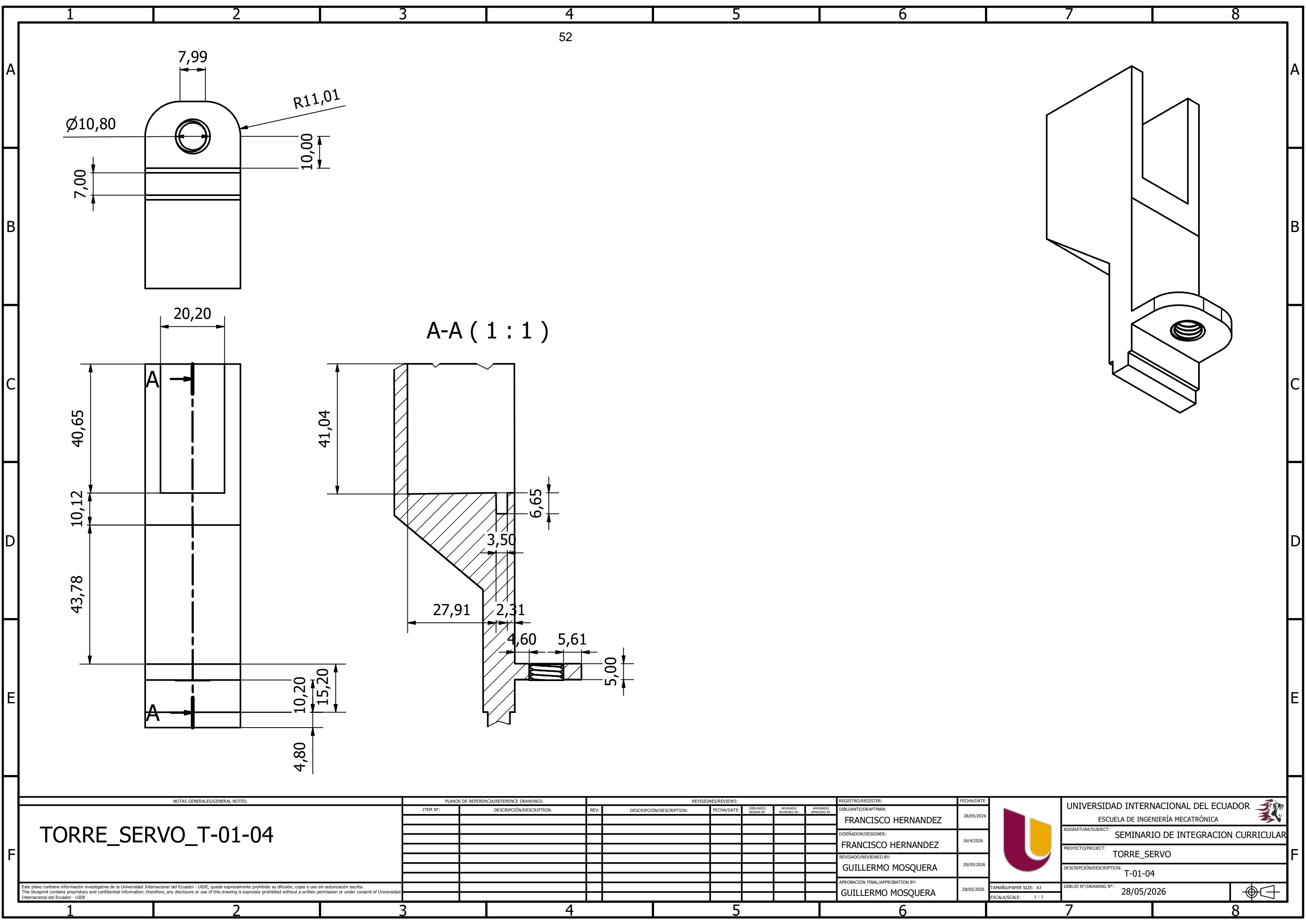
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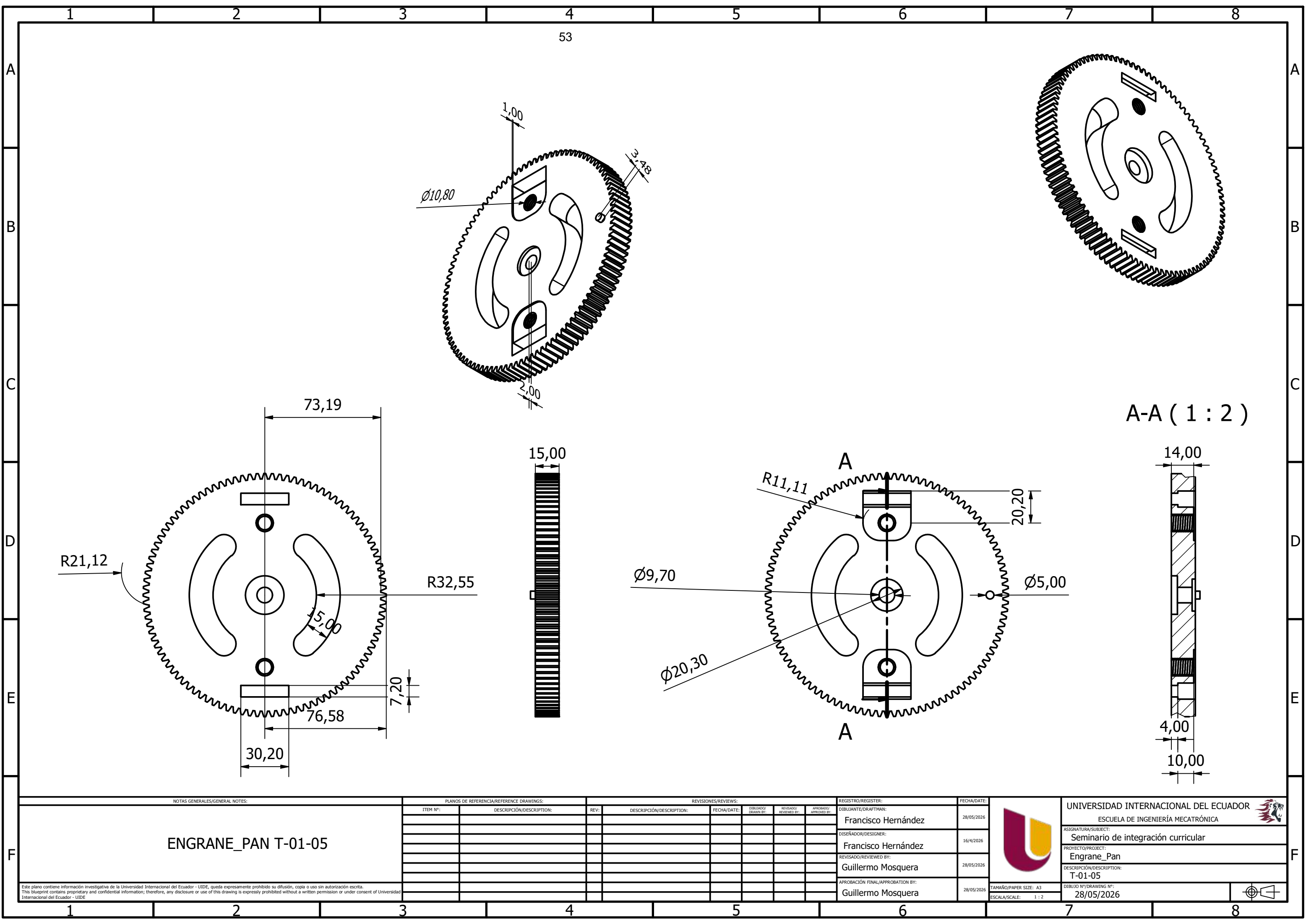
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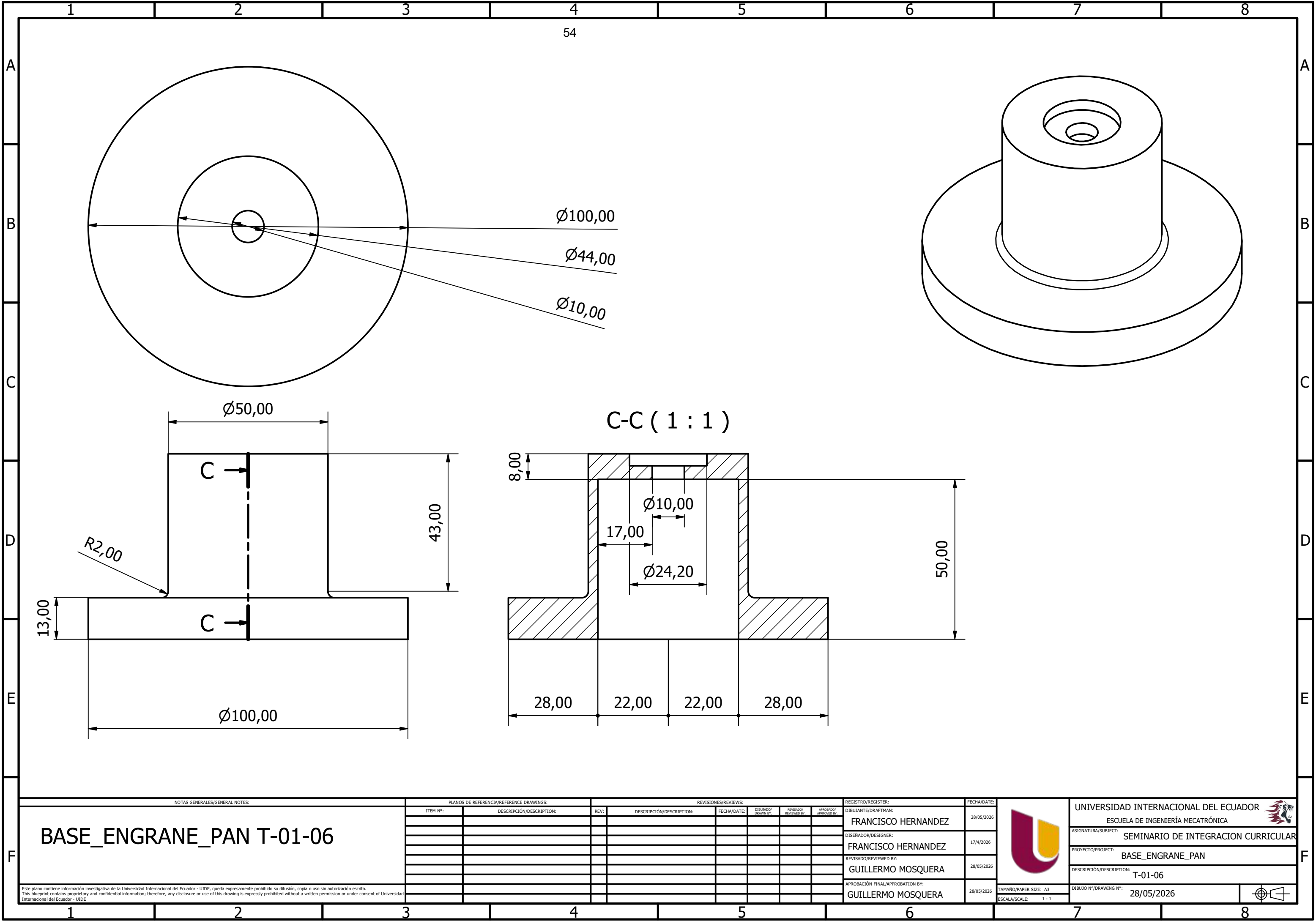
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ASIGNATURA/SUBJECT: SEMINARIO DE INTEGRACION CURRICULAR

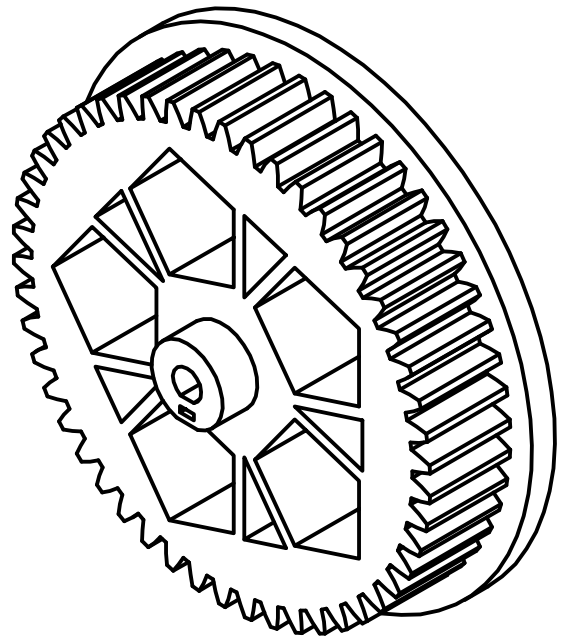
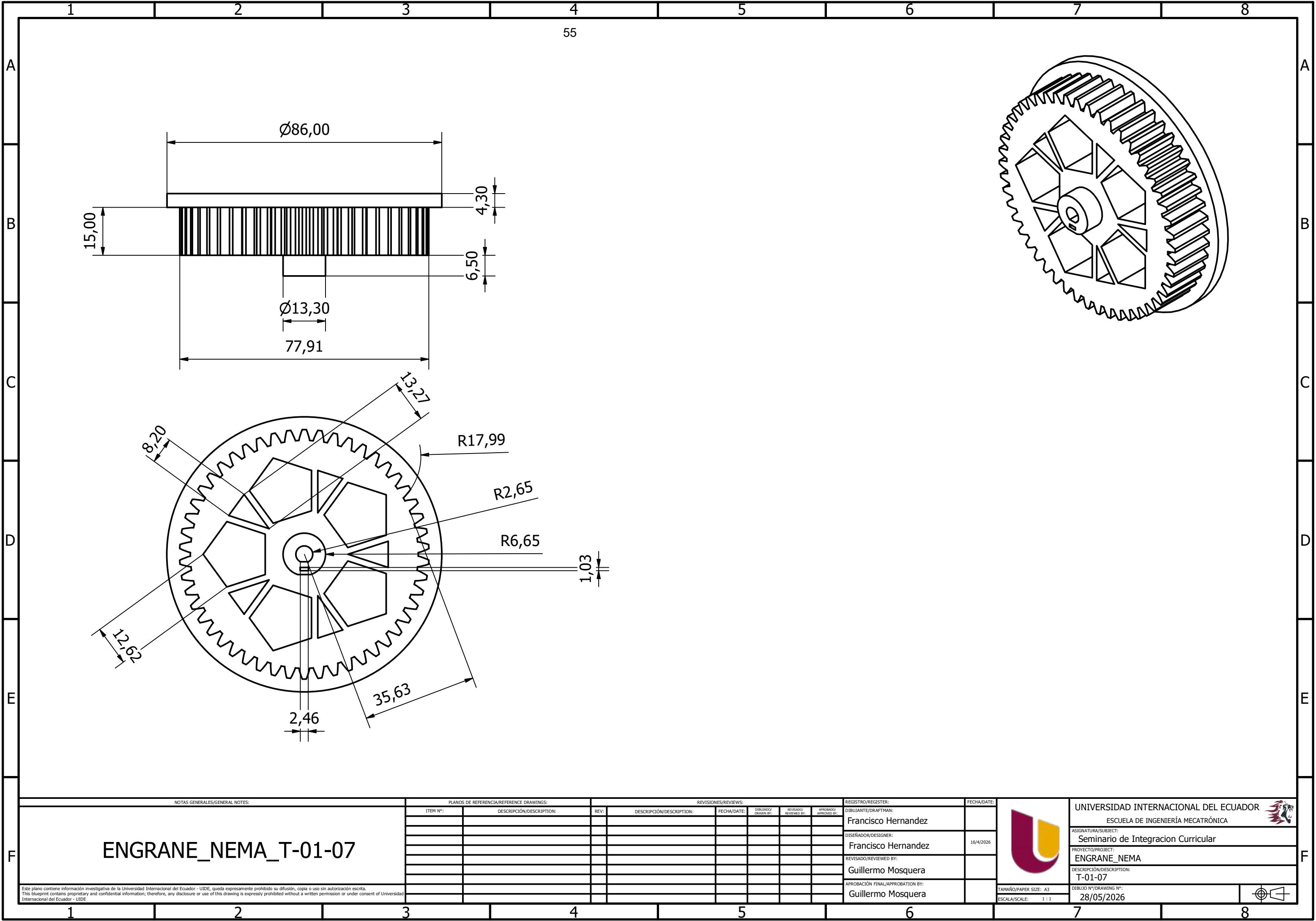
PROYECTO/PROJECT: BASE_ENGRANE_PAN

DESCRIPCIÓN/DESCRIPTION: T-01-06

DIBUJO N°/DRAWING N°: 28/05/2026

TAMAÑO/PAPER SIZE: A3
ESCALA/SCALE: 1 : 1





NOTAS GENERALES/GENERAL NOTES:

PLANOS DE REFERENCIA/REFERENCE DRAWINGS:

REVISIONES/REVIEWS:

REGISTRO/REGISTER:

FECHA/DATE:

ENGRANE_NEMA_T-01-07

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DIBUJANTE/DRAFTMAN:	Francisco Hernandez	FECHA/DATE:	
DISEÑADOR/DESIGNER:	Francisco Hernandez	FECHA/DATE:	16/4/2026
REVISADO/REVIEWED BY:	Guillermo Mosquera	FECHA/DATE:	
APROBACI3N FINAL/APPORBATION BY:	Guillermo Mosquera	FECHA/DATE:	



UNIVERSIDAD INTERNACIONAL DEL ECUADOR
ESCUELA DE INGENIERÍA MECATRÓNICA

ASIGNATURA/SUBJECT:
Seminario de Integracion Curricular

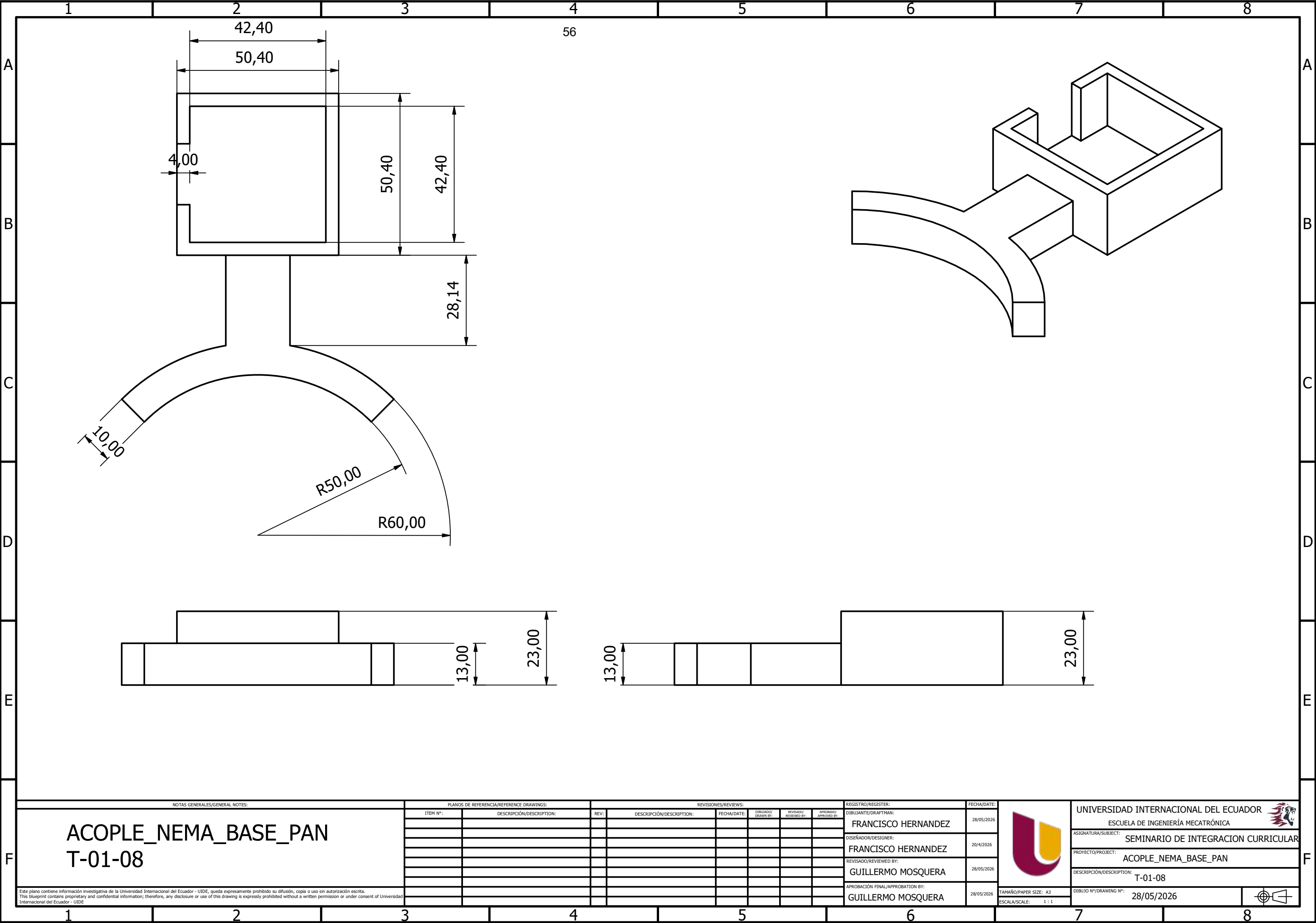
PROYECTO/PROJECT:
ENGRANE_NEMA

DESCRIPCI3N/DESCRIPTION:
T-01-07

TAMAÑO/PAPER SIZE: A3
ESCALA/SCALE: 1 : 1

DIBUJO N°/DRAWING N°:
28/05/2026





NOTAS GENERALES/GENERAL NOTES:

ACOPLE_NEMA_BASE_PAN
T-01-08

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DIBUJANTE/DRAFTMAN: FRANCISCO HERNANDEZ	28/05/2026
DISEÑADOR/DESIGNER: FRANCISCO HERNANDEZ	20/4/2026
REVISADO/REVIEWED BY: GUILLERMO MOSQUERA	28/05/2026
APROBACIÓN FINAL/APPORBATION BY: GUILLERMO MOSQUERA	28/05/2026



TAMAÑO/PAPER SIZE: A3
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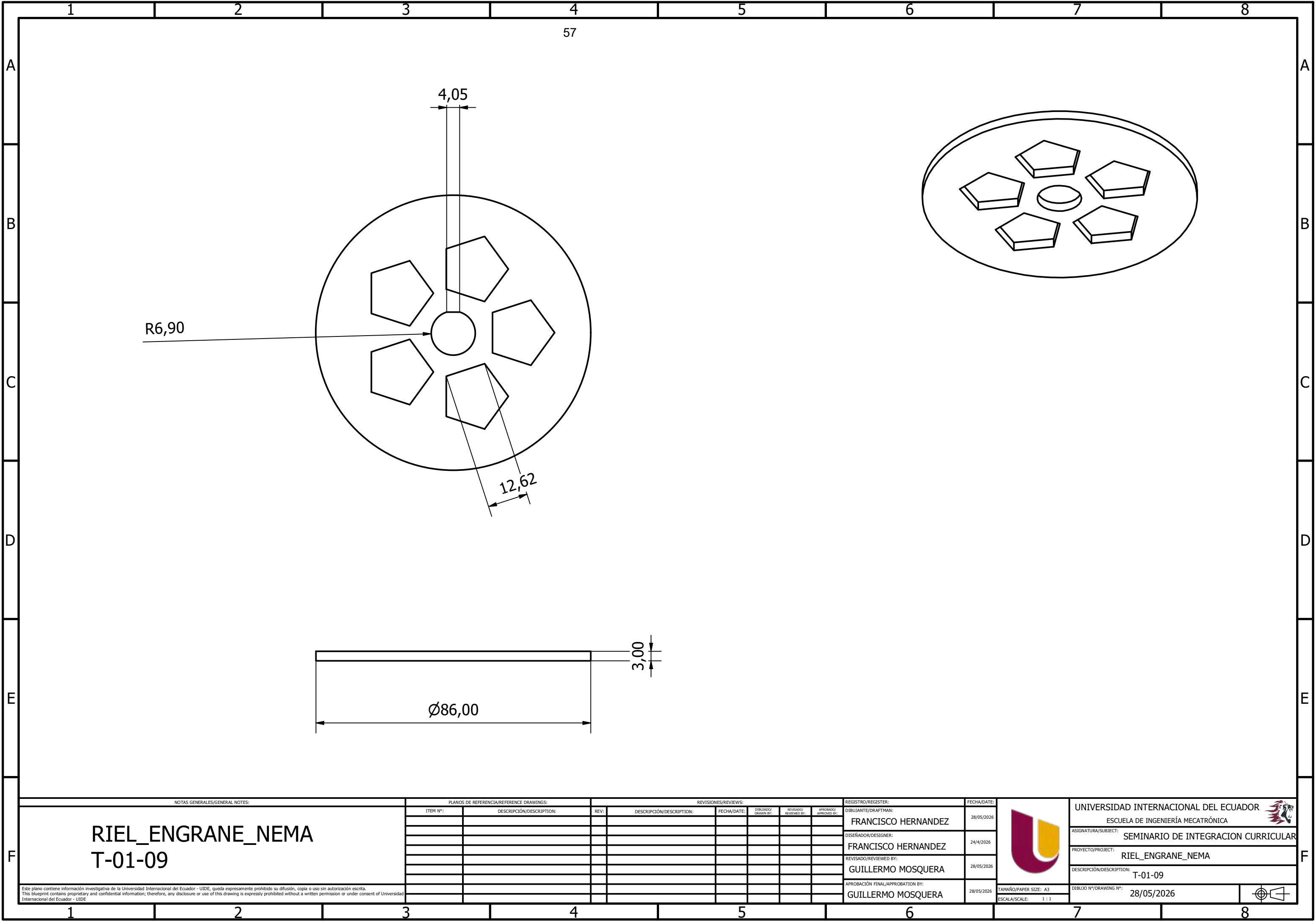
ASIGNATURA/SUBJECT: SEMINARIO DE INTEGRACION CURRICULAR

PROYECTO/PROJECT: ACOUPLE_NEMA_BASE_PAN

DESCRIPCIÓN/DESCRIPTION: T-01-08

DIBUJO N°/DRAWING N°: 28/05/2026





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	RIEL_ENGRANE_NEMA T-01-09		ITEM N°:	DESCRIPCIÓN/DESCRIPTION:	REV:	DESCRIPCIÓN/DESCRIPTION:	FECHA/DATE:	DIBUJADO/ DRAWN BY:	REVISADO/ REVIEWED BY:	APROBADO/ APPROVED BY:	DIBUJANTE/DRAFTMAN:		28/05/2026	ESCUELA DE INGENIERÍA MECATRÓNICA				
											DISEÑADOR/DESIGNER:		24/4/2026	SEMINARIO DE INTEGRACION CURRICULAR				
											REVISADO/REVIEWED BY:		28/05/2026	RIEL_ENGRANE_NEMA				
											GUILLERMO MOSQUERA			T-01-09				
											APROBACIÓN FINAL/PROBATION BY:		28/05/2026	DIBUJO N°/DRAWING N°:				
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