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SISTEMA AUTOMATIZADO DE ALMACENAMIENTO Y RECUPERACIÓN DE ESTANTES

AUTOMATED SHELF STORAGE AND RETRIEVAL SYSTEM

QUITO – ECUADOR | 2025

CERTIFICATION OF AUTHORSHIP

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TUTOR APPROVAL

I, Guillermo Alfredo Mosquera Canchingre, certify that I know the author of this project entitled "AUTOMATED SHELF STORAGE AND RETRIEVAL SYSTEM", Jordy Joel Morillo Sanchez, being the sole person responsible for both its originality and authenticity, as well as its content.

GMosquera

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GUILLERMO ALFREDO MOSQUERA CANCHINGRE

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1. INTRODUCTION

The automation of processes in the logistics and storage sectors has become a crucial area of focus in modern engineering, as organizations increasingly seek to optimize operational efficiency, reduce time and resource wastage, and improve inventory management. Automated Storage and Retrieval Systems (AS/RS) have emerged as innovative solutions that integrate mechanical, electronic, and computational technologies to manage inventory with precision and speed. This project focuses on the design and implementation of an automated system that incorporates intuitive interface. The proposed system aims to contribute to the field of industrial automation, offering a scalable and adaptable solution for warehouses and similar environments.

After an exhaustive review of the existing literature, it can be stated that the main problem addressed in this research project is the lack of optimization, organization, and control of inventory on shelves. This issue often leads to significant product losses, inefficient operations, and delays in material retrieval, especially in systems without automation.

For example, Romero's work[1] highlights a 20% reduction in operating times achieved by automating verification and dispatch processes in industrial environments, demonstrating the critical need for automation to mitigate delays and human error. Similarly, Torres Ortiz[2] identifies that inefficient warehouse layouts can result in up to 15% wasted space and prolonged operational times, further underscoring the importance of systematic storage solutions.

The absence of proper records and classifications exacerbates these inefficiencies. Toaquiza Yugcha[3] reports that up to 18% of stored spare parts in traditional systems can become misplaced or lost due to poor organization, leading to extended retrieval times and increased operational costs. Mora and Moran[4] note that the integration of IoT technologies into inventory management systems can reduce discrepancies by over 25%, enhancing real-time tracking and control while ensuring inventory reliability.

Losses in inventory also occur when items are not returned to their proper locations. FIFO systems (First-In-First-Out) have proven effective in mitigating these issues by maintaining an organized sequence of product movement. Dumani Carrillo and Rodríguez Gómez[5] demonstrate that implementing FIFO controls can reduce product expiration losses by approximately 30%. Similarly, Acevedo Ospina et al.[6] emphasize the importance of automated storage solutions, noting a 40% improvement in inventory rotation efficiency through the use of stacker cranes.

Considering that time is a critical factor for business profitability, manual inventory management increases operational times and reduces productivity. Rosales Vázquez[7] illustrates that automating internal transport systems for handling heavy products can decrease manual efforts by up to 35%, significantly reducing operational delays. Moreover, Mora Roca[8] applies ABC classification to prioritize frequently accessed items, which improves inventory access efficiency and reduces unnecessary movements, achieving a 25% reduction in retrieval times.

In summary, the lack of automation in inventory systems results in substantial losses, inefficient product handling, increased operating times, and unnecessary resource expenditure. By adopting strategies such as IoT-based inventory management, optimized layout designs, automated handling systems, and control algorithms, it is possible to improve the accuracy, organization, and reliability of inventory systems while addressing the root causes of inefficiencies and losses[9][10].

The development of automated systems for inventory and storage optimization has been extensively explored in various research studies. These works provide valuable insights into methodologies and technologies for enhancing operational efficiency, particularly in storage and retrieval systems.

A major challenge in industrial automation is the verification and dispatch processes in production environments. Romero's work focuses on automating these tasks in a bakery, reducing operating times and minimizing human error, which aligns with the need for repetitive process optimization in automated systems like AS/RS [1]. Similarly, Torres Ortiz highlights the importance of efficient warehouse layouts, which improve robot navigation and minimize operation times[2]. These contributions underscore the foundational role of layout optimization in automated inventory systems.

In the context of spare part storage, Toaquiza Yugcha analyzes the optimization of warehouse space to improve item retrieval and minimize losses. This study is relevant for automated systems that require efficient organization to avoid unnecessary delays[3]. On the other hand, Mora and Moran explore the implementation of IoT in warehouses, introducing inventory tracking and biometric validation, which enhances real-time control and monitoring of inventory processes[4].

Research on handling heavy industrial products introduces automation strategies that can inspire mobile robots. Rosales Vázquez proposes an automated clamping mechanism for moving heavy items, which could be adapted to optimize the handling of large loads in storage systems[7]. Likewise, Mora Roca applies the ABC classification to redesign storage systems, emphasizing the prioritization of frequently used items, which improves retrieval efficiency[8]. Idrovo Toala complements these findings by emphasizing systematic organization in raw material warehouses to enhance inventory control[9].

For systems that prioritize product turnover, FIFO (First-In-First-Out) principles are key. Dumani Carrillo and Rodríguez Gomez demonstrate the importance of implementing FIFO systems to maintain an organized sequence of storage and retrieval, which directly benefits automated solutions[5]. Furthermore, Acevedo Ospina et al. introduce stacker crane algorithms for energy-efficient mass storage automation, a relevant approach for optimizing the movement and storage of large quantities of items[6]. Similarly, Bahos León and Blanco Caballero focus on AS/RS systems for storing electronic components, leveraging vertical movement mechanisms to maximize space usage[10].

Mehta and Sahu [11] present an autonomous robot for inventory management using RFID tags and Dijkstra's algorithm for navigation. This approach ensures precise inventory control and navigation, which directly aligns with the need for efficient item retrieval and organization in automated systems. Similarly, Somai et al. [12] propose IoT-based smart shelves equipped with load sensors, enabling real-time tracking of stored products through data analytics. These two studies emphasize the integration of advanced identification and monitoring technologies to optimize inventory management.

Fausto et al. [13] and Almeida et al. [14] explore the design and implementation of Automated Storage and Retrieval Systems (AS/RS) with innovative features. Fausto et al. focus on integrating digital image processing to identify and manage stored items, while Almeida et al. implement a pneumatic AS/RS using QR code recognition. Both works demonstrate how automation and advanced identification technologies can significantly improve accuracy and efficiency in storage systems, providing inspiration for the automated box retrieval mechanism in this project.

Lewczuk [15] analyzes the dependability of AS/RS systems using simulation tools to evaluate reliability under varying conditions, highlighting factors such as material flow and system maintenance. On the other hand, Al-Mahjari et al. [16] introduce a low-cost AS/RS based on Arduino and RFID technologies for chemical warehouses, showcasing the feasibility of economical yet efficient automation solutions. Both studies contribute to understanding the importance of system reliability and cost optimization in the development of automated inventory systems.

Xia et al. [17] and Bargiotas et al. [18] emphasize the operational efficiency and scalability of storage systems. Xia et al. compare traditional AS/RS with Automated Vehicle Storage and Retrieval Systems (AVS/RS), demonstrating the latter's superiority in high-density storage environments. Similarly, Bargiotas et al. propose a scalable AS/RS design suitable for small and medium enterprises (SMEs), offering a modular and cost-effective solution that optimizes resource usage and operational efficiency.

Finally, Fikri and Nawawi [19] present an AS/RS integrated with SCADA systems and infrared sensors, enabling real-time remote monitoring and control. Chow [20] further evaluates the efficiency of AS/RS systems using queuing models to optimize response times and material flow in manufacturing environments. These works underline the importance of incorporating real-time monitoring, control, and simulation-based optimizations to ensure robust performance and reliability in automated systems.

Together, these studies provide a comprehensive foundation for designing and implementing an efficient automated storage and retrieval system. By integrating technologies such as RFID, IoT, image processing, and simulation-based optimization, this work aims to enhance inventory control, reduce retrieval times, and ensure reliable operation in dynamic storage environments.

The implementation of an automated system for inventory management and retrieval is essential to addressing the inefficiencies observed in traditional storage systems, such as product losses, increased operational times, and resource wastage. Studies like Romero[1] and Toaquiza Yugcha[3] highlight reductions of 20% in operating times and losses of up to 18% in inventory due to disorganization, respectively, underscoring the need for automation. This project proposes a system that integrates advanced features, including IoT and automation technologies, to enhance inventory organization, reduce delays, and minimize human error. Additionally, the implementation of an automated system that can be intuitively controlled by the user expands interaction capabilities with the work environment and provides a valuable tool for optimizing time and resources. By addressing these critical challenges, the proposed solution not only aligns with contemporary research but also delivers tangible benefits for improving operational efficiency, reliability, and adaptability in dynamic storage environments.

To develop the following degree work, the following general objective was proposed:

- Design and implement an automated storage and retrieval system.

To meet the general objective, the following specific objectives were established:

- Design the storage and retrieval mechanism applied to shelves.
- Develop a storage space allocation algorithm that optimizes shelf use, considering factors such as the frequency of access to products and their physical characteristics.
- Conduct performance tests in controlled environments.

2. METHODOLOGY AND DESIGN

This section outlines the methodology and design process for the development of the Automated Shelf Storage and Retrieval System. The design includes the selection and analysis of key components where torque calculations and force estimations were performed to ensure reliable operation. The shelf structure dimensions were determined based on space requirements and safety considerations, adhering to relevant standards. The subsequent subsections present detailed calculations, motor specifications, and system requirements necessary for the optimal design and implementation of the project.

2.1. REQUIREMENTS

This research project seeks to automate a process of extracting and recovering boxes on a shelf to maintain order and correct inventory by using the products available in a work organization. To do this, certain requirements were met to achieve a satisfactory result in the operation of the robot, which are detailed below:

Functional requirements

- Ability to store boxes of different products on a shelf.
- Ability to recover requested products.

Non-Functional requirements

- Maximum capacity of 6 product storage boxes.
- Maximum time of 5 minutes for processing recovery or storage orders.
- Intuitive interface for workers in charge of interacting with the system.
- Store 80 x 25 x 50 mm boxes on a 500 x 320 x 160 mm shelving unit.
- Maximum weight of 100 grams for each box to pick it up or return it to its respective storage location.

2.2. CONCEPT DESIGN

For the conceptual design of the robot, the functionality of the robot and the essential elements and tools used to achieve its objective were taken into account. Therefore, its concept is divided into the following distinct parts:

Mechatronics structure

The basic system is composed of 3 mechanisms corresponding to the robot carriage, lifting structure and double-axis load that form the 3-degree-of-freedom system. The limit switch sensors identify the closing of the same to carry out the operations ordered by the user with the interaction of the processing unit through an interface. The NEMA 17 and 28BYJ-48 motors use their own drivers to regulate the current supplied and guarantee their operation. The mechatronics structure of the system is detailed in Fig.1.

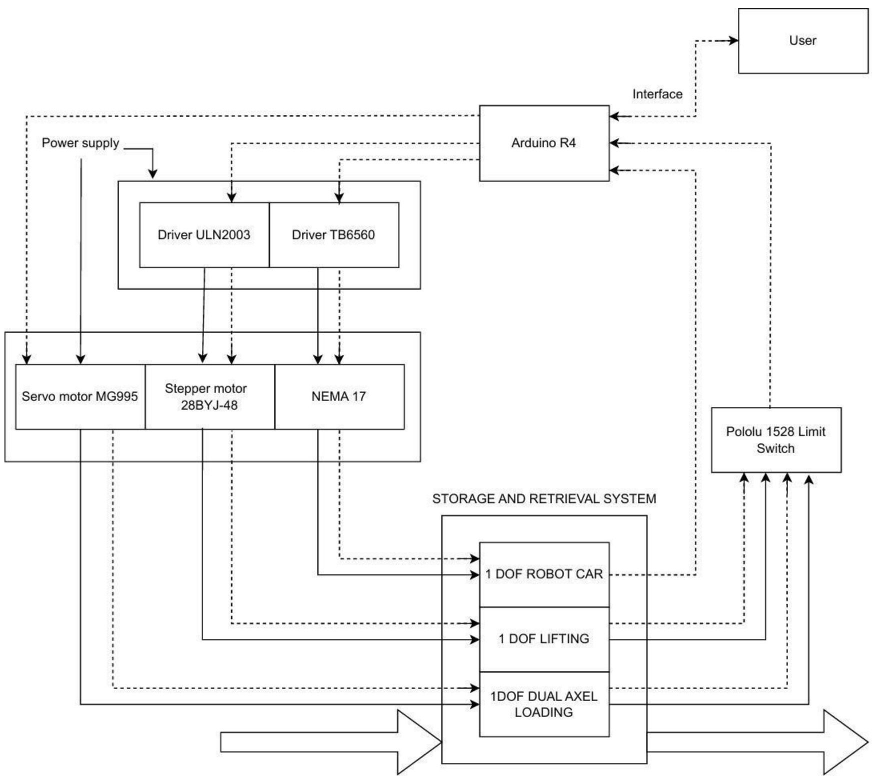

Figure 1. Diagram of the mechatronics structure

System behavior

The behavior of the system helps the user to understand the functioning of the robot, that is, the operating modes it has when performing a specific task and its respective steps to follow during the work processes. First, if the system is not in the home position, it begins to return to its initial position so that the user can decide whether to pick up or return a box. If picking is chosen, the user selects the respective box and clicks on Pick Up so that the system is located where the product is, then picks it up and returns to its initial position to be removed. If returning is chosen, the user must place the box to be returned in the system, select it and click on Drop Off so that the robot is positioned in the place of the box, returns it to its space and returns to its waxed position.

It should be noted that the system, when sending the order to bring or return a box, has a series of steps that only complete one cycle and then gives a new order. The diagram of the same is shown in Fig.2.

2.3. SPECIFIC DESIGN

In the specific design of the system, it was considered that it is desired to extract and recover 80 x 25 x 50 mm boxes on a shelf. To do this, certain considerations were taken into account, which are detailed below:

Dual axel loading mechanism

The Fig.3 shows the CAD design made of this mechanism that fulfills the function of moving forward or backward when performing an operation, composed of a rack and pinion mechanism that, through a servo motor, helps it move in the Z axis of the system.

For the respective calculations of its actuator and considerations of the mechanism relationship, the following was taken into account:

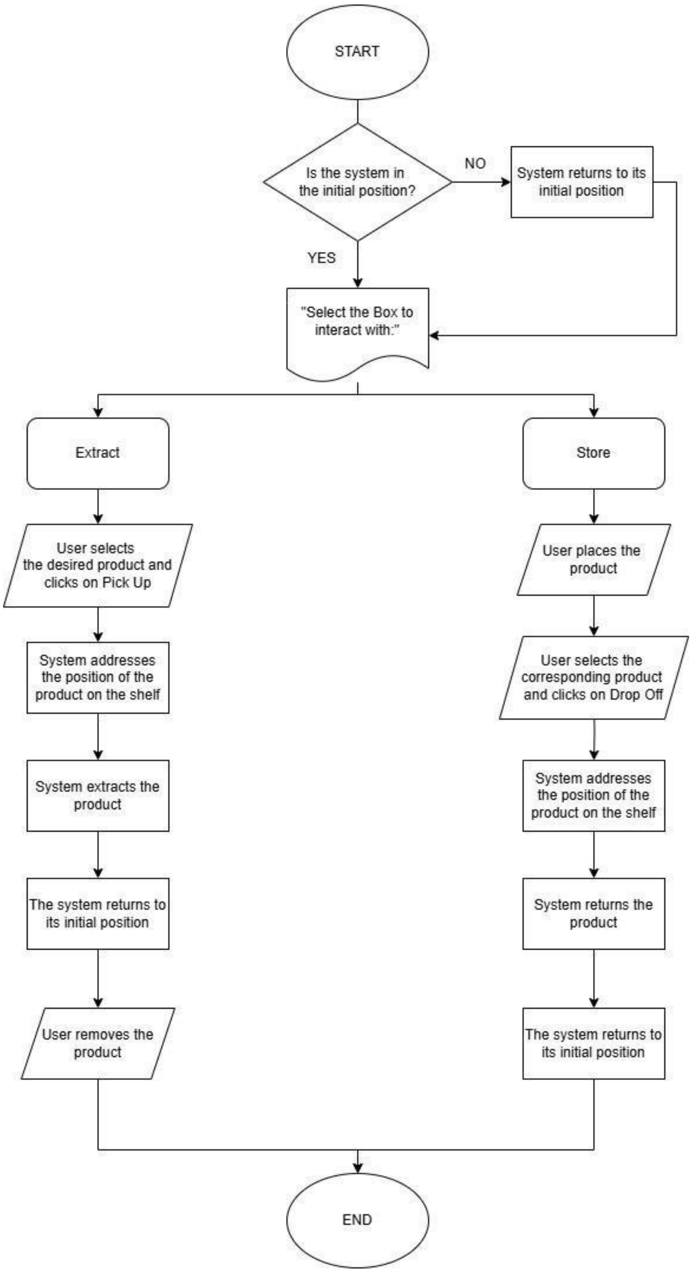

Figure 2. Diagram of the system's behavior

Servo Motor Selection for the Dual Axle Loading Structure The selection of the servo motor for the dual axle loading structure is based on geometric and mechanical calculations. The video guide by *[CA.Learning]*, which explains rack and pinion sys- tems[21], has been referenced to develop the following calculations. The focus was on determining key parameters such as linear displacement, pitch diameter, the number of teeth, and rack dimensions.

Rack and Pinion Calculations Linear Displacement:

The linear displacement was defined based on a full rotation of 360°, which corre-

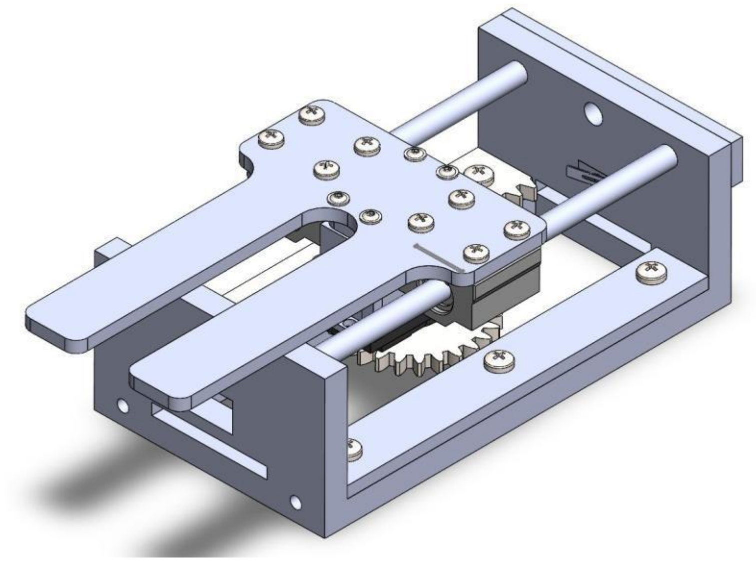

Figure 3. CAD of the dual axel loading mechanism

sponds to 160 mm of movement. By proportioning this movement to additional rotations:

$$360^\circ \to 160\,\text{mm}$$
$$360^\circ \to \frac{(160)\,(360)}{360} = 160\,\text{mm}.$$

Pitch Diameter:

The pitch diameter was calculated using the relationship with the linear displacement divided by π:

$$\text{Pitch Diameter} = \frac{\text{Linear Displacement}}{\pi}$$
$$= \frac{160}{\pi} \approx 50.93\,\text{mm}.$$

Number of Teeth:

The number of teeth z was determined using the pitch diameter and the gear module. Here, the gear module was assumed to be 2:

$$z = \frac{\text{Pitch Diameter}}{\text{Gear Module}}$$
$$= \frac{50.93}{2} \approx 25.$$

Rack Parameters:

Using the relationship for rack parameters, the pitch diameter d was revalidated:

$$\text{Pitch Diameter } (d) = z \cdot \text{Gear Module}$$
$$= 25 \cdot 2 = 50\,\text{mm}.$$

Other Dimensions:

Additional parameters included:

- Mounting Distance $a = 50$ mm,
- Pitch Diameter $d = 50$ mm.

Relation Between Height and Diameter:

The relationship between height H and diameter d was derived as follows:

$$a = H + \frac{d}{2},$$
$$H = a - \frac{d}{2},$$
$$H = 50 - \frac{50}{2} = 25\,\text{mm}.$$

Torque Estimation for the MG955 Servo Motor To determine the torque of the MG955 360-degree servo motor at a specific voltage, the following known torque values were provided in it's datasheet[22]:

- At $6V$, the torque $T(6)$ is **0.9807 N·m.**
- At $4.8V$, the torque $T(4.8)$ is **0.8336 N·m.**

Using linear interpolation, the torque at **5V** was calculated with the formula:

$$T(V) = T_1 + \frac{(T_2 - T_1)(V - V_1)}{(V_2 - V_1)}$$

Substituting the known values $V_1 = 4.8V$, $V_2 = 6V$, $T_1 = 0.8336$ N·m, and $T_2 = 0.9807$ N·m:

$$T(5) = 0.8336 + \frac{(0.9807 - 0.8336)(5 - 4.8)}{6 - 4.8}$$

Simplifying the terms:

$$T(5) = 0.8336 + \frac{(0.1471)(0.2)}{1.2} = 0.8336 + 0.0245 = 0.8581 \text{ N·m}.$$

Thus, the torque at **5V** is approximately **0.8581 N·m**.

Proportional Relationship for Torque:

To analyze the torque force at different lever arm lengths, the torque at 10 mm was given as:

$$T(10 \text{ mm}) = 8.75 \text{ kg}.$$

Using a linear proportional relationship, the equivalent torque force at 160 mm was calculated:

$$T(160 \text{ mm}) = \frac{T(10 \text{ mm})}{160}.$$

Substituting the known value:

$$T(160 \text{ mm}) = \frac{8.75}{160} = 0.547 \text{ kg}.$$

Thus, the force at **160 mm** is approximately **0.547 kg**.

Lifting mechanism

The Fig.4 shows the CAD design made of the mechanism that fulfills the function of raising or lowering when carrying out a task, composed of two stepper motors, with drivers, that help stabilize the structure and move in the Y axis of the system.

For the respective calculations of its actuators, the following was taken into account:

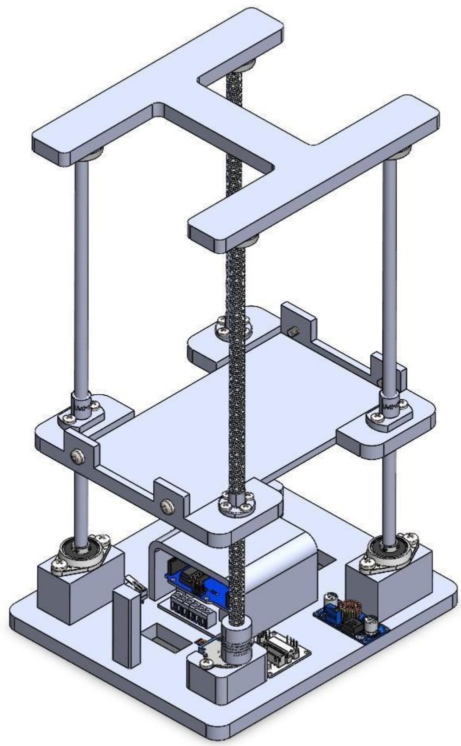

Figure 4. CAD of the lifting mechanism

Motors selection for the lifting structure To ensure optimal performance of the lifting structure, it was essential to calculate the forces acting on the system and determine the torque requirements for selecting appropriate stepper motors. The following calculations were based on standard mechanical engineering principles and equations obtained from Shigley's [23],Norton's and [24]Hugle's book[25].

Mass and Force Calculations:

The mass of the load M_z, the vertical force F_z, and the effective pitch displacement D_{mp} were calculated as follows:

$$M_z = 1.5 \times 0.6116 = 0.9174 \text{ kg},$$

$$F_z = M_z \times g = 0.9174 \times 9.81 = 9 \text{ N},$$

$$D_{mp} = \frac{300 \text{ mm}}{360} = 0.83 \text{ mm}.$$

These values are fundamental for understanding the static forces acting on the lifting system and will aid in the subsequent torque calculations.

Force Decomposition:

The forces acting on the system were decomposed into horizontal (W_x) and vertical (W_y) components. This decomposition allows to evaluate the distribution of forces during operation:

$$W_x = M_z \times \sin(90^\circ) + 0.3 = 0.949 \, \mathbf{N},$$

$$W_y = M_z \times \cos(90^\circ) = 0.649 \, \mathbf{N}.$$

The calculated forces are critical to determine how the load behaves in different directions, which directly influences the motor torque requirements.

Thread Step Torque:

The torque required for the threaded screw step, T_{pm}, was computed as follows:

$$T_{pm} = 0.004 \times 9.06 = 0.03624 \, \mathbf{Nm}.$$

This torque represents the effort required to overcome the resistance in the threaded system due to the load and friction.

Force and Total Torque:

The total force F and torque T needed to drive the system were determined using the following relationships:

$$F = m \cdot g = 0.6116 \times 9.81 = 6 \, \mathrm{N},$$

$$T = \frac{F \cdot p}{2\pi \cdot n} = \frac{6 \, \mathrm{N} \cdot 0.002 \, \mathrm{m/rev}}{2\pi \cdot 0.8} \approx 0.00239 \, \mathbf{Nm}.$$

The torque required for the motors to drive the lifting structure was determined. The calculations consider the dimensions and forces acting on the system components, which are derived based on mechanical design principles.

Dimensions of Components:

The following parameters were defined:

$$P = 2\ \text{mm} \quad \text{(Thread Pitch)}$$

$$F = 0.5716\ \text{Kg} \times 9.81\ \text{m/s}^2 = 5.61\ \text{N (Load Force)}$$

$$f_c = 0.1 \quad \text{(Coefficient of Friction for Thread Contact)}$$

$$f = 0.1 \quad \text{(Friction Coefficient for Components)}$$

$$d_m = 7\ \text{mm} \quad \text{(Mean Diameter of Thread)}$$

$$d = d_m + \frac{P}{2} = 7\ \text{mm} + \frac{2\ \text{mm}}{2} = 8\ \text{mm} \quad \text{(Outer Diameter)}$$

$$d_r = d - P = 8\ \text{mm} - 2\ \text{mm} = 6\ \text{mm} \quad \text{(Root Diameter)}$$

$$d_c = 10\ \text{mm} \quad \text{(Contact Diameter)}$$

$$l = np = 1(2)\ \text{mm} = 2\ \text{mm} \quad \text{(Lead Distance)}.$$

Load Torque Calculation:

The load torque T_R required to lift the load was calculated using the equation:

$$T_R = \frac{F \cdot d_m}{2} \frac{l + \pi f d_m}{\pi d_m - fl} + \frac{F \cdot f_c d_c}{2}.$$

Substituting the values:

$$T_R = \frac{0.00561 \cdot 7}{2} \frac{2 + \pi(0.1)(7)}{\pi(7) - (0.1)(2)} + \frac{0.00561(0.1)(10)}{2},$$

$$\approx 0.00564 + 0.00281 = 0.00659\ \text{Nm}.$$

Required Total Torque:

The total torque T_{total} was determined by considering the efficiency of the system and a safety factor (SF):

$$T_{\text{total}} = \frac{(T_R + T)}{\text{Efficiency}} \cdot \text{SF}.$$

Substituting the known values:

$$T_{\text{total}} = \frac{0.00659 + 0.00239}{0.7} \cdot 2,$$
$$\approx 0.02556 \text{ Nm}.$$

The total torque required for the motor to operate the lifting structure is approximately 0.02556 Nm. This torque value guided the selection of a stepper motor for the lifting mechanism.In this case, the 28BYJ-48 stepper motor was chosen, which according to its datasheet[26] indicates that it reaches a torque of 0.02942 Nm, which helped to give it thrust and raise the structure. In addition, two of them were used to give balance to the structure, which divides the calculated torque in two and would require much less than necessary, specifically 0.01471 Nm, being effective when using them.

Robot car mechanism

The Fig.5 shows the CAD design made of the structure that performs the function of moving forward and backward when performing an operation, composed of a motor with its driver that helps it move along the X axis of the system.

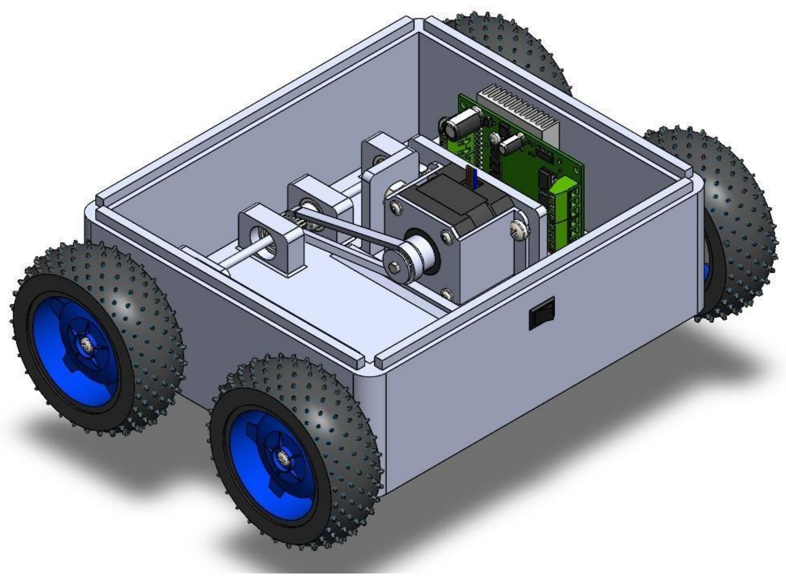

Figure 5. CAD of the robot car mechanism

For the respective calculations of the actuator, the following was taken into account:

Motor selection for the vehicle system Based on Oriental Motor website[27], when selecting the robot motor, certain considerations were taken into account so that it could function without overloads that could alter the system at the time of its operation. The vehicle system is characterized by the following parameters:

- **Vehicle mass (m_1):** 3.179 kg
- **Wheel outer diameter (D_1):** 85 mm
- **Wheel mass (m_{D1}):** 0.054 kg per wheel
- **Number of wheels (n_1):** 4
- **Rolling friction coefficient between wheel and floor (μ_1):** 0.15
- **Drive mechanism efficiency (η):** 80%
- **Primary pulley pitch circle diameter (D_{p1}):** 12 mm
- **Primary pulley mass (m_{p1}):** 0.006 kg
- **Secondary pulley pitch circle diameter (D_{p2}):** 12 mm
- **Secondary pulley mass (m_{p2}):** 0.006 kg
- **Floor slope angle (α):** 0
- **Operating speed (V_1):** 0.3 m/min
- **Operating speed (V_2):** 0.6 m/min
- **Acceleration/deceleration time (t_1):** 2 seconds
- **Stopping accuracy (Δl):** 0 mm
- **Safety factor ($S.F.$):** 1.5

On the same website[27], it is indicated that when choosing the motor for the robot, there are some forces that were applied when the robot performs a work operation.For a vehicle system with a NEMA 17 motor along with its driver and timing belt controlled by the ARDUINO R4, the following was considered and calculated:

Inertia load:

$$\text{Vehicle} \quad J_V = \left(m_1 + \frac{1}{2}m_{D_1} \times n_1\right) \times \left(\frac{D_1 \times 10^{-3}}{2}\right)^2$$

$$\text{Carts} \quad J_C = \left(m_2 + \frac{1}{2}m_{D_2} \times n_2\right) \times \left(\frac{D_1 \times 10^{-3}}{2}\right)^2 \times N$$

$$\text{Total load inertia} \quad J_L = J_V + J_C = 5.9374 \times 10^{-3}\,\text{kg} \cdot \text{m}^2$$

Required speed:

$$V_m = \frac{V_1}{\pi D1 \times 10^{-3}}$$

V_1 = 1.124 **r/min**,

V_2 = 2.248 **r/min**

Required torque:

$$T = (T_a + T_L) \times (\text{Safety Factor}) = 0.3987\ \text{N} \cdot \text{m}$$

Acceleration torque:

$$T_a = J_L \left(\frac{V_m}{9.55 \times t_1}\right) = 6.9882 \times 10^{-4}\,\text{N} \cdot \text{m}$$

Load torque:

$$F = 9.8\left((m_1 + n_1 \times m_{D1}) \times (\sin\alpha + \mu_1 \cos\alpha) + (m_2 + n_2 \times m_{D2}) \times N \times (\sin\alpha + \mu_2 \cos\alpha)\right)$$

$$T_L = \frac{F \times D1 \times 10^{-3}}{2\eta \times 0.01} = 0.2651\ \text{N} \cdot \text{m}$$

Required stopping accuracy:

$$\Delta\vartheta = \Delta l \quad \frac{360^{\circ}}{\pi D1} \quad = 0\,\text{deg}$$

This is why the NEMA 17 motor was chosen stepper motor (model 42SHD0034-20D) since its datasheet[28] indicates a stall torque of 0.45 Nm, which satisfies the force required to move the cart with its entire structure.

Shelf considerations

Compliance with Standards The shelf design for the system adheres to established safety and structural guidelines to ensure reliability, durability, and efficient utilization of space. Specifically, the following standards were considered:

- **ISO 11262:** Static storage systems for domestic use [29].
- **ANSI MH28.1-2013:** Design, testing, and utilization of industrial steel storage racks [30].
- **INEN 1503:** Ecuadorian standards for safety in storage structures [31].

These standards were used to determine the appropriate dimensions, spacing, and material strength requirements, ensuring the shelf's structural stability under operating conditions.

Shelf Dimensions A feasible space was considered necessary to collect and position the boxes on the shelf.

The shelf was built with 6mm MDF wood and had a space of 3 columns and 2 rows to place the 6 necessary boxes. The boxes had a space where the clamps can enter to pick up or leave them. With this requirement, the following were established:

Length measurement:
For the length of the shelf, a space of 39.34 mm was considered on the sides of the

boxes. For this purpose, the following equation was applied:

L = (MDF measures * Number of separations of the length) + (Length of the boxes * Number of boxes in a row) + (Number of boxes in a row * Box side separations)

L = (6 mm * 4) + (80 mm * 3) + (3 * 78.68 mm) = 500 mm

Height measurement:

For the height of the shelf, a space of 126 mm was considered in the height space of each box. For this purpose, the following equation was applied:

H = (MDF measures * Number of separations of the height) + (Height of the boxes * Number of boxes in a column) + (Number of boxes in a column * Box height space)

H = (6 mm * 3) + (25 mm * 2) + (2 * 126 mm) = 320 mm

Width measurement:

For the width of the shelf, a space of 104 mm was considered for the push of the box. For this purpose, the following equation was applied:

W = MDF measures + Weight of the boxes + Box push space

W = 6 mm + 50 mm + 104 mm = 160 mm

Final Dimensions:

With the results obtained, the dimensions of the shelf were defined as:

$$500\,\text{mm} \times 320\,\text{mm} \times 160\,\text{mm}.$$

These dimensions ensure adequate space for six boxes while meeting the requirements for accessibility, structural stability and efficient use of space. The design can be seen in Fig.6

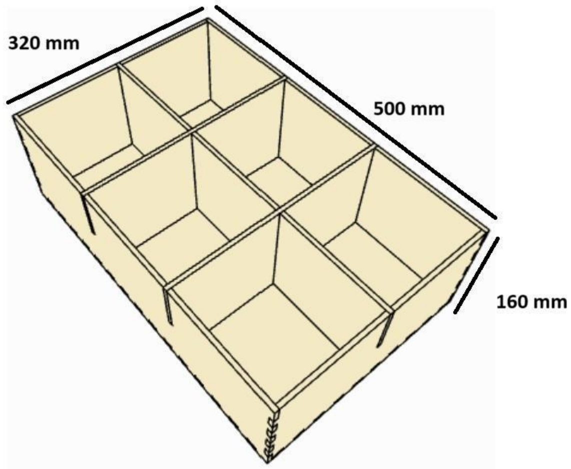

Figure 6. Design and dimensions of the shelf

In Appendix1, it can be seen the mechanical drawings of each part of the prototype and its assembly. In Appendix2, the electronics schematic diagram of each selected component is displayed.

3. RESULTS

The results section shows the integration of the prototype made by attributing the selection of the previously calculated elements, CAD design and assembly of the same, then the property verification where the focus is on the verification of the proposed requirements and the experimental design where the respective performance tests were carried out to show the results obtained.

3.1. INTEGRATION

Based on the elements previously selected by the calculations, a respective CAD design was made, considering other materials that helped fulfill the function of the prototype. First, in Fig.7, there is an exploded view of the double axis loading and lifting structure, where the corresponding materials that helped raise and lower the loads of the boxes are shown.

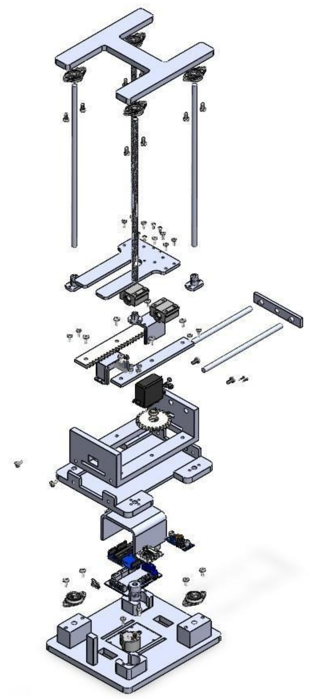

Figure 7. Exploded view of the double axis loading and lifting structure

Likewise, Fig.8 shows the exploded view of the structure of the robot cart which, in addition to the elements necessary for its assembly, allowed movement together with the two structures shown previously.

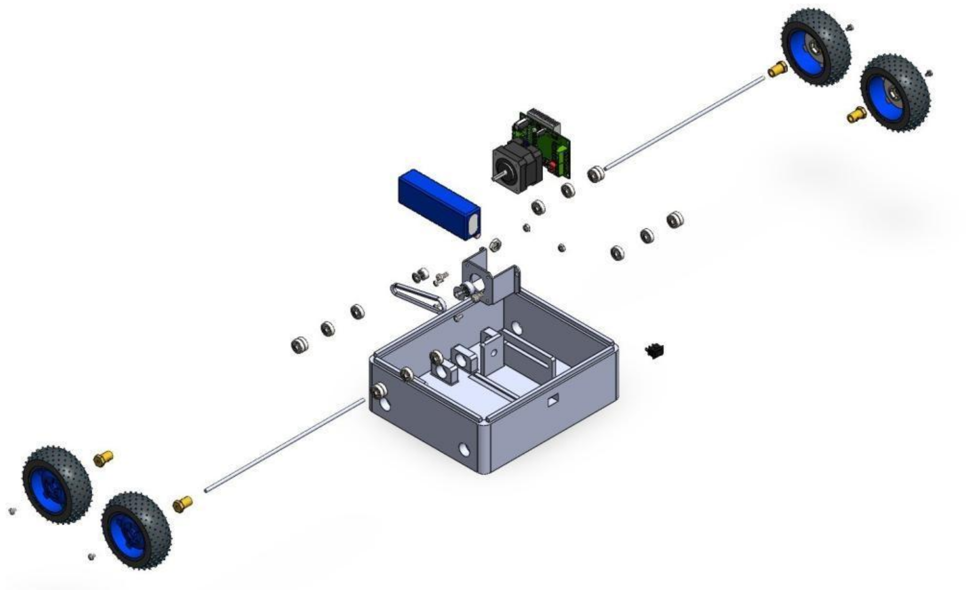

Figure 8. Exploded view of the robot car structure

By integrating all the elements of the three structures, a complete assembly was obtained at the CAD level, which served as a guide for the construction of the prototype with dimensions of 442.97 x 207.20 x 270.84 mm. Fig.9 shows the CAD design on the left and the implemented prototype on the right.

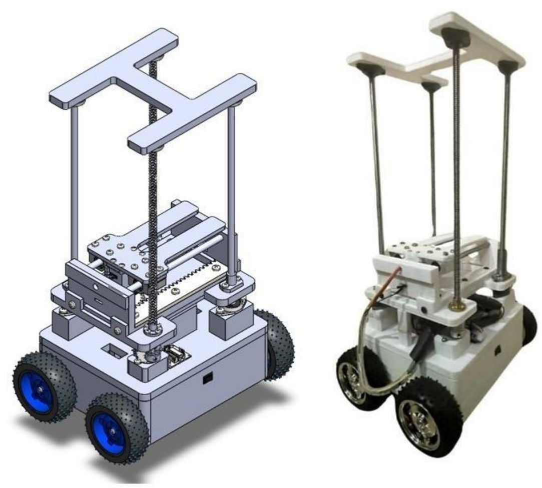

Figure 9. CAD design and implemented prototyping of the robot

Finally, a graphical interface, shown in Fig.10, was implemented to access the operation of the robot through the same internet network connected to the Arduino R4 and the computer, in which can be used to choose 1 of the 6 boxes listed on the shelf and select the pick up option to bring the box or drop out to return it to its respective place.

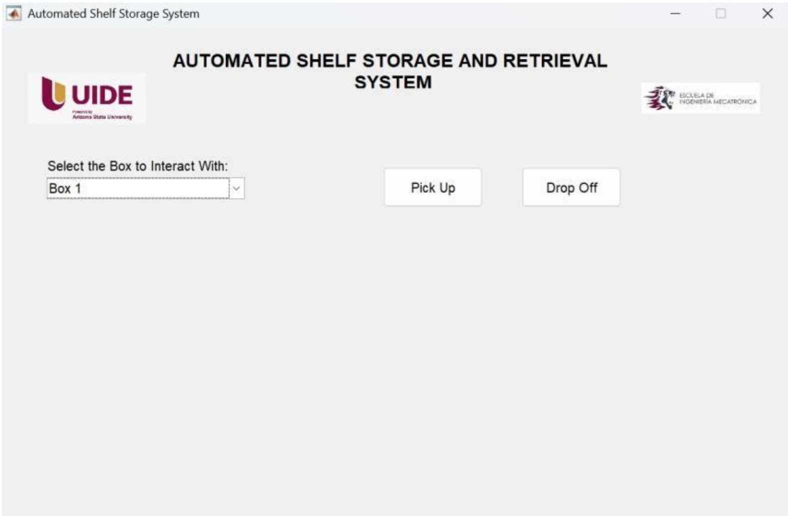

Figure 10. Graphical interface of the robot

3.2. PROPERTY VERIFICATION

To ensure that all the properties defined above were being met, a series of activities were assigned to monitor in what want to be achieve. For this reason, two sections are presented that define the corresponding tasks according to what was verified or tested.

Requirements verification

The requirements defined above are essential to meet the proposed goals of the system built, which is why their respective monitoring was done to validate its operation. The Table 1 indicates the fulfillment of each verification of the requirements defined when carrying out each proposed activity.

Experiments Design

Based on the books by Montgomery[32] and Melo[33], the experimental design is very essential to be able to identify the variables to control the system and the various random factorial tests to carry out to obtain what was desired with a replication strategy.To

Table 1. Requirements checklist

Functional requirements activities	**Item completed**
Perform a CAD design and physical testing by placing and removing multiple boxes of products on the shelf.	YES
Perform physical tests and verify that the missing products can be returned to their respective place once the order is given in the graphical interface.	YES
Non-functional requirements activities	**Item completed**
Perform timed tests to confirm that the system can process orders within the 5 minutes limit.	YES
Carry out tests with users so that when handling the graphical interface, they find it easy to use and understand how it works to carry out the work of storing and retrieving products from the shelf.	YES
Perform physical tests and verify that the 80 x 25 x 50 mm boxes can be stored in their respective space and place on the assigned shelf.	YES
Perform physical tests and verify that each box to be picked up or returned does not exceed 100 grams.	YES

do this, a detailed experiment plan was carried out, identifying all the properties necessary for its development, as shown below:

Experiment Objectives Evaluate and optimize the performance of the automated storage and retrieval system.

Factors and Levels

- Position of the Boxes on the Shelf: Positions 1, 2, 3, 4, 5, 6.
- Action type: Store or Extract a box.

Selected Experimental Design Full factorial design 3^3 or randomized block design if sources of external variability are identified.

Randomization Scheme Random assignment of combinations of factor levels to box positions on the shelf.

Replication Strategy Perform two replicates for each treatment combination to ensure statistical accuracy.

Because of this, two test sequences were carried out to pick the 6 boxes randomly, and two to return the 6 boxes to the shelf. A total of 24 tests were performed, and 3 respective analyses were carried out.

Results analysis The first analysis indicates that of the 24 tests performed, 20 were correct in positioning well, which represents 83.33% efficiency of the prototype. Fig.11 shows that of the correct tests, 42.1% are for retrieving and 57.9% are for storaging, this being the highest percentage of precision in the operation performed.

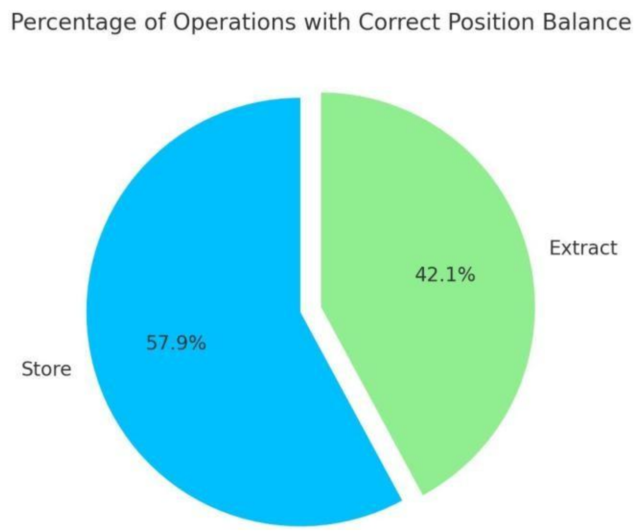

Figure 11. Pie chart of the first analysis

The second analysis in the Fig.12 indicates the operation time of the tests performed, being 179.91 s are for retrieving and 184.92 s are for storaging, this indicating the one that took the longest time carrying out the operation.

The third and last analysis in the Fig.13 indicates the servo motor current of the tests performed, being 0.93 A are for retrieving and 0.94 A are for storaging, this indicating the one that took the highest current to did the operation, and the box 2 is the one that consumed the most current compared to the others.

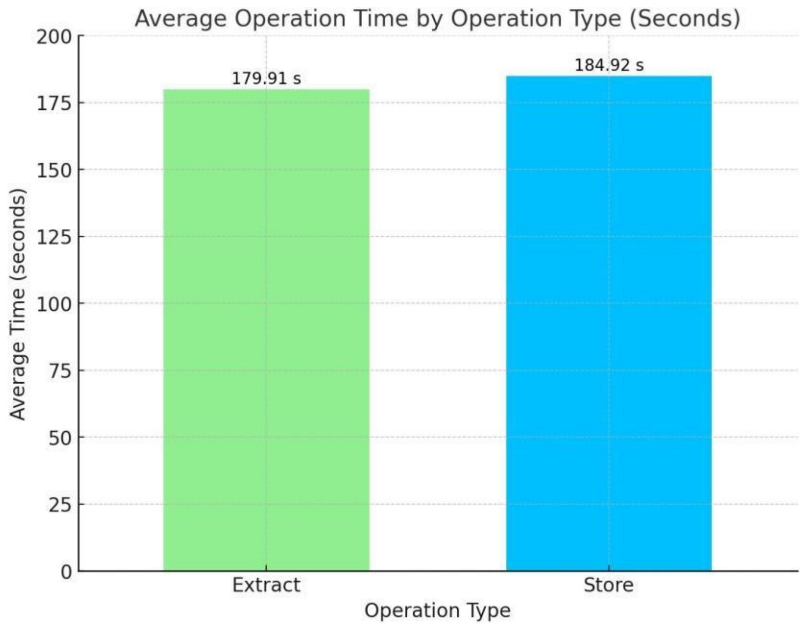

Figure 12. Bar chart of the second analysis

Bugs Found

The errors found when carrying out the tests were due to the fact that the movement of the cart fails due to the tension of the power cable or even because its own structure did not move well, and the bad initial position when not placing the box in its space due to a collision of the support axes with the pallet, since the prototype was positioned from left to right at a distance of 17 mm before reaching the beginning of the parallel shelf, which was at a height of 210 mm and the pallets with their boxes centered in the corresponding space, at a distance of 10 mm from the lifting structure in its waxed position, in such a way that it did not affect the movement of the cart.

With the initial position of the prototype explained, the box was at most 25 mm away from the top of the double loading axis so that it could reach its correct position and there were no defects in it.

Cost Analysis and Pricing

To determine the final selling price of the prototype, the following factors were considered:

- **Material Costs:** The total cost of materials, including electronic components,

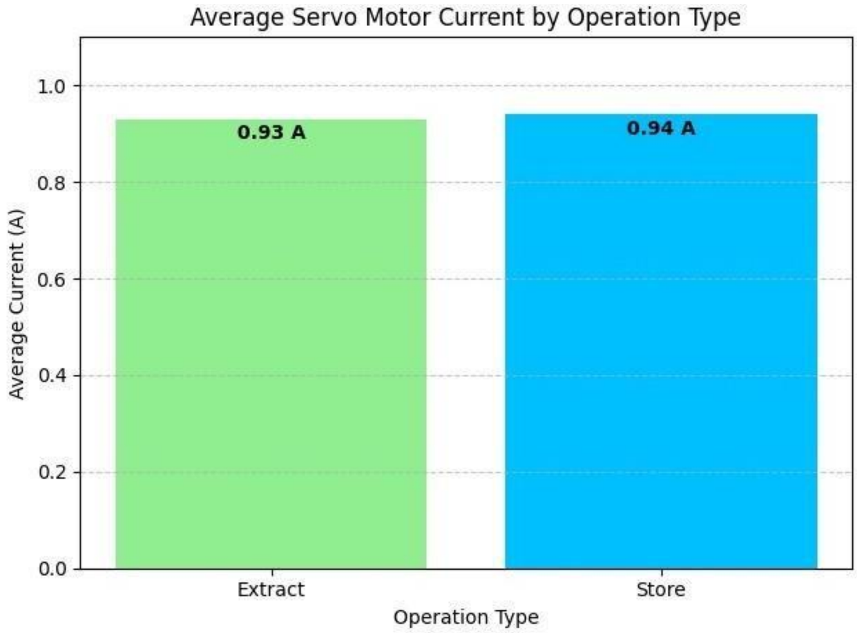

Figure 13. Bar chart of the third analysis

mechanical parts, and manufacturing processes, amounts to \$504.11.

- **Labor Cost:** The labor cost was calculated based on the time invested in the project. A total of 436 working hours were considered, with an hourly rate of \$7.50, which is the estimated rate for a recently graduated Mechatronics Engineer in Ecuador:

$$\text{Labor Cost} = 436\ \text{hours} \times 7.50\ \$/\text{hour}$$

$$\text{Labor Cost} = 3,270\ \$.$$

- **Profit Margin:** A profit margin of 20% was added to account for the value of the prototype and ensure a competitive price. The total cost, including materials and labor, was calculated as follows:

$$\text{Total Cost} = \text{Material Cost} + \text{Labor Cost}$$

$$= 504.11 + 3,270$$

$$= 3,774.11\ \$.$$

Adding a 20% profit margin:

$$\text{Final Selling Price} = \text{Total Cost} \times (1 + \text{Profit Margin})$$
$$= 3,774.11 \times 1.2$$
$$= 4,528.93\,\$.$$

The selling price of the prototype has been rounded to **$4,500** for presentation purposes. This price accounted for the material costs, labor efforts, and a reasonable profit margin, ensuring a fair valuation for the development of the system.

To improve economic feasibility and facilitate broader adoption, a production strategy has been proposed that focused on manufacturing a minimum of 5 units and a maximum of 10 units per order. This strategy leverages economies of scale, reducing the cost per unit and making the system more accessible to a wider range of clients. Additionally, the system's design can be customized to address the specific requirements of the region where it will be deployed, offering a tailored solution that effectively balances functionality, operational needs, and affordability. In Appendix3, it can be seen the detail of the cost table of each element that was acquired for the construction of the prototype.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1. CONCLUSIONS

- The automated storage and retrieval system was successfully designed and implemented, achieving its goal of automating the handling of boxes on the shelves with an accuracy of 83.33% obtained from the tests carried out.
- The storage and retrieval mechanism was designed and integrated with 190 mm maximum reach limitations for the lifting structure and 110 mm for the forward reach of the double-axis load. In addition, the robot trolley has no distance limit as it can be adapted to racks of different lengths, ensuring optimal operation of the axes during handling of the boxes.
- A storaging space allocation algorithm was implemented, optimizing the use of shelf space, considering that the average retrieving time was 179.91 s and recovery time was 184.92 s in the location of the products.
- Controlled performance tests of accuracy, time and current for each operation validated the reliability of the system. Box 2 had the highest consumption of 1.04 A during recovery and 1 A during extraction without any malfunctions.

4.2. RECOMMENDATIONS

- Integrate artificial intelligence (AI) to identify the types and quantities of objects inside the boxes. The AI can also optimize storage by determining the best locations for objects and managing retrieval routes for maximum efficiency.
- Develop an API-based system that allows multiple robots to communicate via a web-based interface using a URL endpoint. This would enable centralized control and coordination of multiple robots for advanced warehouse operations.
- Incorporate advanced computer vision techniques to monitor the status of stored objects in real time, which would allow the robot to identify if any product is damaged or incorrectly placed and automatically notify it, helping to maintain the quality and accuracy of the inventory system.

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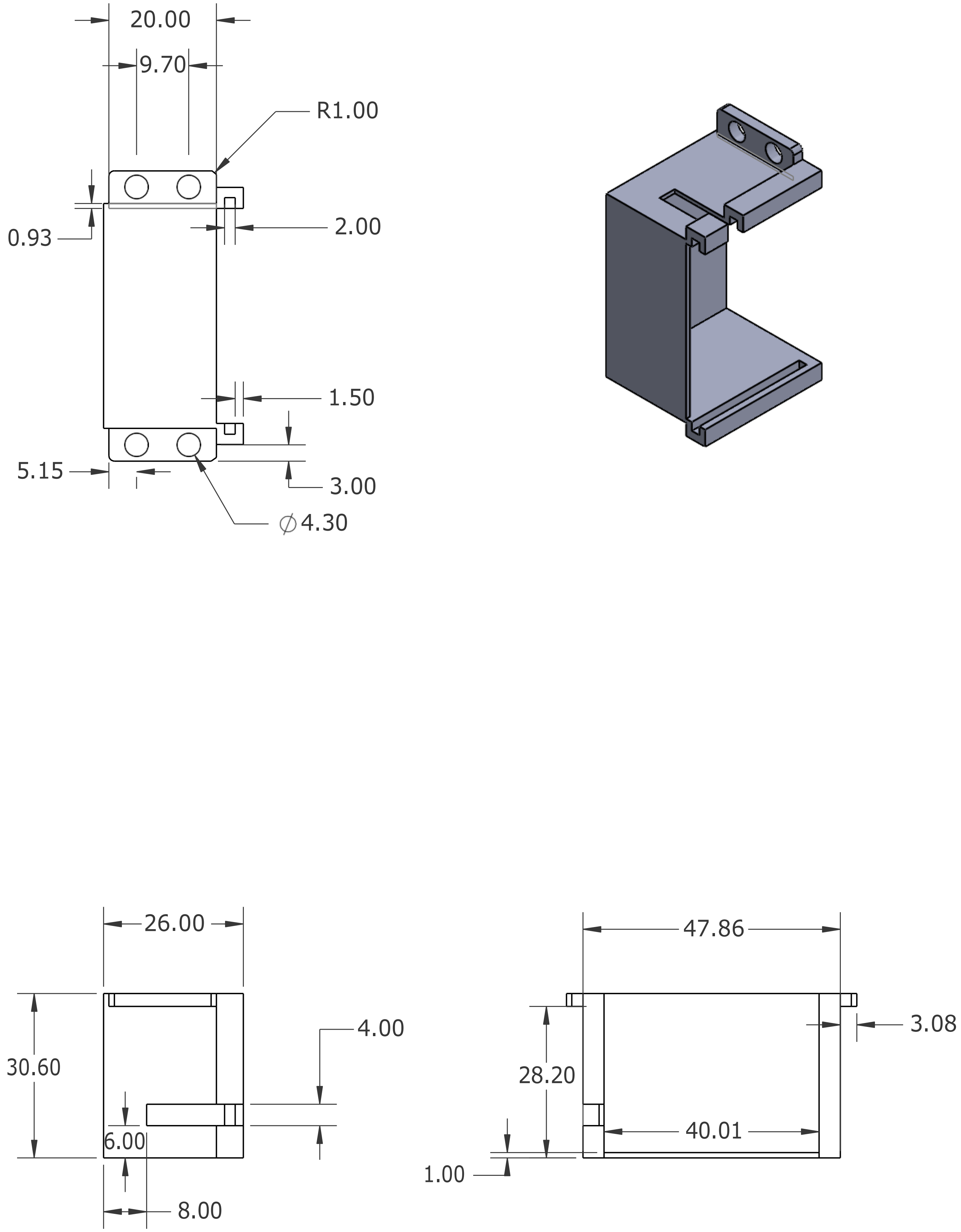
APPENDIX1. MECHANICAL DRAWINGS.



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	DISEÑADOR/DESIGNER: JORDY JOEL MORILLO SANCHEZ	09/13/2024
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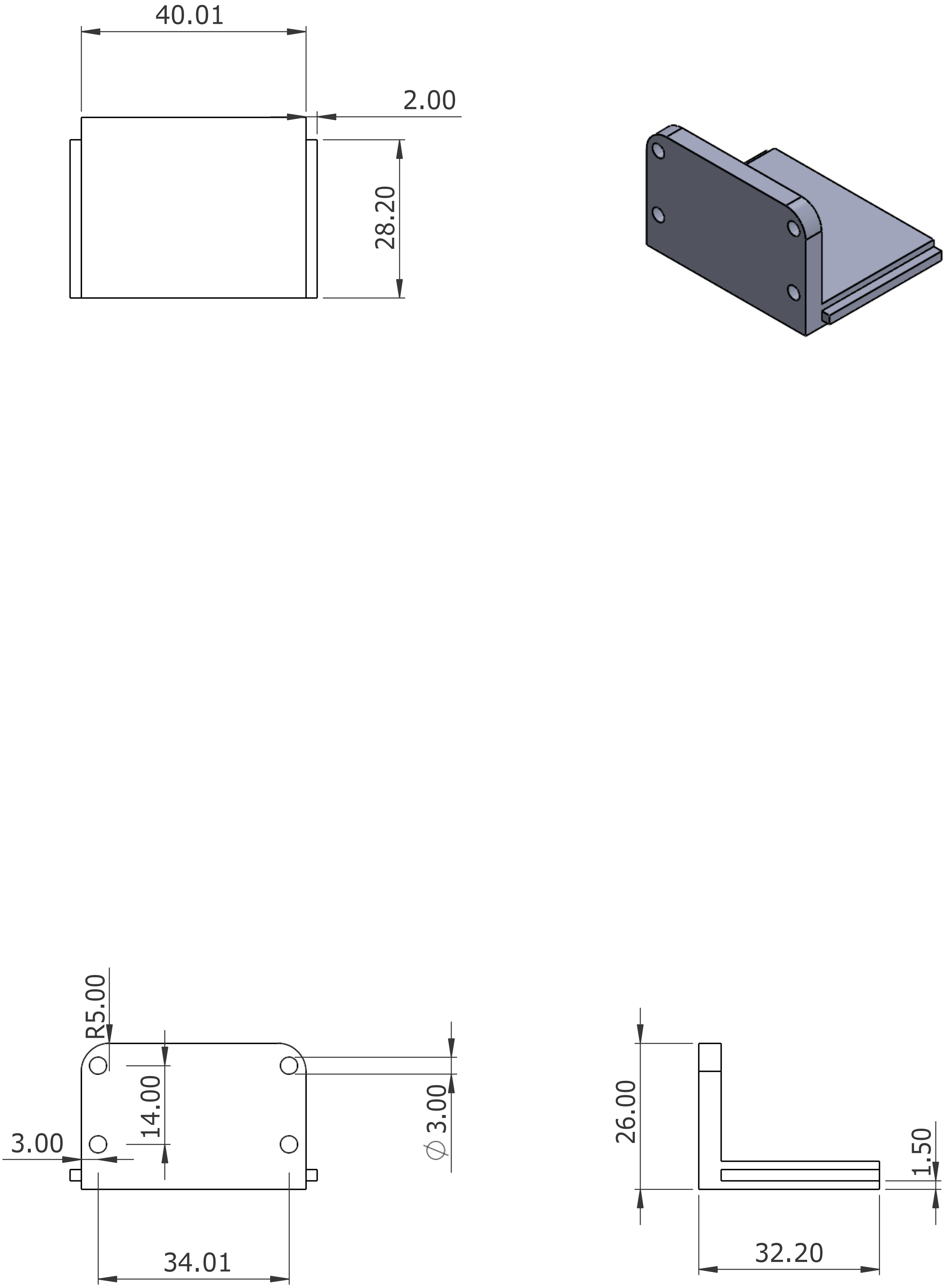
ESCUELA DE INGENIERIA MECATRONICA

ASIGNATURA/SUBJECT: CURRICULAR INTEGRATION SEMINAR
PROYECTO/PROYECT: AUTOMATED SHELF STORAGE AND RETRIEVAL SYSTEM
DESCRIPCION/DESCRIPTION: MG995 SERVO MOTOR BASE
DIBUJO Nº/DRAWING Nº: D01-001



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	DISEÑADOR/DESIGNER: JORDY JOEL MORILLO SANCHEZ	09/13/2024		PROYECTO/PROYECT: AUTOMATED SHELF STORAGE AND RETRIEVAL SYSTEM
	REVISADO/REVIEWED BY: GUILLERMO ALFREDO MOSQUERA CANCHINGRE	09/13/2024		DESCRIPCION/DESCRIPTION: DOUBLE AXLE LOAD SAFE BASE
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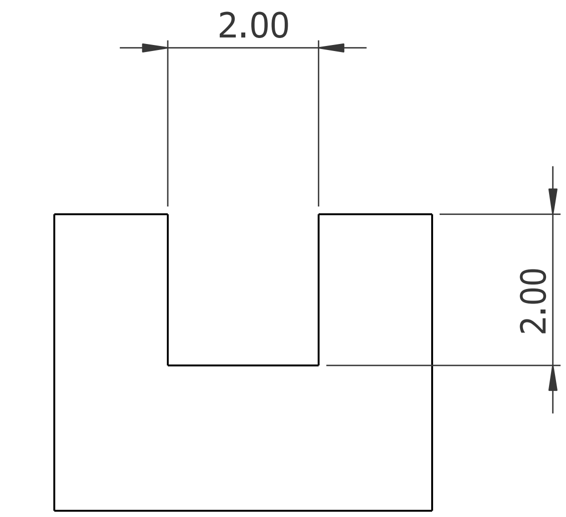

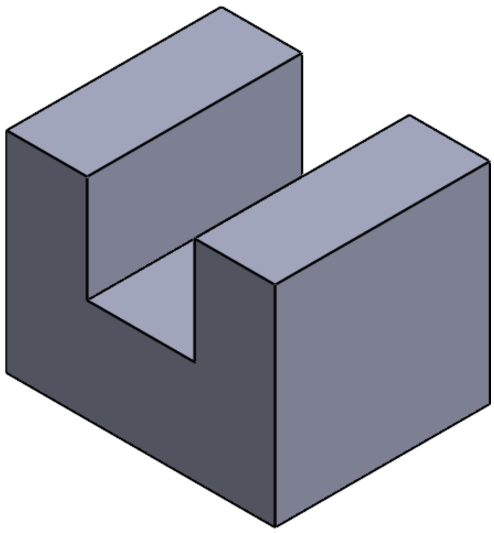

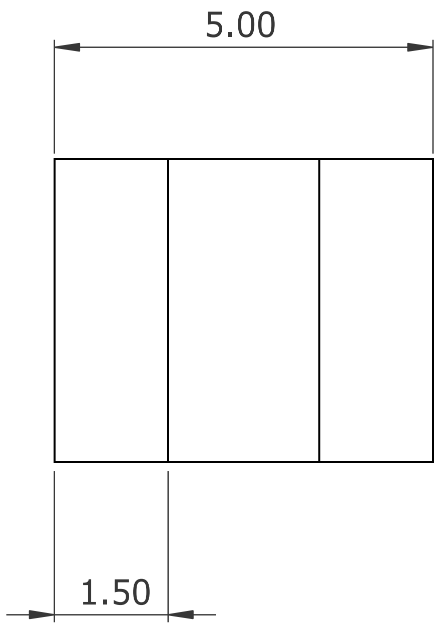

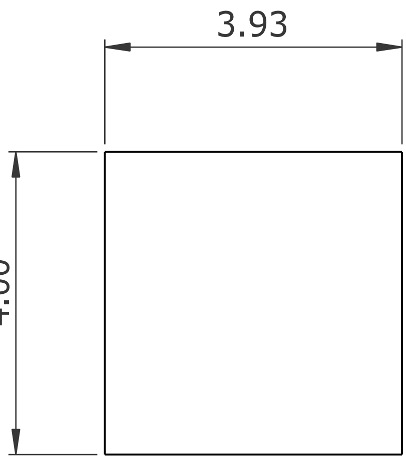

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ASIGNATURA/SUBJECT:	CURRICULAR INTEGRATION SEMINAR
PROYECTO/PROYECT:	AUTOMATED SHELF STORAGE AND RETRIEVAL SYSTEM
DESCRIPCION/DESCRIPTION:	MG995 SERVO MOTOR FRAME INSURER
DIBUJO Nº/DRAWING Nº:	D01-003
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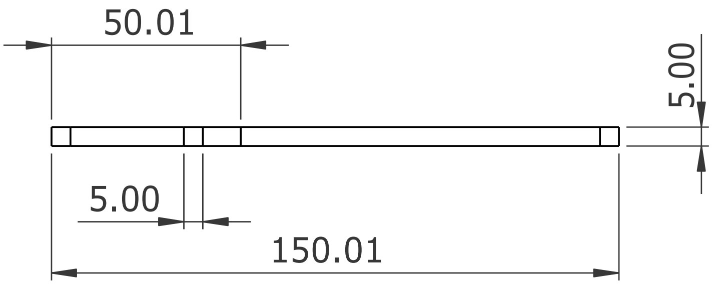

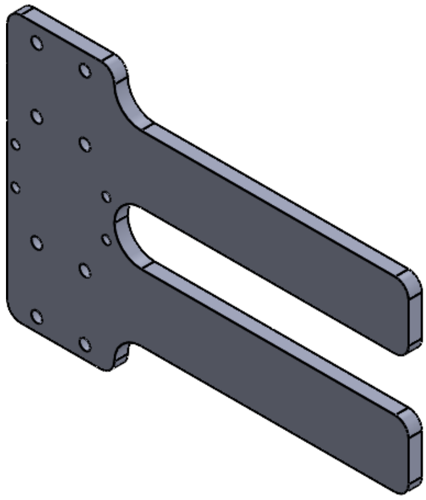

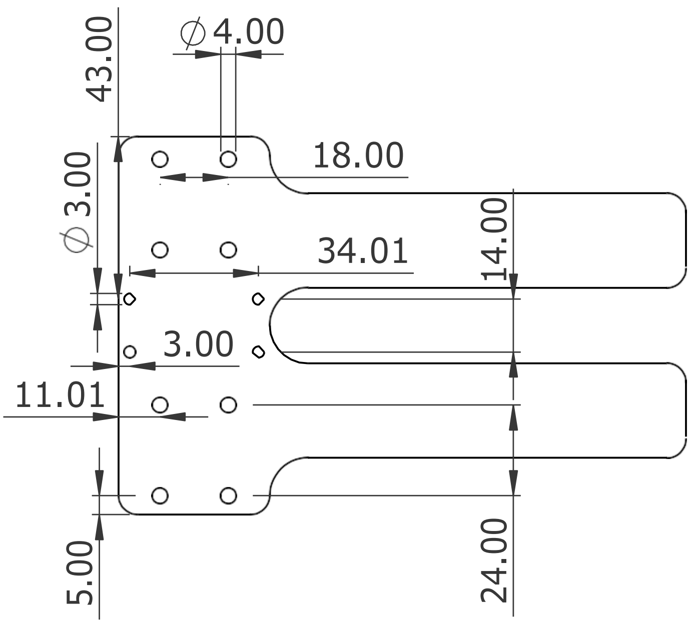

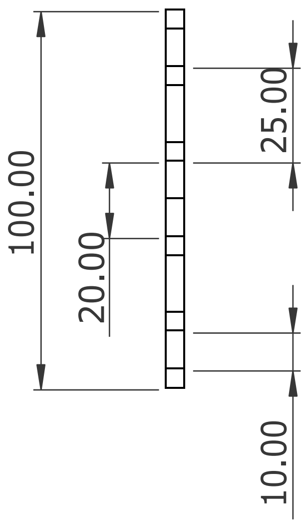

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PROYECTO/PROYECT:	AUTOMATED SHELF STORAGE AND RETRIEVAL SYSTEM
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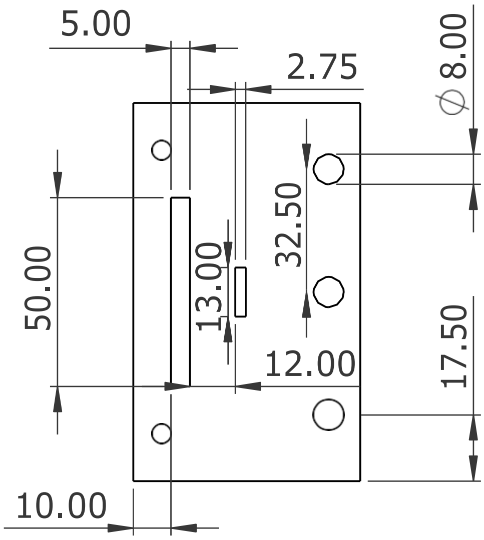
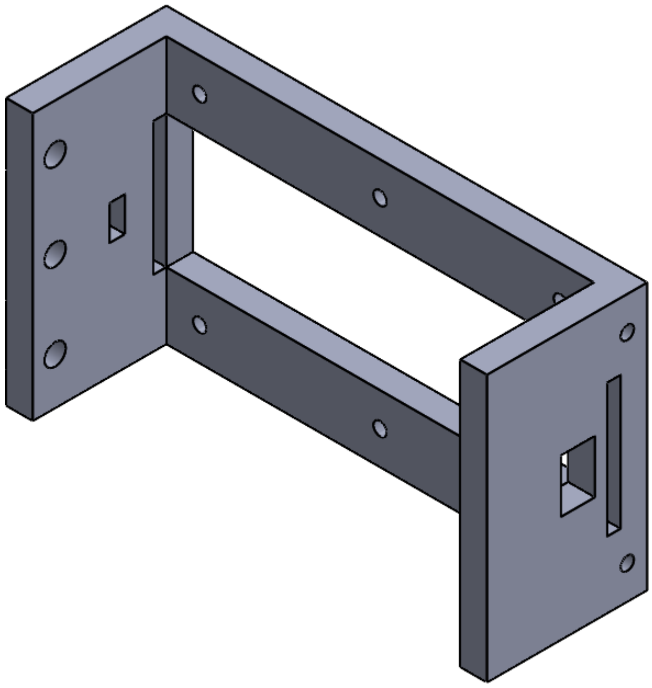
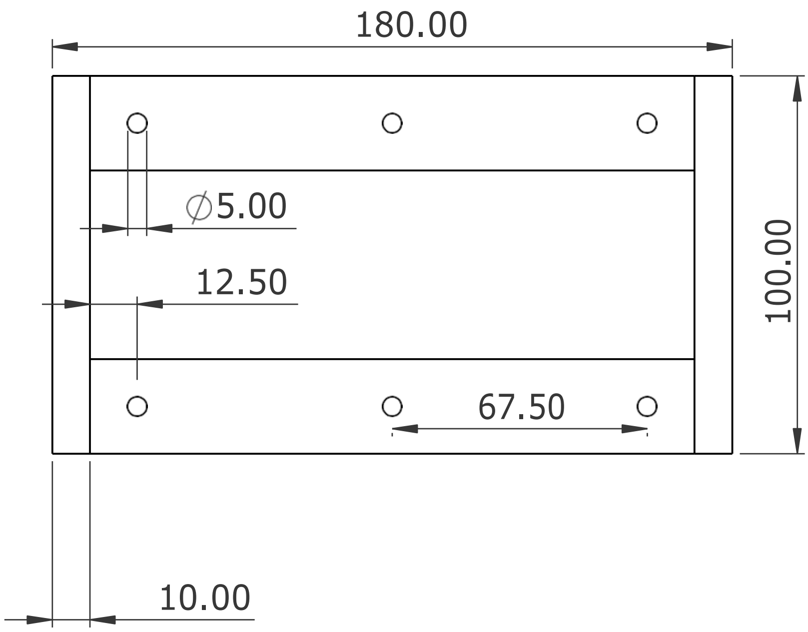
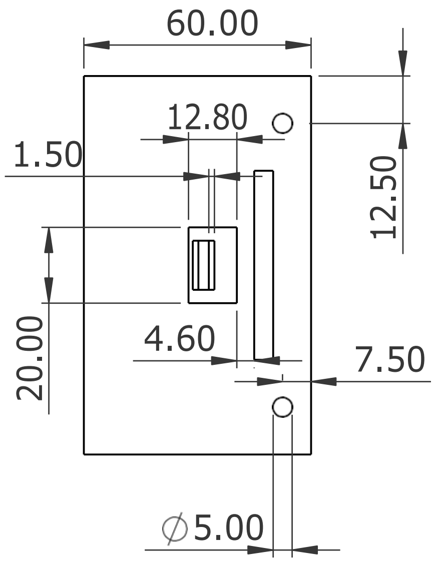
DIBUJO Nº/DRAWING Nº:	D01-004









NOTAS GENERALES/GENERAL NOTES:	REGISTRO/REGISTER:	FECHA/DATE:
	DIBUJANTE/DRAFTMAN: JORDY JOEL MORILLO SANCHEZ	07/24/2024
	DISEÑADOR/DESIGNER: JORDY JOEL MORILLO SANCHEZ	09/13/2024
	REVISADO/REVIEWED BY: GUILLERMO ALFREDO MOSQUERA CANCHINGRE	09/13/2024
	APROBACION FINAL/APPROBATION BY/: GUILLERMO ALFREDO MOSQUERA CANCHINGRE	01/05/2025

TAMAÑO/PAPER SIZE: A4
ESCALA/SCALE: 1:2

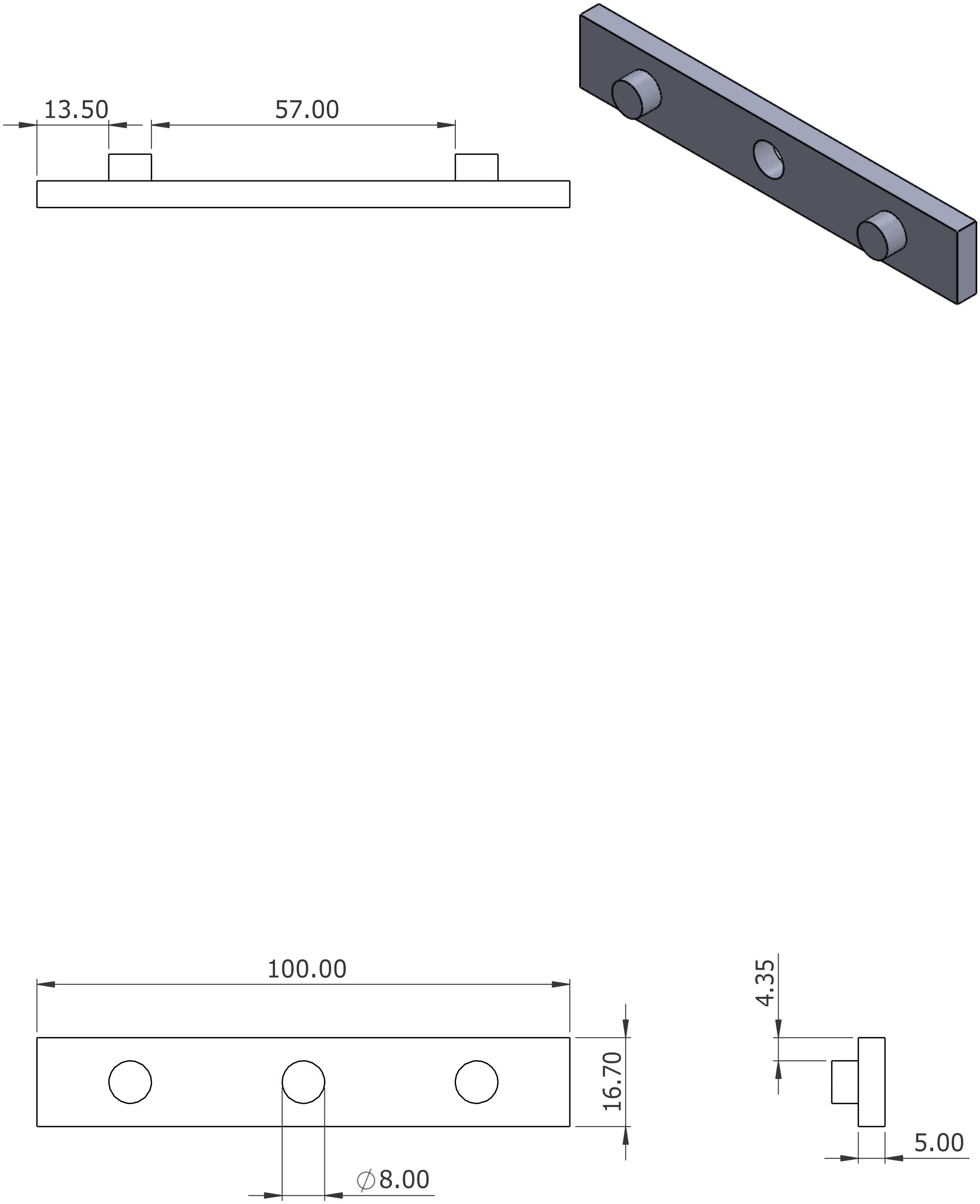
UNIVERSIDAD INTERNACIONAL DEL ECUADOR
ESCUELA DE INGENIERIA MECATRONICA

ASIGNATURA/SUBJECT: CURRICULAR INTEGRATION SEMINAR

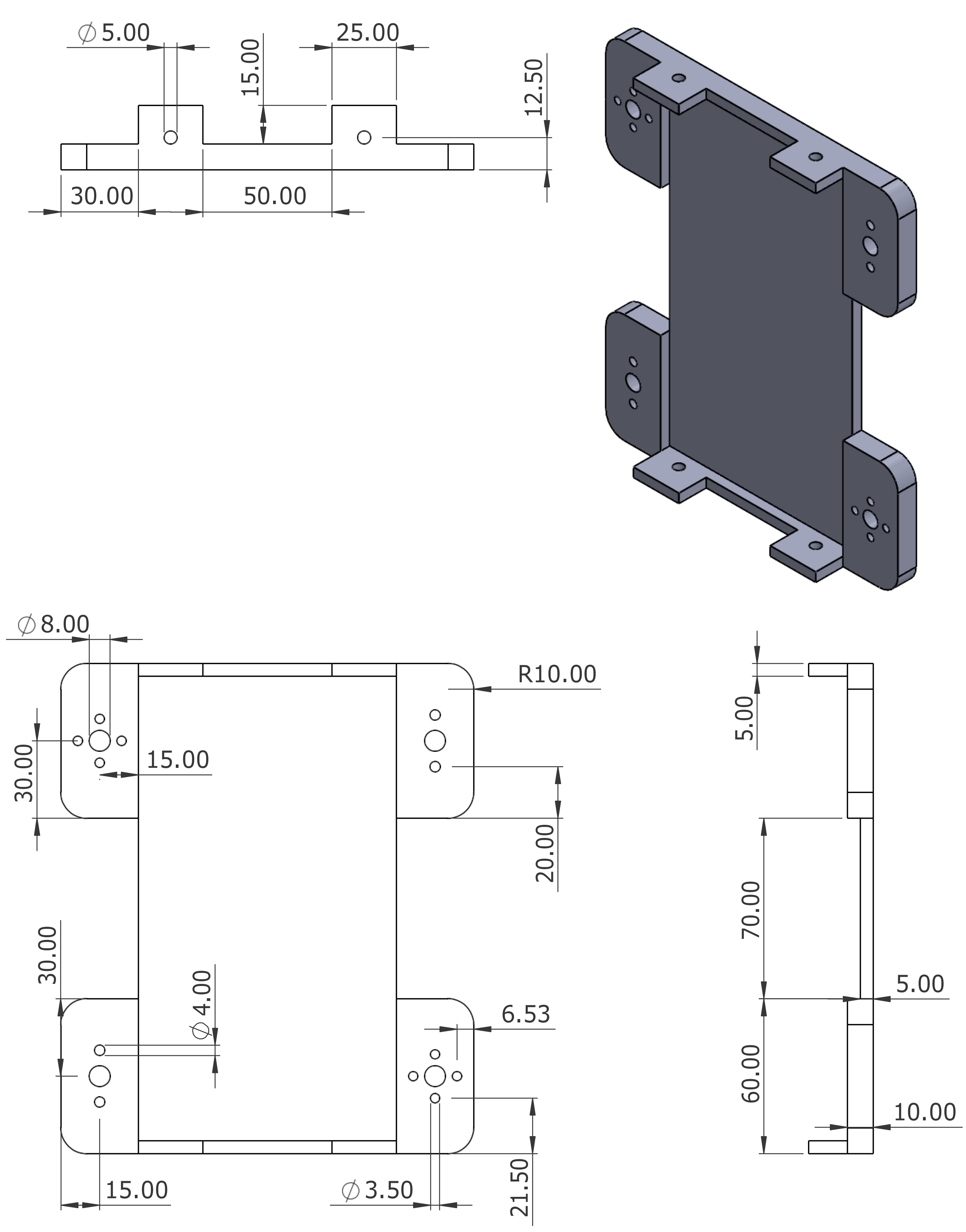
PROYECTO/PROYECT: AUTOMATED SHELF STORAGE AND RETRIEVAL SYSTEM

DESCRIPCION/DESCRIPTION: RACK AND PINION BASE

DIBUJO Nº/DRAWING Nº: D01-005



NOTAS GENERALES/GENERAL NOTES:	REGISTRO/REGISTER:	FECHA/DATE:	UNIVERSIDAD INTERNACIONAL DEL ECUADOR ESCUELA DE INGENIERIA MECATRONICA
	DIBUJANTE/DRAFTMAN: JORDY JOEL MORILLO SANCHEZ	07/24/2024	ASIGNATURA/SUBJECT: CURRICULAR INTEGRATION SEMINAR
	DISEÑADOR/DESIGNER: JORDY JOEL MORILLO SANCHEZ	09/13/2024	PROYECTO/PROYECT: AUTOMATED SHELF STORAGE AND RETRIEVAL SYSTEM
	REVISADO/REVIEWED BY: GUILLERMO ALFREDO MOSQUERA CANCHINGRE	09/13/2024	DESCRIPCION/DESCRIPTION: RACK AND PINION BASE COVER
	APROBACION FINAL/APPROBATION BY/: GUILLERMO ALFREDO MOSQUERA CANCHINGRE	01/05/2025	TAMAÑO/PAPER SIZE: A4 — ESCALA/SCALE: 1:1 — DIBUJO Nº/DRAWING Nº: D01-006

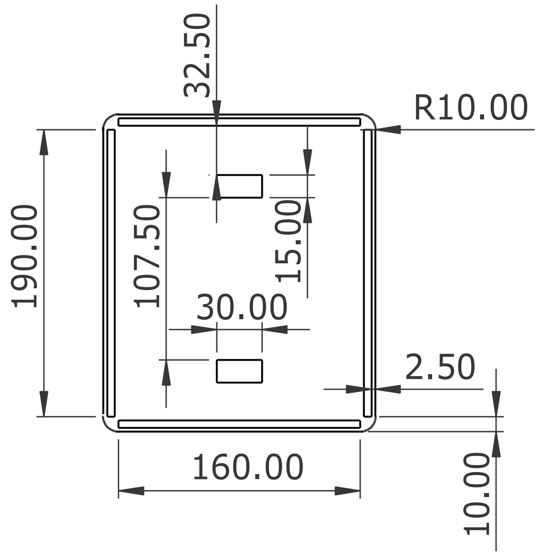


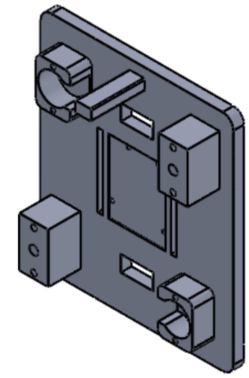
NOTAS GENERALES/GENERAL NOTES:	REGISTRO/REGISTER:	FECHA/DATE:
	DIBUJANTE/DRAFTMAN: JORDY JOEL MORILLO SANCHEZ	07/24/2024
	DISEÑADOR/DESIGNER: JORDY JOEL MORILLO SANCHEZ	09/13/2024
	REVISADO/REVIEWED BY: GUILLERMO ALFREDO MOSQUERA CANCHINGRE	09/13/2024
	APROBACION FINAL/APPROBATION BY/: GUILLERMO ALFREDO MOSQUERA CANCHINGRE	01/05/2025

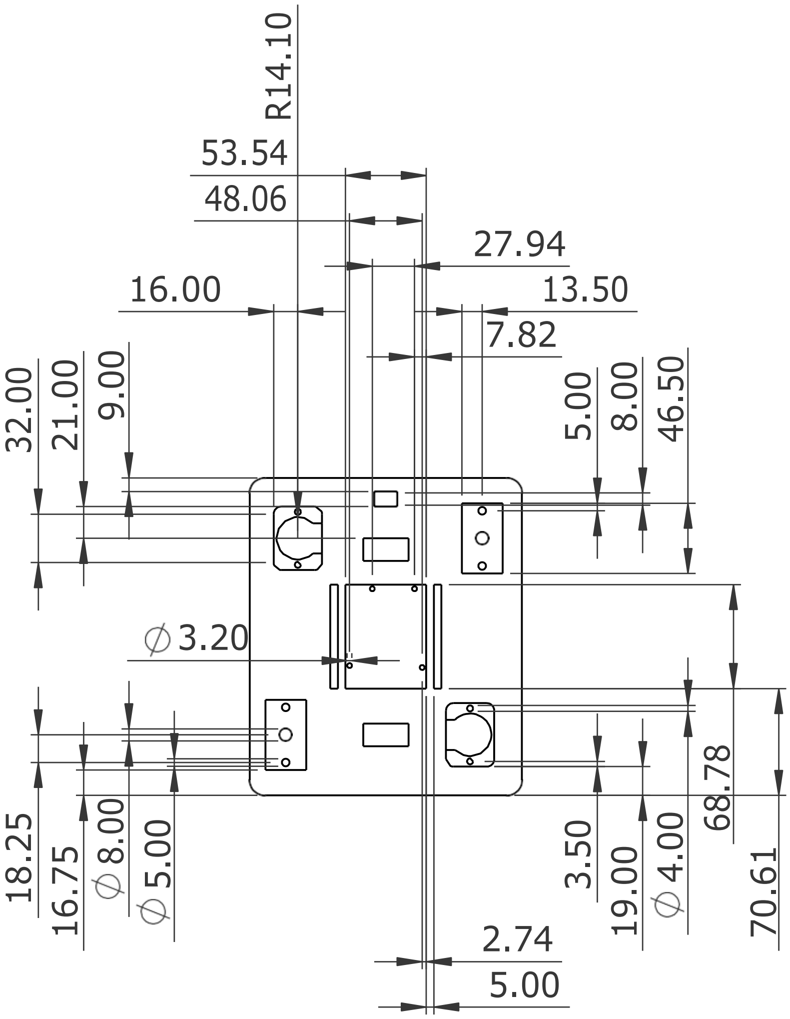
UNIVERSIDAD INTERNACIONAL DEL ECUADOR

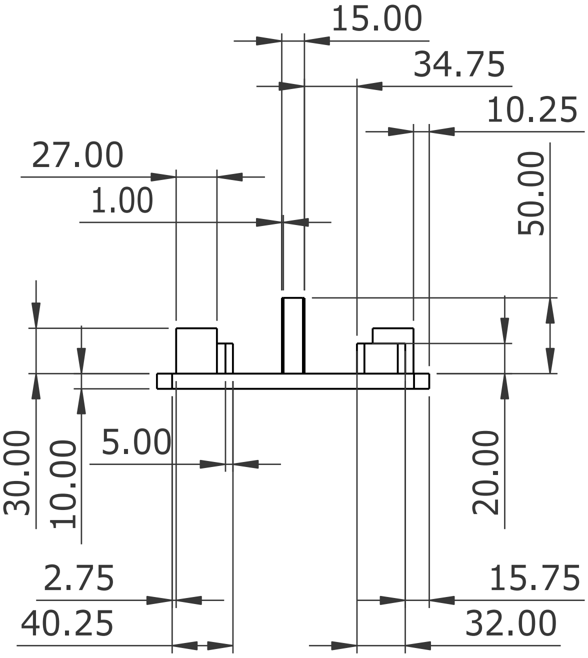
ESCUELA DE INGENIERIA MECATRONICA

ASIGNATURA/SUBJECT:	CURRICULAR INTEGRATION SEMINAR
PROYECTO/PROYECT:	AUTOMATED SHELF STORAGE AND RETRIEVAL SYSTEM
DESCRIPCION/DESCRIPTION:	BASE OF THE LIFTING STRUCTURE
DIBUJO Nº/DRAWING Nº:	D01-007
TAMAÑO/PAPER SIZE:	A4
ESCALA/SCALE:	1:2









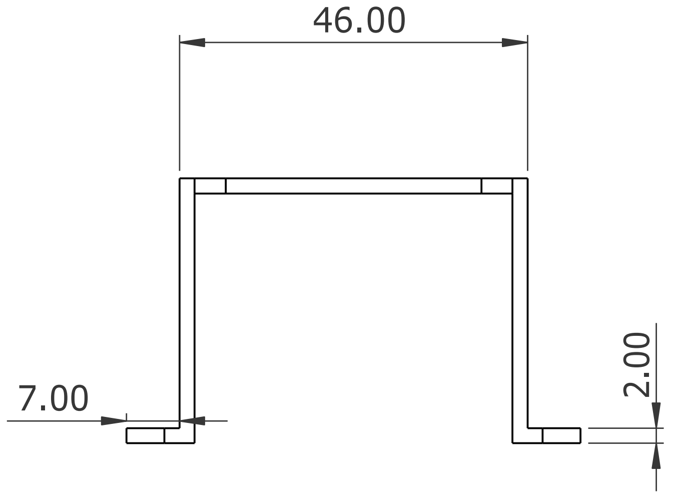
NOTAS GENERALES/GENERAL NOTES:	REGISTRO/REGISTER:	FECHA/DATE:
	DIBUJANTE/DRAFTMAN: JORDY JOEL MORILLO SANCHEZ	07/24/2024
	DISEÑADOR/DESIGNER: JORDY JOEL MORILLO SANCHEZ	09/13/2024
	REVISADO/REVIEWED BY: GUILLERMO ALFREDO MOSQUERA CANCHINGRE	09/13/2024
	APROBACION FINAL/APPROBATION BY/: GUILLERMO ALFREDO MOSQUERA CANCHINGRE	01/05/2025

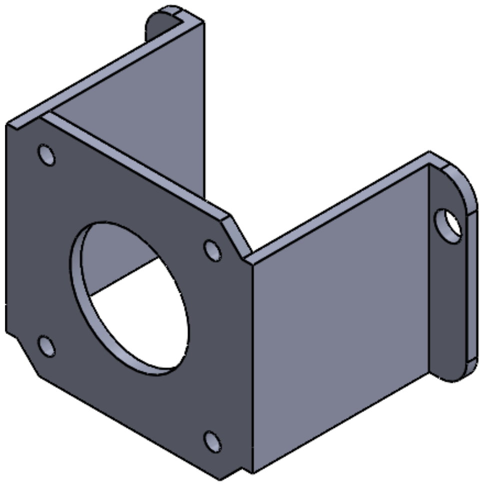
TAMAÑO/PAPER SIZE:	A4
ESCALA/SCALE:	1:5

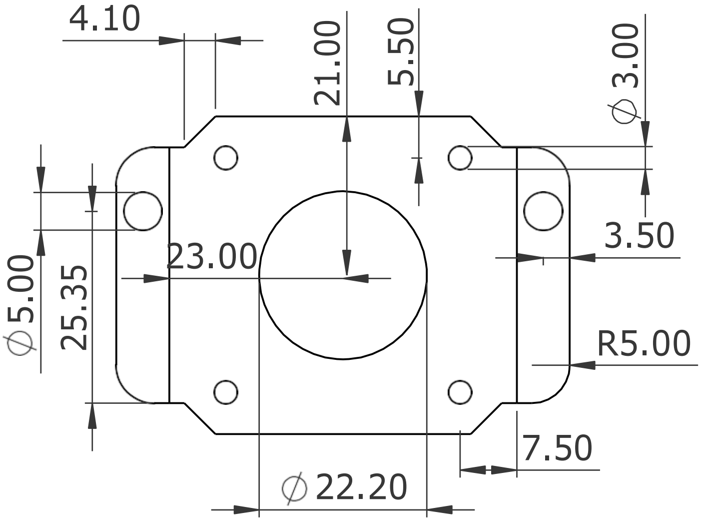
UNIVERSIDAD INTERNACIONAL DEL ECUADOR

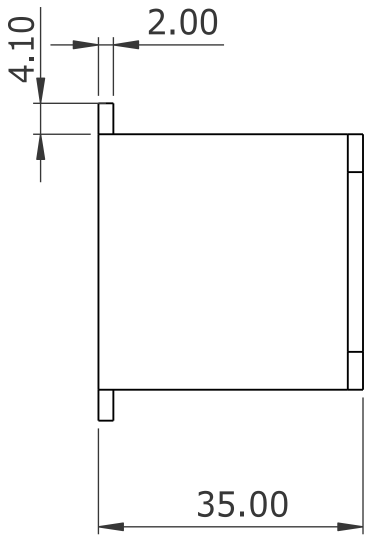
ESCUELA DE INGENIERIA MECATRONICA

ASIGNATURA/SUBJECT:	CURRICULAR INTEGRATION SEMINAR
PROYECTO/PROYECT:	AUTOMATED SHELF STORAGE AND RETRIEVAL SYSTEM
DESCRIPCION/DESCRIPTION:	ROBOT BASE
DIBUJO Nº/DRAWING Nº:	D01-008

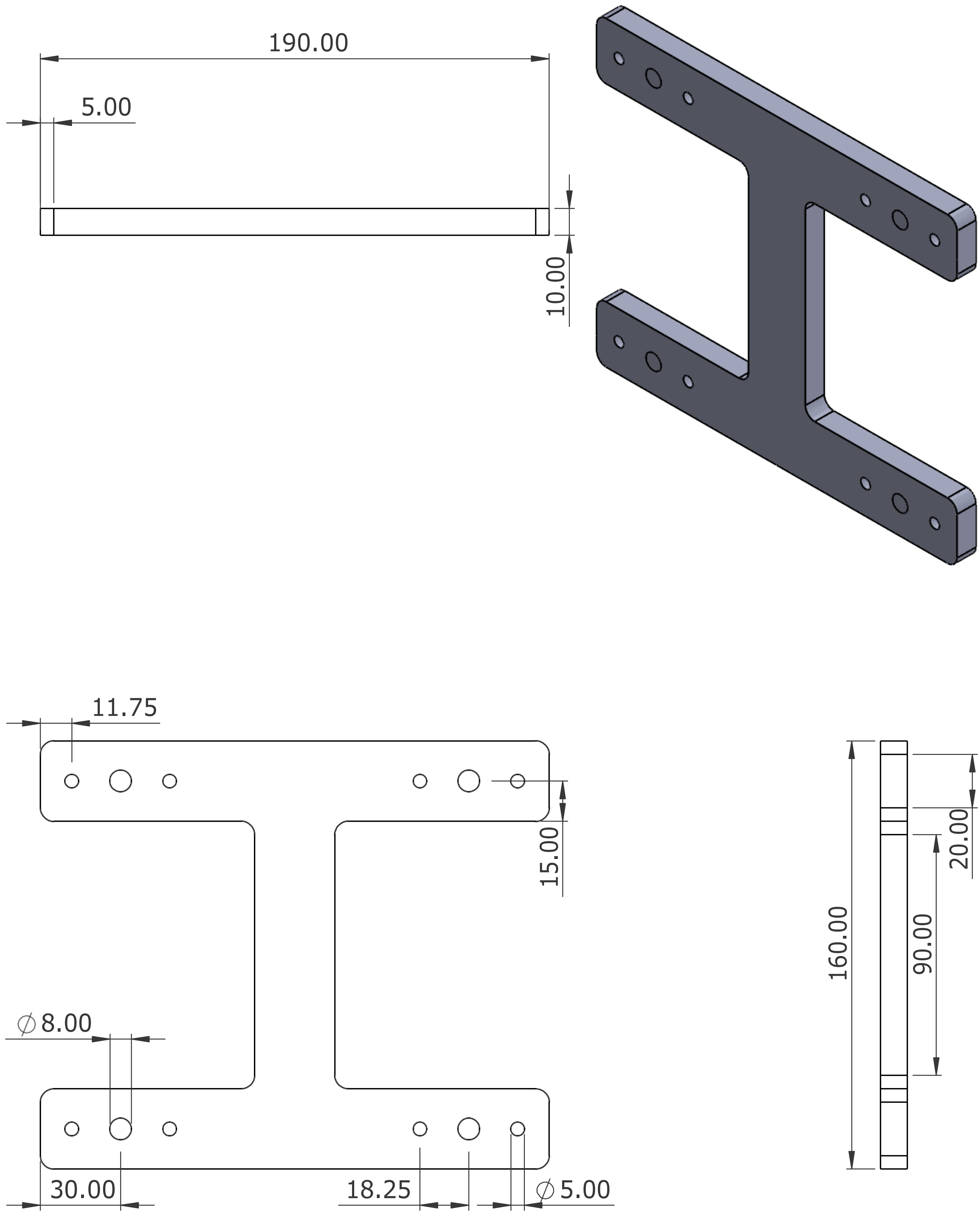




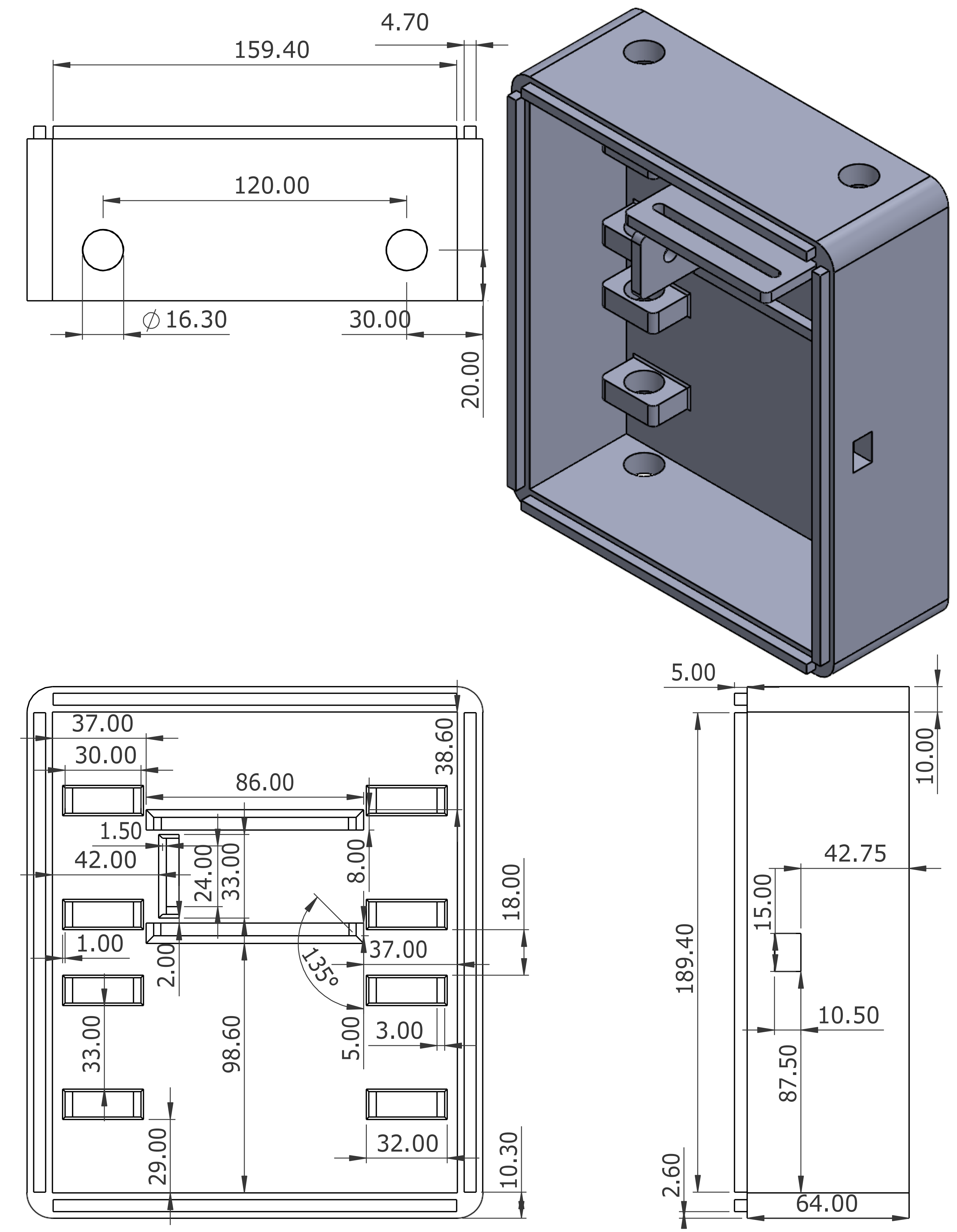




NOTAS GENERALES/GENERAL NOTES:	REGISTRO/REGISTER:	FECHA/DATE:		UNIVERSIDAD INTERNACIONAL DEL ECUADOR ESCUELA DE INGENIERIA MECATRONICA
	DIBUJANTE/DRAFTMAN: JORDY JOEL MORILLO SANCHEZ	07/24/2024		ASIGNATURA/SUBJECT: CURRICULAR INTEGRATION SEMINAR
	DISEÑADOR/DESIGNER: JORDY JOEL MORILLO SANCHEZ	09/13/2024		PROYECTO/PROYECT: AUTOMATED SHELF STORAGE AND RETRIEVAL SYSTEM
	REVISADO/REVIEWED BY: GUILLERMO ALFREDO MOSQUERA CANCHINGRE	09/13/2024		DESCRIPCION/DESCRIPTION: NEMA 17 MOTOR BASE
	APROBACION FINAL/APPROBATION BY/: GUILLERMO ALFREDO MOSQUERA CANCHINGRE	01/05/2025	TAMAÑO/PAPER SIZE: A4 ESCALA/SCALE: 1:1	DIBUJO Nº/DRAWING Nº: D01-009



NOTAS GENERALES/GENERAL NOTES:	REGISTRO/REGISTER:	FECHA/DATE:		UNIVERSIDAD INTERNACIONAL DEL ECUADOR ESCUELA DE INGENIERIA MECATRONICA
	DIBUJANTE/DRAFTMAN: JORDY JOEL MORILLO SANCHEZ	07/24/2024		ASIGNATURA/SUBJECT: CURRICULAR INTEGRATION SEMINAR
	DISEÑADOR/DESIGNER: JORDY JOEL MORILLO SANCHEZ	09/13/2024		PROYECTO/PROYECT: AUTOMATED SHELF STORAGE AND RETRIEVAL SYSTEM
	REVISADO/REVIEWED BY: GUILLERMO ALFREDO MOSQUERA CANCHINGRE	09/13/2024		DESCRIPCION/DESCRIPTION: LIFTING STRUCTURE SUPPORT
	APROBACION FINAL/APPROBATION BY/: GUILLERMO ALFREDO MOSQUERA CANCHINGRE	01/05/2025	TAMAÑO/PAPER SIZE: A4 ESCALA/SCALE: 1:2	DIBUJO Nº/DRAWING Nº: D01-010



NOTAS GENERALES/GENERAL NOTES:	REGISTRO/REGISTER:	FECHA/DATE:
	DIBUJANTE/DRAFTMAN: JORDY JOEL MORILLO SANCHEZ	07/24/2024
	DISEÑADOR/DESIGNER: JORDY JOEL MORILLO SANCHEZ	09/13/2024
	REVISADO/REVIEWED BY: GUILLERMO ALFREDO MOSQUERA CANCHINGRE	09/13/2024
	APROBACION FINAL/APPROBATION BY/: GUILLERMO ALFREDO MOSQUERA CANCHINGRE	01/05/2024

TAMAÑO/PAPER SIZE: A4
ESCALA/SCALE: 1:2

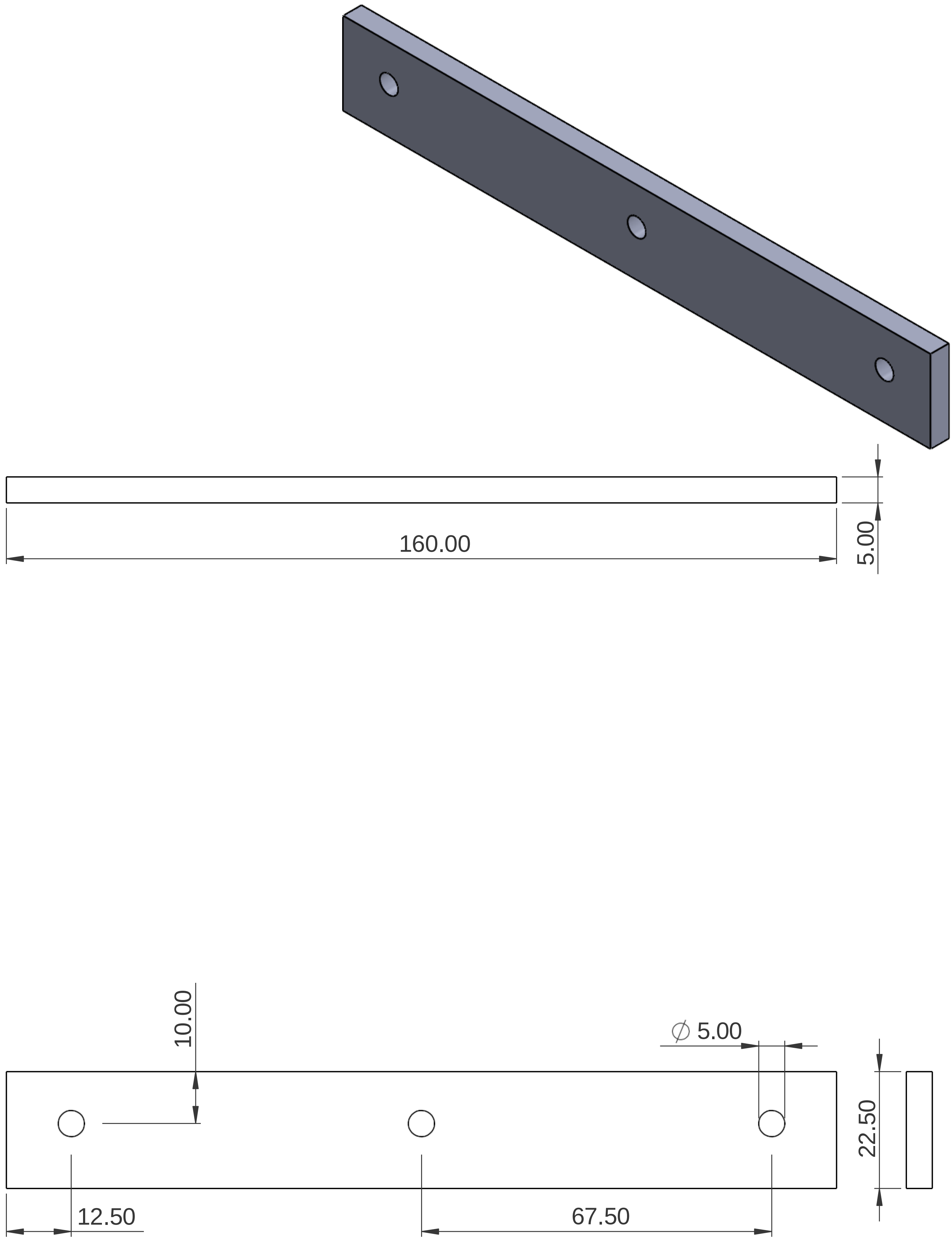
UNIVERSIDAD INTERNACIONAL DEL ECUADOR
ESCUELA DE INGENIERIA MECATRONICA

ASIGNATURA/SUBJECT: CURRICULAR INTEGRATION SEMINAR

PROYECTO/PROYECT: AUTOMATED SHELF STORAGE AND RETRIEVAL SYSTEM

DESCRIPCION/DESCRIPTION: ROBOT CAR BASE

DIBUJO Nº/DRAWING Nº: D01-011

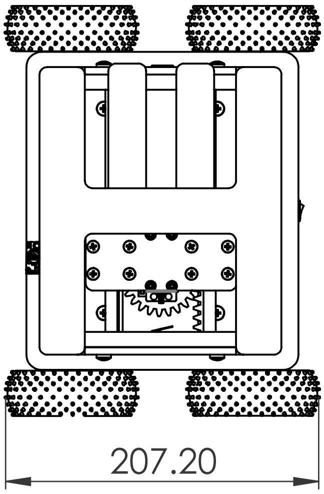


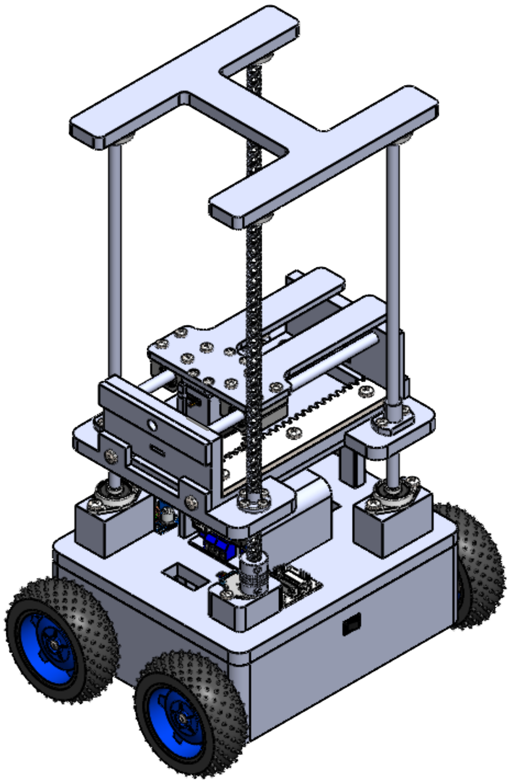
NOTAS GENERALES/GENERAL NOTES:	REGISTRO/REGISTER:	FECHA/DATE:
	DIBUJANTE/DRAFTMAN: JORDY JOEL MORILLO SANCHEZ	07/24/2024
	DISEÑADOR/DESIGNER: JORDY JOEL MORILLO SANCHEZ	09/13/2024
	REVISADO/REVIEWED BY: GUILLERMO ALFREDO MOSQUERA CANCHINGRE	09/13/2024
	APROBACION FINAL/APPROBATION BY/: GUILLERMO ALFREDO MOSQUERA CANCHINGRE	01/05/2025

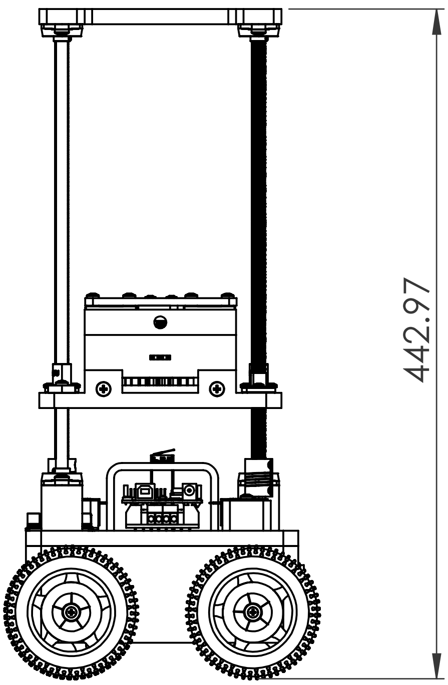
TAMAÑO/PAPER SIZE:	A4
ESCALA/SCALE:	1:1

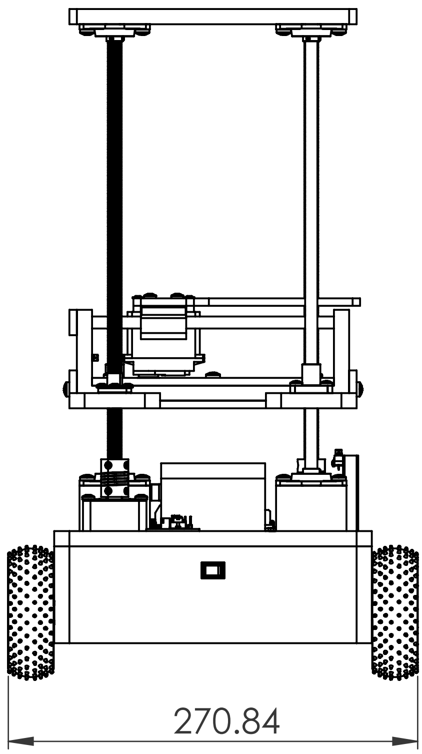
UNIVERSIDAD INTERNACIONAL DEL ECUADOR
ESCUELA DE INGENIERIA MECATRONICA

ASIGNATURA/SUBJECT:	CURRICULAR INTEGRATION SEMINAR
PROYECTO/PROYECT:	AUTOMATED SHELF STORAGE AND RETRIEVAL SYSTEM
DESCRIPCION/DESCRIPTION:	BASE COPY OF RACK FOR PINION
DIBUJO Nº/DRAWING Nº:	D01-012



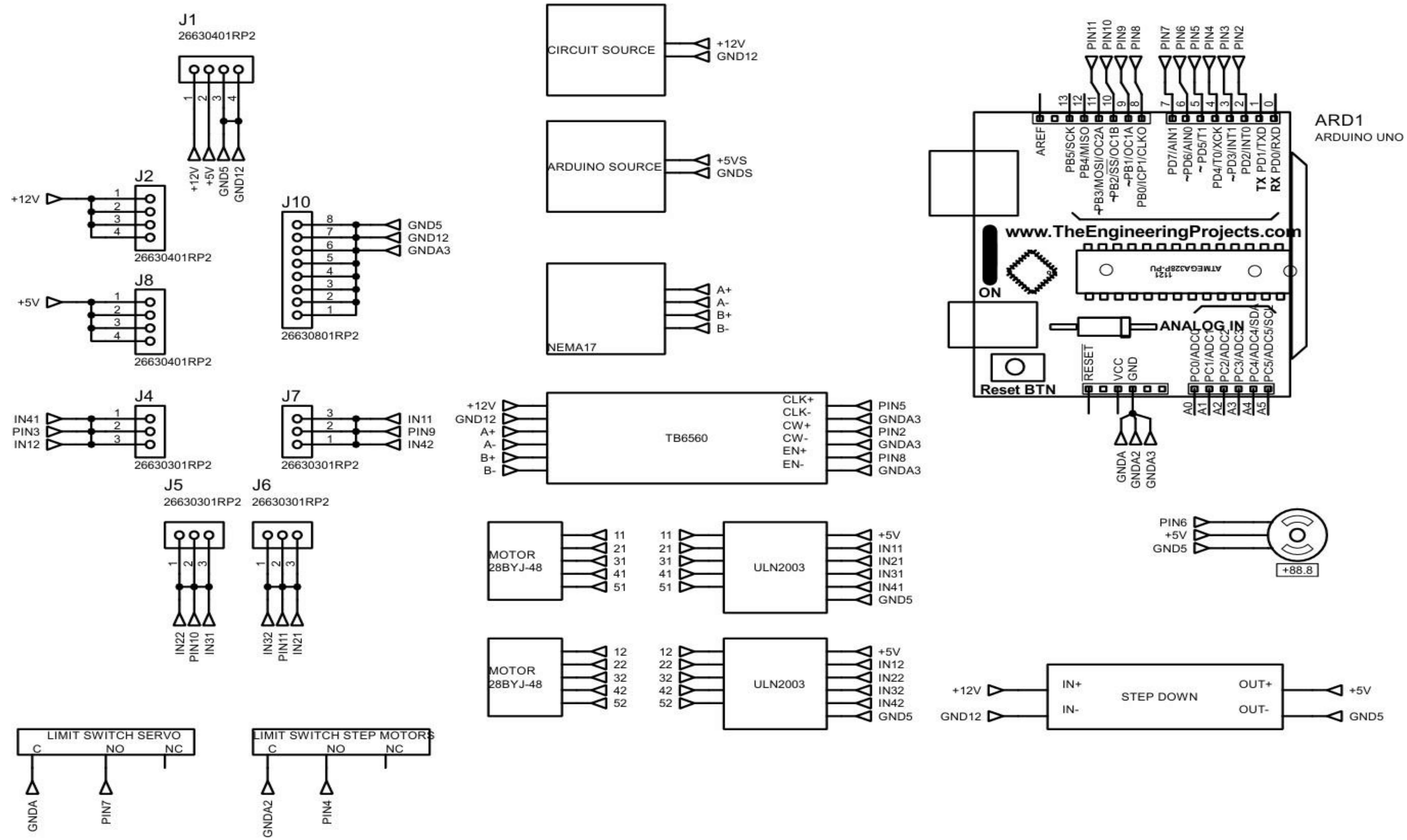






NOTAS GENERALES/GENERAL NOTES:	REGISTRO/REGISTER:	FECHA/DATE:		UNIVERSIDAD INTERNACIONAL DEL ECUADOR ESCUELA DE INGENIERIA MECATRONICA
	DIBUJANTE/DRAFTMAN: JORDY JOEL MORILLO SANCHEZ	07/24/2024		ASIGNATURA/SUBJECT: CURRICULAR INTEGRATION SEMINAR
	DISEÑADOR/DESIGNER: JORDY JOEL MORILLO SANCHEZ	09/13/2024		PROYECTO/PROYECT: AUTOMATED SHELF STORAGE AND RETRIEVAL SYSTEM
	REVISADO/REVIEWED BY: GUILLERMO ALFREDO MOSQUERA CANCHINGRE	09/13/2024		DESCRIPCION/DESCRIPTION: FINAL PROTOTYPE
	APROBACION FINAL/APPROBATION BY/: GUILLERMO ALFREDO MOSQUERA CANCHINGRE	01/05/2025	TAMAÑO/PAPER SIZE: A4 ESCALA/SCALE: 1:5	DIBUJO Nº/DRAWING Nº: D01-101

APPENDIX2. ELECTRONICS SCHEMATIC DIAGRAM.



NOTAS GENERALES/GENERAL NOTES:

PLANOS DE REFERENCIA/REFERENCE DRAWINGS:	
ITEM Nº:	DESCRIPCIÓN/DESCRIPTION:

REVISIONES/REVIEWS:					
REV.	DESCRIPCION/DESCRIPTION:	FECHA/DATE:	DIBUJADO/DRAWN BY:	REVISADO/REVIEWED BY:	APROBADO/APPROVED BY:

REGISTRO/REGISTER:	FECHA/DATE:
DIBUJANTE/DRAFTMAN: JORDY JOEL MORILLO SANCHEZ	25/11/2024
DISEÑADOR/DESIGNER: JORDY JOEL MORILLO SANCHEZ	25/11/2024
REVISADO/REVIEWED BY: GUILLERMO ALFREDO MOSQUERA CANCHINGRE	27/11/2024
APROBACION FINAL/APPROBATION BY/: GUILLERMO ALFREDO MOSQUERA CANCHINGRE	27/11/2024

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

UNIVERSIDAD INTERNACIONAL DEL ECUADOR
ESCUELA DE INGENIERIA MECATRONICA

ASIGNATURA/SUBJECT: CURRICULAR INTEGRATION SEMINAR

PROYECTO/PROYECT: AUTOMATED SHELF STORAGE AND RETRIEVAL SYSTEM

DESCRIPCION/DESCRIPTION: ELECTRICAL DIAGRAM OF THE FINAL PROTOTYPE

DIBUJO Nº/DRAWING Nº: D02-001

APPENDIX3. COST TABLE.

Item	Quantity	Unit Price ($)	Total Cost ($)
NEMA 17 with Cable	1	15.75	15.75
TB6560 3A Driver	1	12.99	12.99
5V Stepper Motor	2	2.99	5.98
ULN2003 Driver	2	1.99	3.98
Bearings	16	2.5	40
GT2 Pulley 5mm	1	2.9	2.9
GT2 Pulley 4mm	1	4	4
GT2 Timing Belt	1	2.25	2.25
Flexible Coupling	2	2.9	5.8
Worm Screw 8mm and Nut	2	12.5	25
Steel Shafts 8mm	2	8.9	17.8
Linear Bearing LMK8LUU	2	7.5	15
Linear Bearing SC8UU	2	4.5	9
Flange Bearing KFL08	6	2.99	17.94
Spiral Wrap Band (per meter)	5	0.75	3.75
MG995 Servo Motor 360 Degrees	1	12.9	12.9
Arduino R4	1	30	30
Jumpers (Pack of 40)	2	4.5	9
Wheels	4	4.5	18
Wheel Couplings	4	1.99	7.96
M5 Screws	24	0.3	7.2
M3 Screws	12	0.25	3
M4 Screws	16	0.25	4
MDF Cutting (Shelving)	1	10.5	10.5
Glue	1	3.92	3.92
Cardboard for Boxes	1	6.44	6.44
3D Printing	1	132.57	132.57
Steel Shafts 4mm	1	4.1	4.1
Step Down Converter	1	1.99	1.99
IA Service (per month)	2	20	40
12V 2.2A LiPo Battery	1	29.99	29.99
M8 Nut	1	0.4	0.4
Labor Hours	436	7.5	3270
Total	-	-	**3774.11**