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End Effector: Final Design Report

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Contents

1 Abstract

This project presents the design and implementation of a flexible robotic depalletizing system optimized for use in supermarket warehouse logistics. The system combines advanced sensing techniques with pneumatic actuation to automate the handling and unloading of boxes with varying sizes, weights, and surface textures. A key innovation is the integration of Time-of-Flight (ToF) sensors for precise box detection and angular alignment, enhancing the gripping accuracy of the End-of-Arm Tooling (EOAT). The EOAT features bellows-type vacuum suction cups powered by a pneumatic ejector system, enabling reliable lifting of uneven surfaces. A microcontroller-based firmware orchestrates the entire process, including sensor data acquisition, motor control, valve switching, and communication with the host system. The system emphasizes adaptability, real-time responsiveness, and efficient integration of mechanical and electronic subsystems to achieve high performance in automated box handling tasks.

2 System Overview

The depalletizing system is centered around a robotic arm equipped with a custom-designed end effector capable of picking up and moving boxes from pallets. The system consists of the following core components:

- **Vacuum Suction Cups:** Bellows-type suction cups made of NBR-ESD material are used to adapt to various box surfaces and ensure secure gripping.
- **Vacuum Generation:** A compact pneumatic vacuum ejector is used to generate the necessary suction force, utilizing the existing compressed air infrastructure.
- **ToF Sensors:** Time-of-Flight sensors are mounted on the EOAT to detect box presence and orientation. Two methods are used for alignment: a 64×64 pixel depth array sensor and a multi-sensor triangulation setup.
- **Microcontroller Unit:** An ATmega2560 microcontroller manages real-time control tasks including sensor communication, motor control, vacuum actuation, and data transmission.
- **Solenoid Valves:** Double solenoid 5/2 valves are used to direct airflow to pneumatic cylinders and the vacuum ejector, enabling controlled movement and suction.
- **Firmware Architecture:** The microcontroller firmware is responsible for real-time task execution, including distance filtering, alignment calculations, motor actuation, vacuum control, and communication with the PC.

The integration of mechanical and electronic subsystems results in a robust and adaptable robotic platform capable of handling depalletizing tasks with high reliability and precision, even in unstructured environments.

3 Review of Existing Products for Reconfigurable End Effector

3.1 MCS-RP Gripper Series by WSR Solutions

The MCS-RP Gripper Series by WSR Solutions offers a versatile and modular approach to robotic gripping applications. These grippers are designed to handle a wide range of part geometries and sizes, making them suitable for various industrial automation tasks.

3.1.1 Key Features

- **Modular Design:** The gripper series features a modular construction, allowing for easy customization and adaptation to different application requirements.
- **High Grip Force:** The MCS-RP grippers provide a high grip force relative to their size, ensuring secure handling of parts during automation processes.

- **Precision and Repeatability:** These grippers offer high precision and repeatability, essential for tasks requiring consistent performance.
- **Versatility:** Capable of handling various part shapes and sizes, the MCS-RP grippers are suitable for diverse applications across different industries.

3.1.2 Applications

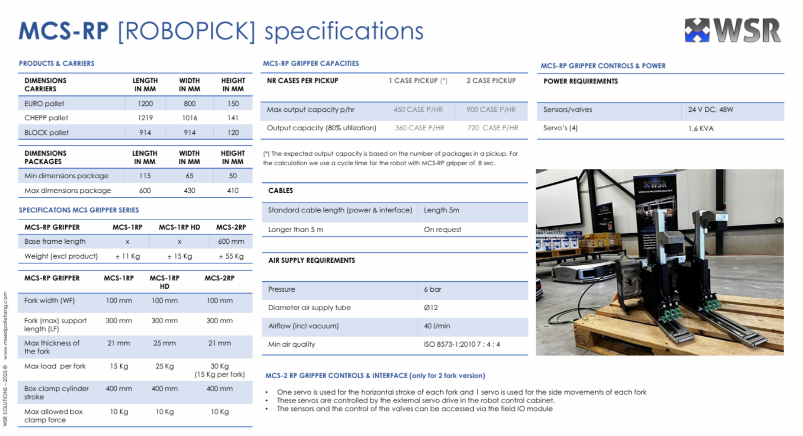
The MCS-RP Gripper Series is utilized in various industries for tasks such as:

- **Assembly Automation:** Facilitating the assembly of components in manufacturing lines.
- **Material Handling:** Efficiently moving parts within production facilities.
- **Quality Control:** Assisting in the inspection and testing of products.

3.1.3 Advantages

- **Enhanced Flexibility:** The modular design allows for quick adjustments and reconfigurations to meet changing production needs.
- **Improved Efficiency:** High grip force and precision contribute to faster and more reliable automation processes.
- **Cost-Effectiveness:** The adaptability of the grippers reduces the need for multiple specialized tools, leading to cost savings.

Figure 1: MCS-RP Gripper Series by WSR Solutions



MCS-RP [ROBOPICK] specifications

PRODUCTS & CARRIERS

DIMENSIONS CARRIERS	LENGTH IN MM	WIDTH IN MM	HEIGHT IN MM
EURO pallet	1200	800	150
CHEPP pallet	1219	1016	141
BLOCK pallet	914	914	120

DIMENSIONS PACKAGES	LENGTH IN MM	WIDTH IN MM	HEIGHT IN MM
Min dimensions package	115	65	50
Max dimensions package	600	430	410

SPECIFICATONS MCS GRIPPER SERIES

MCS-RP GRIPPER	MCS-1RP	MCS-1RP HD	MCS-2RP
Base frame length	x	x	600 mm
Weight (excl product)	± 11 Kg	± 15 Kg	± 55 Kg

MCS-RP GRIPPER	MCS-1RP	MCS-1RP HD	MCS-2RP
Fork width (WF)	100 mm	100 mm	100 mm
Fork (max) support length (LF)	300 mm	300 mm	300 mm
Max thickness of the fork	21 mm	25 mm	21 mm
Max load per fork	15 Kg	25 Kg	30 Kg (15 Kg per fork)
Box clamp cylinder stroke	400 mm	400 mm	400 mm
Max allowed box clamp force	10 Kg	10 Kg	10 Kg

MCS-RP GRIPPER CAPACITIES

NR CASES PER PICKUP	1 CASE PICKUP (*)	2 CASE PICKUP
Max output capacity p/hr	450 CASE P/HR	900 CASE P/HR
Output capacity (80% utilization)	360 CASE P/HR	720 CASE P/HR

(*) The expected output capacity is based on the number of packages in a pickup. For the calculation we use a cycle time for the robot with MCS-RP gripper of 8 sec.

CABLES	
Standard cable length (power & interface)	Length 5m
Longer than 5 m	On request

AIR SUPPLY REQUIREMENTS	
Pressure	6 bar
Diameter air supply tube	Ø12
Airflow (incl vacuum)	40 l/min
Min air quality	ISO 8573-1:2010 7 : 4 : 4

MCS-RP GRIPPER CONTROLS & POWER

POWER REQUIREMENTS	
Sensors/valves	24 V DC, 48W
Servo's (4)	1,6 KVA

MCS-2 RP GRIPPER CONTROLS & INTERFACE (only for 2 fork version)

- One servo is used for the horizontal stroke of each fork and 1 servo is used for the side movements of each fork
- These servos are controlled by the external servo drive in the robot control cabinet.
- The sensors and the control of the valves can be accessed via the field IO module

WSR SOLUTIONS – 2025 © www.mixedpalletizing.com

Figure 2: MCS-RP Gripper Series Specification

4 Stakeholder Mapping

Stakeholder mapping was carried out to identify and prioritize individuals and groups involved in the development of the reconfigurable end effector. Based on their level of influence and interest, stakeholders were categorized into four groups:

- **Manage Closely:** High influence and high interest
  Examples: Robotic engineers, warehouse operators, end users
- **Keep Satisfied:** High influence and low interest
  Examples: Regulatory authorities, procurement specialists
- **Keep Informed:** High interest and low influence
  Examples: Supermarket customers, equipment suppliers
- **Monitor:** Low influence and low interest
  Examples: Safety inspectors, academic researchers

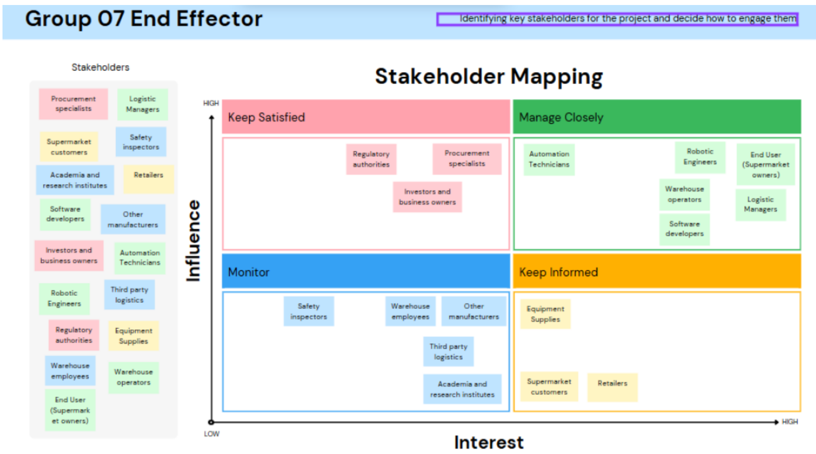


Figure 3: Stakeholder mapping

5 User Needs Analysis

An effective reconfigurable end effector for supermarket depalletizing must meet a range of user-centered requirements. These key user needs were identified based on common logistical challenges and operational demands:

- **Flexible Gripping Mechanism:** Ability to handle packages of various shapes (15–50 cm), weights (0–10 kg), and materials.
- **Dual-Sided Grasping:** Enables lifting from both top and side surfaces, which is crucial for handling stacked or irregularly shaped items.
- **Automatic Reconfiguration:** Utilizes actuated degrees of freedom to adapt the gripping strategy without requiring manual changes.
- **Safety & Stability:** Ensures safe handling of fragile or perforated packaging to avoid damage.
- **Seamless Integration with Robotic Arms:** Compatible with standard robotic systems for straightforward deployment.
- **Sensor-Driven Adaptability:** Employs Time-of-Flight (ToF) sensors and load cells for real-time object detection, weight estimation, and orientation correction.

- **Operational Efficiency:** Aims to reduce manual labor and time spent on depalletizing, improving overall logistics performance.
- **Durability & Low Maintenance:** Built to withstand frequent use in supermarkets with minimal maintenance needs.
- **Compact and Lightweight Design:** Ensures effectiveness in space-limited supermarket environments.
- **Cost-Effective Implementation:** Should be affordable and feasible for use in developing regions.

6 Conceptual Designs

6.1 Initial Sketches

The initial sketches served as a starting point for exploring different design concepts for the depalletizing system. Various ideas were considered, focusing on functionality, efficiency, and ease of integration. These sketches allowed us to visualize potential solutions and identify key features that would later be refined in the final design.

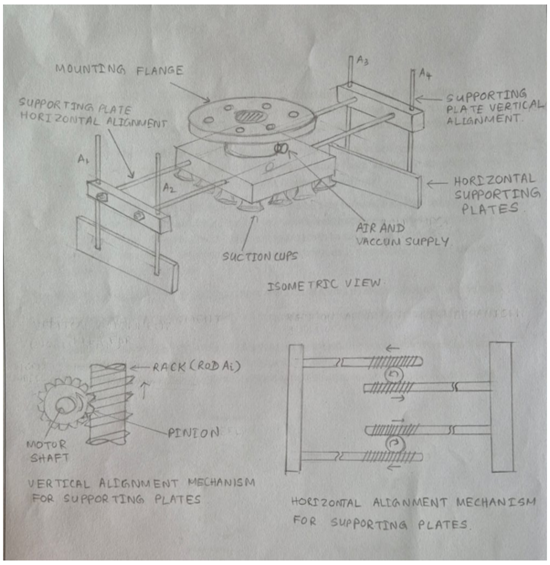


Figure 4: Conceptual Design 01

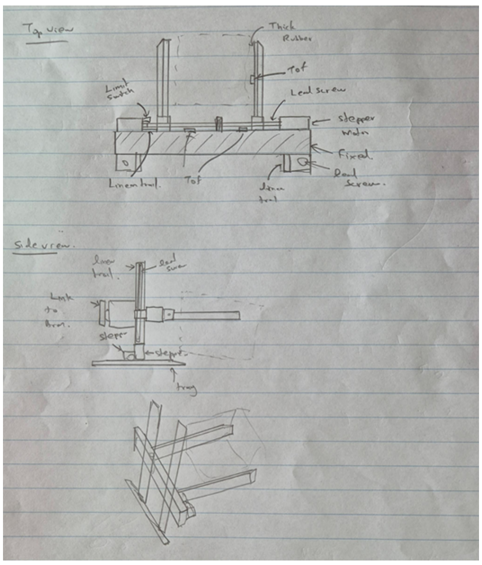


Figure 5: Conceptual Design 02

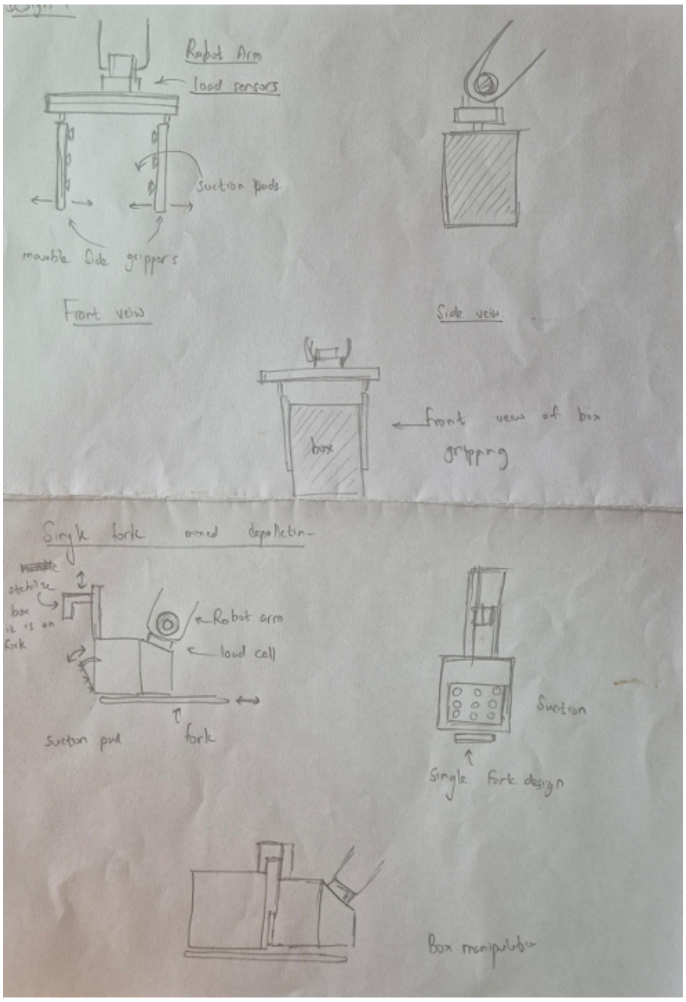


Figure 6: Conceptual Design 03

6.2 Refined Design

After evaluating and cross-pollinating the best features from several initial designs, we have created a refined conceptual sketch that incorporates the most effective elements of each. This design ensures optimal performance and reliability in depalletizing tasks.

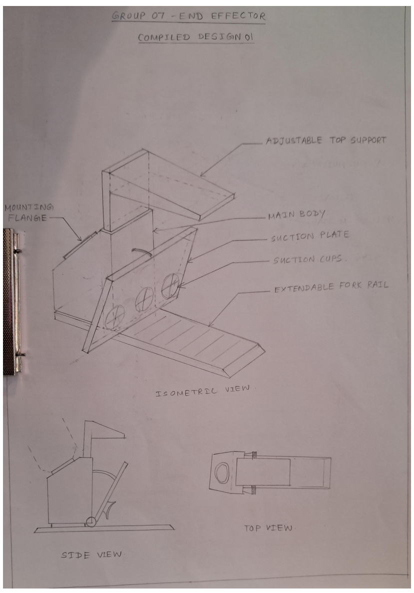


Figure 7: Final Conceptual Design

The final conceptual design features suction cups mounted vertically on a suction plate. The suction plate grips the box using the suction cups and is slightly lifted by a rodless cylinder attached to the structure. Forks are then slid under the box, and the suction plate is lowered to position the box onto the forks. To secure the box in place and prevent it from toppling, a top support is moved downward using a pneumatic cylinder, ensuring a stable grip throughout the process.

7 Functional Block Diagram

Initial Functional Block Diagram

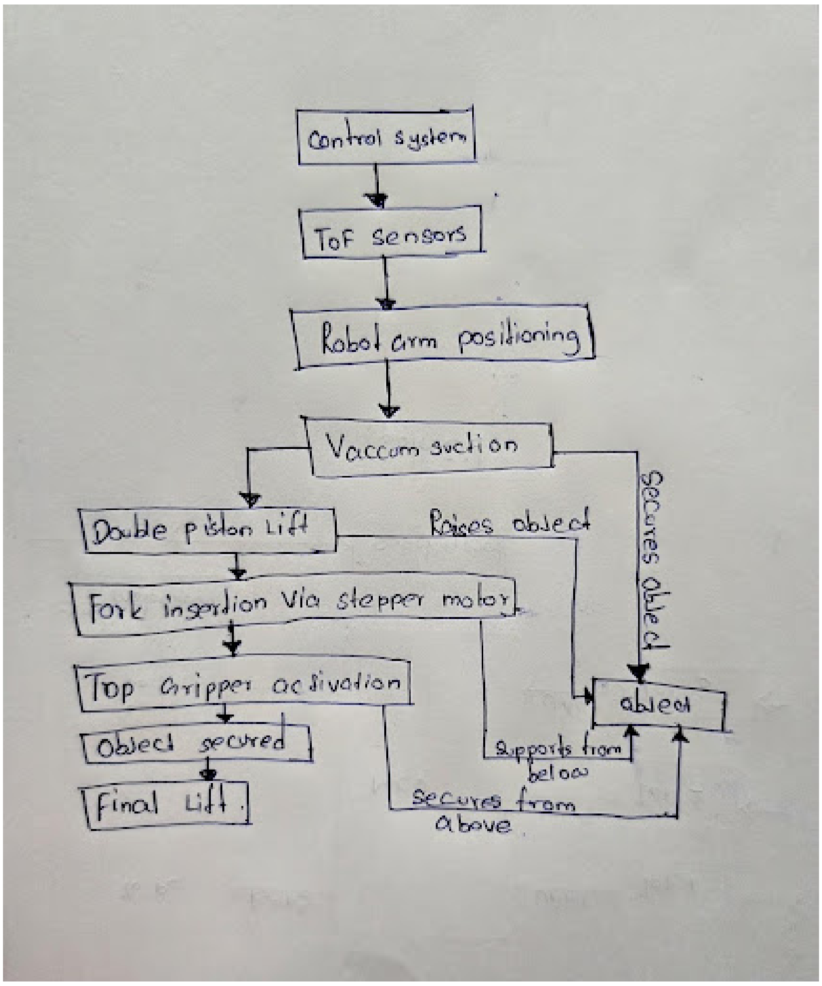


Figure 8: Functional block diagram of the End Effector

Final Block Diagram

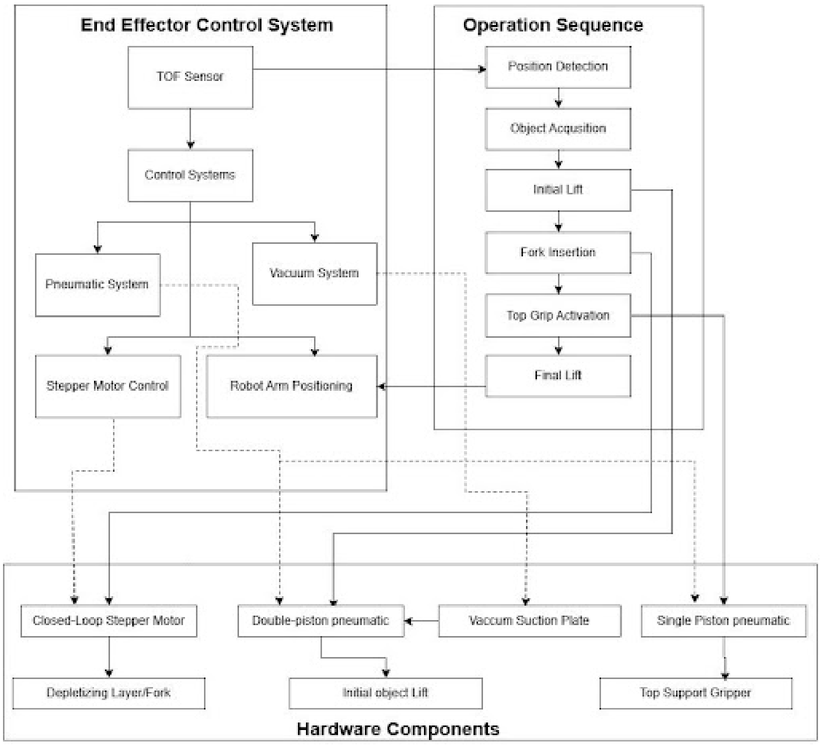


Figure 9: Functional block diagram of the End Effector

8 Component Selection

Each component in the end effector was chosen based on functionality, availability, and performance under industrial conditions. This section elaborates on the core modules.

8.1 Closed-Loop Stepper Motors and Motor Drivers

In the depalletizing robot arm end effector, a **closed-loop stepper motor** is used to insert and retract the fork mechanism. The motor is coupled to a pinion gear, which engages with a linear rack. As the motor rotates the pinion, it converts the rotary motion into linear displacement, thereby pushing or pulling the fork.

This mechanism requires **high positional accuracy** and **consistent torque delivery**, particularly under variable loads when interacting with the box in different phases of the lifting sequence. Hence, a closed-loop stepper motor was chosen to ensure reliable performance without the risk of step loss under load.

Motor Selection: 42HSE47 Closed-Loop Stepper Motor

The selected motor is the **42HSE47 closed-loop stepper motor**. Its specifications match the torque and speed demands calculated from the rack and pinion setup.

Figure 10: 42HSE47 Closed-Loop Stepper Motor

Key Specifications

- **Step Angle**: 1.8°
- **Holding Torque**: 0.6 N m
- **Rated Current**: 2.5 A
- **Encoder Resolution**: 1000 lines
- **Weight**: 0.7 kg
- **Dimensions**: 42 mm frame size (NEMA 17)

The maximum torque requirement occurs during the acceleration and deceleration phases. With a holding torque of 0.6 N m, the **42HSE47** meets the expected requirements with a small margin, supporting safe and consistent operation.

Product details: `http://www.chinajingbo.com/en/product-detail/53ad564283dd4fe4a286167c54d5ea03#content`

Motor Driver Selection: HSE42 Closed-Loop Stepper Driver

The **HSE42 driver** is selected as it is designed to match the 42HSE47 motor and offers extensive control features.

Figure 11: HSE42 Closed-Loop Stepper Driver

Key Specifications

- **Input Voltage Range**: 24–80 VDC
- **Output Current**: 0–6.0 A
- **Pulse Frequency**: Up to 200 kHz
- **Microstepping**: 200 to 51200 steps/rev
- **Feedback Input**: Encoder A+/A, B+/B
- **Feedback Control Modes**: Position, Velocity
- **Protections**: Overcurrent, Overvoltage, Overheat, Tracking error

Features

- Built-in position and speed control mode
- Encoder feedback for real-time position correction
- Electronic gear ratio configuration for flexible control
- Digital display and buttons for easy tuning and diagnostics

Product details: `http://www.chinajingbo.com/en/product-detail/2ebcdfe755f244b8b62cabf932c3272a`

8.2 Pneumatic Cylinders

Pneumatic cylinders are integrated into two key areas of the End-of-Arm Tooling (EOAT) system of the depalletizing robot arm. These components play an essential role in both gripping and stabilizing operations during box manipulation.

First, the pneumatic cylinders are used to lift the vacuum gripper plate when they are gripping the boxes by the vacuum grippers in the initial stages of the box holding.

The second instance the pneumatic cylinders are used is to stabilize the box on the arm and avoid the boxes being toppled over the fork during the box moving phase.

1. Vacuum Gripper Plate Lifting Mechanism – TN10X50

In the initial phase of gripping, pneumatic cylinders are used to lift the vacuum gripper plate after the vacuum grippers have engaged with the box surfaces. This movement ensures secure lifting and reduces any shear force acting on the suction cups during detachment.

After evaluating multiple cylinder types—such as single/double rod cylinders, linear actuators, and rodless cylinders—the Dual Rod Double Acting Cylinder TN10X50 was selected. This choice was guided by considerations of size constraints, required degrees of freedom, load requirements, and mounting compatibility.

Selected Cylinder: Airtac TN10X50

- **Bore size**: 10 mm
- **Stroke**: 100 mm
- **Acting**: double acting
- **Operating Pressure**: 0.1 - 10 MPa
- **Mounting**: Mounting Holes
- **Cushioning**: Bumper

- **Rod end**: mounting holes

Figure 12: Airtac TN10X50 Pneumatic cylinder

The dual-rod configuration provides enhanced stability and reduces piston deflection during actuation, which is crucial for the vertical lifting motion of the gripper plate.

Data sheet: `https://airtacmalaysia.com/wp-content/uploads/media_uploads/TN-series.pdf`

2. Box Stabilizing Mechanism – MAL16X100-S

The second application of pneumatic actuation is in the box stabilization mechanism. During transport, especially in dynamic motion phases, there is a risk of the box toppling forward or backward on the fork. A pneumatic stabilizer ensures lateral constraint to prevent such occurrences.

While performance analysis indicated that a rodless cylinder would offer an optimal motion profile and compactness, budgetary constraints necessitated a more cost-effective solution. The chosen alternative was the MAL16X100-S Double Acting Cylinder, which balances functionality and affordability.

Selected Cylinder: Airtac MAL16X100-S

Figure 13: Airtac MAL16X100-S Pneumatic cylinder

- **Bore size**: 16 mm
- **Stroke**: 100 mm
- **Acting**: double acting
- **Operating Pressure**: 0.1 - 10 MPa

- **Mounting**: Rear clevis for pivoting + male mounting thread
- **Cushioning**: Bumper
- **Rod end**: Male thread for connection

Data sheet: `https://airtacmalaysia.com/wp-content/uploads/media_uploads/MAL-series.pdf`

8.3 Vacuum Suction Cups

In the vacuum system, there are a few main components: vacuum suction cups, which act as the interface between the workpiece and the vacuum system; vacuum generator; switching and valves; mounting elements and connectors.

Vacuum suction cups are attached to the end effector to grip the workpiece while the initial lifting is handled. To securely grip the workpiece, depalletizing boxes with varying surfaces and textures, we selected a bellows-type suction cup, which is optimized for adaptability and reliability. The **FSG 20 NBE-ESD-55 M5-AG** suction cup by Schmalz was chosen due to its ability to handle uneven surfaces, making it ideal for the application of depalletizing in supermarket warehouses.

> "Bellows suction cups with a round shape are particularly suited for handling uneven and arched workpieces. Bellows suction cups are used if you need to handle workpieces with different heights, uneven surfaces or even fragile parts. Bellows suction cups of these series cover a wide range of applications. Their optimized design and the fact that they are available in different diameters and materials makes flat suction cups of these series perfect all-rounders." - Schmalz

Figure 14: Vacuum suction cups for object gripping

- **Size**: 20 mm diameter
- **Material**: Nitrile rubber NBR-ESD with 55 Shore A hardness
- **Design**: 2.5 fold bellows with 9 mm stroke
- **Mounting**: M5 Male thread (M5-M) aluminium nipple
- **Suction force**: 5.20 N at -0.6 bar vacuum
- **Pull-off force**: 12.10 N
- **Hose diameter**: 2 mm (for hose length of 2 m)
- **Weight**: 3.3 g

This suction cup offers a compact and robust design that integrates easily into our end effector system, ensuring stable gripping during the complete robot arm movement.

Download datasheet: `https://www.schmalz.com/en/product/10.01.06.04345/download`

8.4 Vacuum Ejectors

The vacuum is generated either pneumatically by ejectors or electrically by pumps or blowers. For our design, we selected a vacuum ejector to utilize the pneumatic system that is already being used in pneumatic cylinders for vertical motion.

The requirements for the ejector are to work under 8 bar input pressure, provide -0.6 bar vacuum level, and sufficient output flow for the suction cups. **SCPS 07 M G02 NC M12-5 PNP** from Schmalz is best suited for the design. However, due to budget constraints, **AZH10BS-06-06** from Airbest is selected, which also satisfies all the requirements for the vacuum system.

Figure 15: AZH10BS-06-06 Vacuum ejector to create suction force

- **Nozzle diameter:** 1 mm
- **Shape:** Box type
- **Air supply port:** 6 mm
- **Vacuum port:** 6 mm
- **Rated air supply pressure:** 4.5 bar
- **Maximum vacuum level:** -88 kPa (High vacuum level)
- **Maximum vacuum flow:** 12 NL/min
- **Air consumption:** 23.5 NL/min
- **Noise level:** 68 dB
- **Working temperature:** 5–50 °C
- **Weight:** 28 g

Datasheet: AZH Series Vacuum Generator PDF

8.5 Solenoid Valves

Solenoid valves control the flow of compressed air to pneumatic components and the vacuum ejector. They are electromechanically operated using electrical signals to switch the position of internal spools and direct air to desired ports.

Solenoid valves are mainly of two types: **single solenoid** and **double solenoid**. A single solenoid has one coil and uses a spring to return the valve to its default position when power is removed; they are commonly used where a default is preferred and for quick actions. A double solenoid has two coils and remains in its last switched state when power is switched off until the other coil is energized. This is ideal for applications where both positions should be held for prolonged durations, thus being more power-efficient.

For our design, we selected a **5/2 double solenoid valve**—featuring five ports and two positions. It allows precise control of double-acting pneumatic cylinders, enabling both extension and retraction using separate signals without relying on spring return.

Figure 16: Solenoid valves for air path control

8.6 Fork

To achieve precise and smooth linear motion for the fork of our end effector, we selected a **linear rail guide combined with a rack-and-pinion mechanism**. The linear rail ensures **high rigidity and low-friction guidance**, which is essential for accurate alignment and stability when lifting or placing objects. Its compact form factor and load-bearing capability make it ideal for space-constrained robotic applications, especially in end effectors that require consistent repeatability.

We initially designed using a single linear guide rail on one end and the rack on the other end. While this design works, it can be less steady and may give rise to bending moments when an uneven distribution of weight is placed on the fork.

Therefore, we incorporated two rails on either end with the rack being set in the center. This configuration provides a balanced and steady foundation for the fork, improving structural integrity and smooth motion.

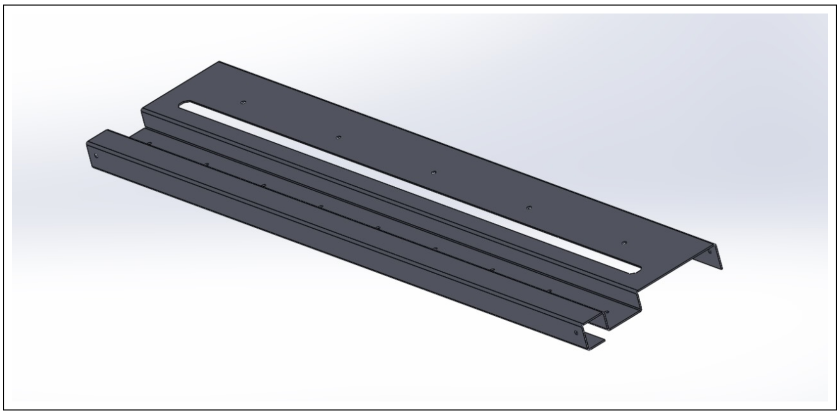


Figure 17: Fork-type linear actuator with a single rail

8.7 Rack and Pinion Mechanism

The **rack-and-pinion system** complements the fork by converting rotational motion from a motor into linear movement of the fork. This setup offers **excellent mechanical advantage**, enabling quick response and reliable control over the fork's motion without slippage, which is common in belt-driven or friction-based systems. Additionally, gear-driven systems are **less sensitive to dust or wear**, increasing durability in industrial-like environments.

Moreover, this design simplifies maintenance and allows easy tuning of speed and force by adjusting gear ratios. This modularity and robustness make the linear rail and rack-and-pinion mechanism an optimal choice for the controlled and reliable actuation of the end effector's fork.

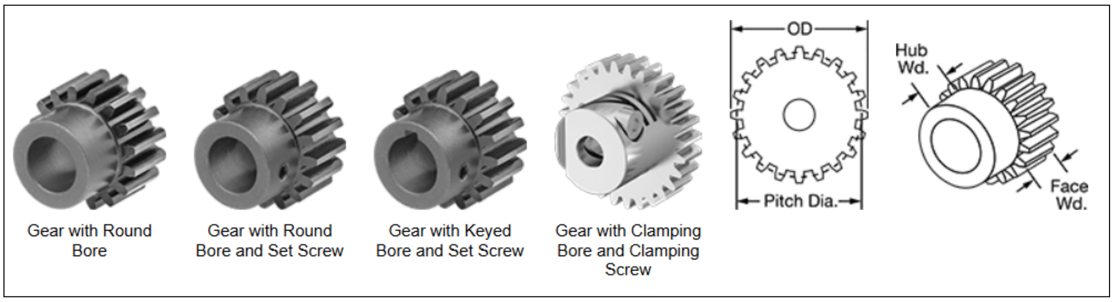


Figure 18: Metal gears used in rack-and-pinion mechanisms

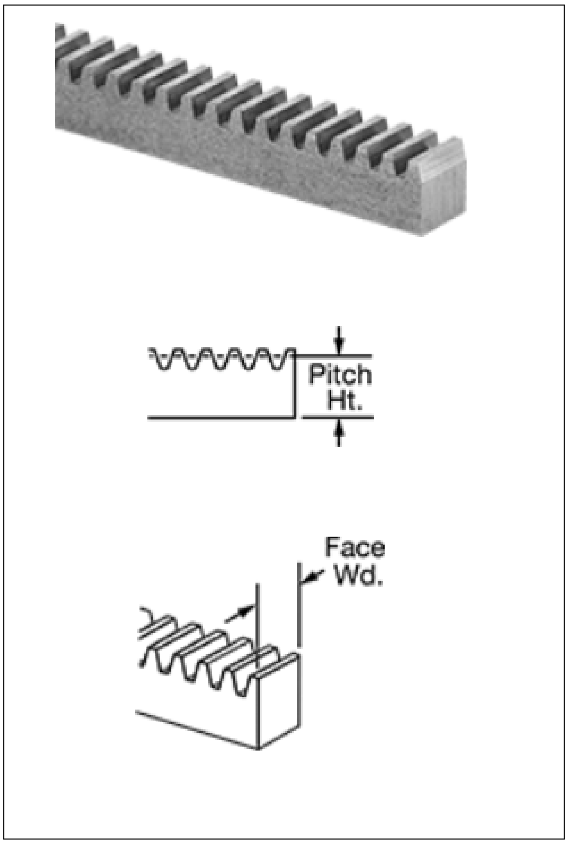


Figure 19: Metal racks corresponding to pinion gears

Gear and Rack Selection for Fork Mechanism

Below is the detailed analysis and justification for the component selection.

8.7.1 System Requirements

- **Payload:** 1 kg (500 g with 100% tolerance)
- **Stroke length:** 500 mm (0.5 m)
- **Mounting orientation:** Horizontal
- **Desired mechanism:** Rack and pinion with linear rail guide
- **Safety factor:** 1.5 (to account for friction and uncertainty)

8.7.2 Force Calculation

We assume a modest acceleration of $a = 0.5\,\text{m/s}^2$ to overcome inertia. The force required to move the load is given by:

$$F = m \cdot a = 1 \cdot 0.5 = 0.5\,\text{N}$$

Applying a safety factor of 1.5:

$$F_{\text{required}} = 0.5 \cdot 1.5 = 0.75\,\text{N}$$

To be conservative, we round up and use $F = 1\,\text{N}$ as the required linear force.

8.7.3 Torque Requirement at Pinion

Assuming a pinion with a pitch diameter of $D = 20\,\text{mm}$, the radius is:

$$r = \frac{D}{2} = 10\,\text{mm} = 0.01\,\text{m}$$

The torque required at the gear is:

$$\tau = F \cdot r = 1 \cdot 0.01 = 0.01\,\text{Nm} = 10\,\text{Ncm}$$

8.7.4 Rack and Pinion Geometry

We select a standard module $M = 1\,\text{mm}$. Choosing a pinion with 20 teeth:

$$\text{Pitch Diameter} = z \cdot M = 20 \cdot 1 = 20\,\text{mm}$$

$$\text{Linear Travel per Revolution} = \pi \cdot D = \pi \cdot 20 \approx 62.8\,\text{mm}$$

For a stroke length of 500 mm:

$$\text{Required Revolutions} = \frac{500}{62.8} \approx 7.96 \approx 8\,\text{turns}$$

8.7.5 Selected Components

- **Pinion Gear:**
  - Module: 1 mm
  - Teeth: 20
  - Pitch Diameter: 20 mm
  - Bore: To match motor shaft (keyed or clamping type recommended)
- **Rack:**
  - Module: 1 mm
  - Face width: $\geq$ 10 mm
  - Length: 500 mm

8.8 ToF Sensors

Time-of-Flight (ToF) sensors are used to detect the presence of boxes and to measure the angle relative to the box. This capability is essential to align the end effector perpendicular to the boxes, ensuring higher gripping accuracy. The sensor was chosen based on its short minimum range, high resolution, and support for well-documented communication protocols.

Based on these requirements, we selected the **TOFSense-UART** sensor by Noop-Loop, which offers the following features:

- Measuring scope: **1 cm – 5 m**

- Adjustable field of view (FOV): **15–27°**
- Resolution: **1 mm**
- Cascade: **8 UART**
- Power supply: **3.7–5.2 V** with anti-reverse protection
- Power consumption: **290 mW**
- Communication: **UART at 115200 baud**
- Weight: **2.7 g**

Figure 20: ToF sensor used for object detection and height measurement

8.9 Microcontroller Unit (MCU)

The microcontroller serves as the central processing unit in our system, managing data acquisition, processing, and communication with the external computer. It is optimized for reliable real-time data handling, ensuring continuous availability for analysis. Additionally, it requires multiple independent UART channels for reliable communication with ToF sensors.

We selected the **ATmega2560** for its robust performance and versatility in both industrial and consumer applications. With a 16 MHz clock speed, it offers sufficient processing power for handling sensor data and control logic. The microcontroller provides 256 KB of Flash memory for program storage and 8 KB of SRAM for data storage, supporting complex algorithms and data structures.

Key Features of ATmega2560

- **Performance and Connectivity:** Operates at 16 MHz with 256 KB of Flash memory and 8 KB of SRAM. Supports UART (4 independent channels), SPI, I^{2}C, and other communication interfaces for integration with various sensors and peripherals.
- **Built-in Peripherals:** Includes 86 programmable GPIO pins, enabling versatile configuration for interfacing with sensors, actuators, and other external devices. This flexibility is essential for tailoring applications to specific project requirements.
- **Development Support:** Fully supported by the Arduino IDE and a wide range of community libraries, which streamline development and prototyping. Arduino libraries provide ready-to-use functions for quick implementation.
- **Reliability and Cost-effectiveness:** Known for its reliability, ease of use, and cost-effectiveness, the ATmega2560 is ideal for applications requiring both stability and affordability.

Figure 21: Microcontroller managing the system

In summary, the ATmega2560 microcontroller is a dependable choice for projects requiring reliable data processing, versatile connectivity, and robust performance in embedded systems. Its extensive community support and rich ecosystem of libraries contribute to accelerated development cycles and deployment of applications across various domains.

9 Sensor Integration

ToF Sensor-Based Alignment System for EOAT

To ensure accurate alignment of the End-of-Arm Tooling (EOAT) with the target box, Time-of-Flight (ToF) sensors are employed as the primary external environment sensing devices. These sensors enable the robot arm to detect the presence and orientation of the box before engaging with it, significantly improving the success rate of gripping and lifting operations.

ToF Sensor Functions

- **Presence Detection:** ToF sensors detect the existence of a box in the robot's field of operation.
- **Alignment Assistance:** They help ensure that the EOAT aligns correctly with the box face, minimizing positional errors during pickup.

Alignment Strategy

To accurately determine the orientation of the box surface, two methods are being explored:

Method 1: ToF Sensor with 64×64 Distance Array

This method involves the use of a ToF sensor module that outputs a 64×64 pixel distance array (e.g., a depth map). The depth map provides spatial distance information across the field of view.

Process Overview:

1. Extract the distance values from the 2D depth array.
2. Use edge detection or thresholding techniques to identify the 4 edges of the box.
3. Apply basic triangulation on the edge distances to compute the relative surface angle of the box.

This method is data-rich and allows precise angular estimation but requires significant processing power for real-time analysis.

Method 2: Multi-Sensor Triangulation (4 ToF Sensors)

The second approach uses four individual, front-facing ToF sensors, each mounted at fixed known positions on the EOAT.

Process Overview:

1. Each sensor provides a single-point distance measurement.
2. The four distances are used in a triangulation algorithm to calculate the relative tilt or rotation angle of the box surface.

This method is computationally lighter and easier to implement in embedded systems but may be less accurate in complex surface geometries or noisy environments.

10 Microcontroller Firmware

Microcontroller Firmware Functionality

The microcontroller firmware acts as the core control logic for the system, responsible for interfacing with sensors, actuators, and communication with the PC. It is designed to operate in real-time, executing a sequence of tasks that ensure coordinated and reliable operation of the full mechanical system.

Key Responsibilities

1. **Sensor Data Acquisition and Filtering:**
   The MCU communicates with four Time-of-Flight (ToF) sensors using its four independent UART channels. These sensors provide continuous distance measurements which are unpacked, filtered, and processed to calculate the relative angle between the end effector and the box surface. This angular information is critical for aligning the robot arm such that the end effector approaches the box perpendicularly.
2. **Motor Actuation and Feedback Processing:**
   The microcontroller interfaces with a motor driver to control the motor responsible for extending the rails that support the box. PWM signals are generated by the MCU to manage motor speed and direction. It also receives feedback signals from the motor, which are used to move between various states of the gripping and release sequences.
3. **Valve Switching and Vacuum Control:**
   Control of pneumatic and vacuum components is handled via GPIOs, enabling the microcontroller to:
   - Activate solenoid valves to control airflow.
   - Engage vacuum ejectors to create suction for the lifting mechanism.
   - Operate top support arms for box stabilization.

   Each valve or actuator is triggered based on sensor inputs and task state, enabling precise timing in sequences like suction engagement, lift, and box release.
4. **Serial Communication with Host System:**
   The microcontroller also maintains a serial communication link with the host PC that controls the robot arm. Through this interface, it can transmit angle data in real-time.

11 Schematic Design

11.1 Circuitry Design Rationale

This subsection provides a detailed justification for the schematic design, focusing on the selection and implementation of critical circuit blocks, their functionality, and their alignment with system requirements.

11.1.1 Communication Interfaces

Communication interfaces were designed to ensure reliable data transfer between the microcontroller unit (MCU), peripherals, and external systems, supporting real-time control and feedback.

USB-to-TTL Interface A USB-to-TTL converter, implemented using the CH340G chip, facilitates MCU programming and serial communication. The CH340G was selected for its cost-effectiveness, wide availability, and dependable USB-to-serial conversion. It operates with a 12 MHz external crystal oscillator, paired with decoupling capacitors to suppress noise. Additionally, this circuit supplies power to the PCB via the USB connection, simplifying power management by reducing the need for an external power source.

RS485-to-TTL Interface For robust, long-distance communication, the MAX485 chip was chosen for UART-to-RS485 conversion. RS485's differential signaling and noise immunity make it ideal for industrial settings, supporting continuous data transfer from Time-of-Flight (ToF) sensors to the PC for real-time position feedback. The MAX485 was selected for its compact size, low power consumption, and compatibility with the system's communication needs.

SPI Interface The Serial Peripheral Interface (SPI) was implemented for high-speed, synchronous communication with high-bandwidth peripherals such as external ADCs or memory modules. The ATmega2560's dedicated SPI pins are routed to headers J3A and J3B, providing a standardized interface for SPI-compatible devices. This design ensures flexibility for future expansions or modifications, leveraging SPI's high data throughput and reliability.

11.1.2 Connectors

Connectors were selected to ensure secure, reliable connections between the PCB and external components, supporting both data transfer and power delivery.

ToF Sensor Connectors The ToF sensors are connected via JST BM04B-GHS headers, chosen for their compact footprint and secure locking mechanism. These headers interface directly with the ATmega2560's UART pins, ensuring dependable data transfer for accurate positioning feedback critical to the system's operation.

Stepper Motor Connector A 10-position connector was implemented for the stepper motor, supporting closed-loop control. This connector provides dedicated lines for power, ground, and control signals, designed to handle the motor's high current demands while ensuring stable and reliable performance during operation.

11.1.3 Solenoid Driver Circuitry

The solenoid drivers utilize N-channel MOSFETs (IRLR type) paired with SS34 Schottky diodes for flyback protection. These components were chosen for their low on-resistance, high current handling (up to 1A at 24V), and fast switching speeds, which are essential for precise solenoid actuation. Each solenoid (Solenoid 1-5) is driven by dedicated MCU pins, with current-limiting and pull-down resistors to ensure defined behavior and protect the circuit during operation.

11.1.4 Power Supply Design

The power supply design ensures a stable voltage for the system, addressing the ATmega2560's 5V requirement while managing input from a 24V source.

Buck Converter Implementation A 24V-to-5V step-down buck converter, based on the LM2678S-5.0, was implemented on a separate PCB dedicated to power regulation. This regulator was selected for its high efficiency (up to 92), 5A output capability, and fixed 260 kHz switching frequency, which minimizes component size and heat dissipation. The design includes input capacitors (15µF), an output inductor (22µH), a Schottky diode (VS-6TQ045STRR), and output capacitors (180µF each) to reduce ripple and ensure stable operation. This separate PCB isolates power regulation from the main board, enhancing thermal management and simplifying maintenance. The design follows the standard application circuit outlined in the Texas Instruments LM2678S-5.0 datasheet, ensuring optimal performance.

MCU Clock Circuitry A 16 MHz crystal oscillator (ABM8AIG-16.000MHZ) provides the ATmega2560's clock signal, supported by 100 nF capacitors to filter noise and stabilize timing. This setup ensures precise clocking for the MCU, critical for synchronous operations and communication interfaces.

11.2 Schematics

11.2.1 Overview

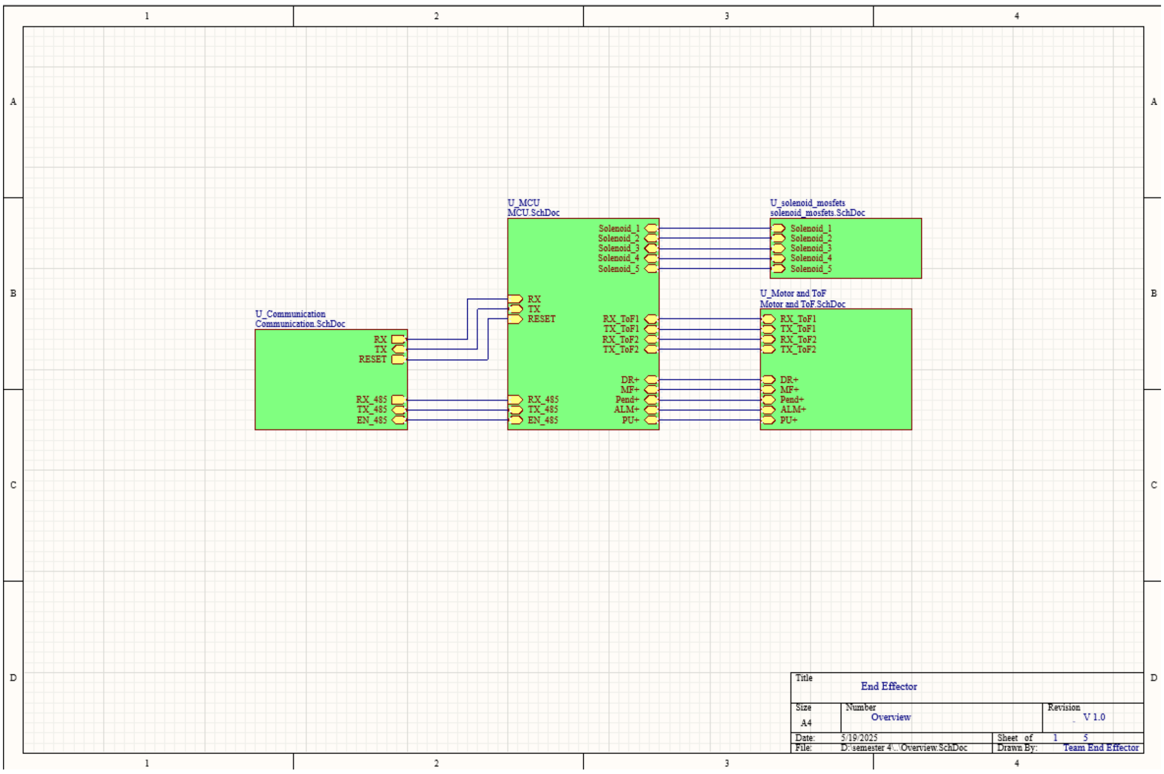


Figure 22: System Overview

11.2.2 Micro Controller Unit (ATMEGA2560)

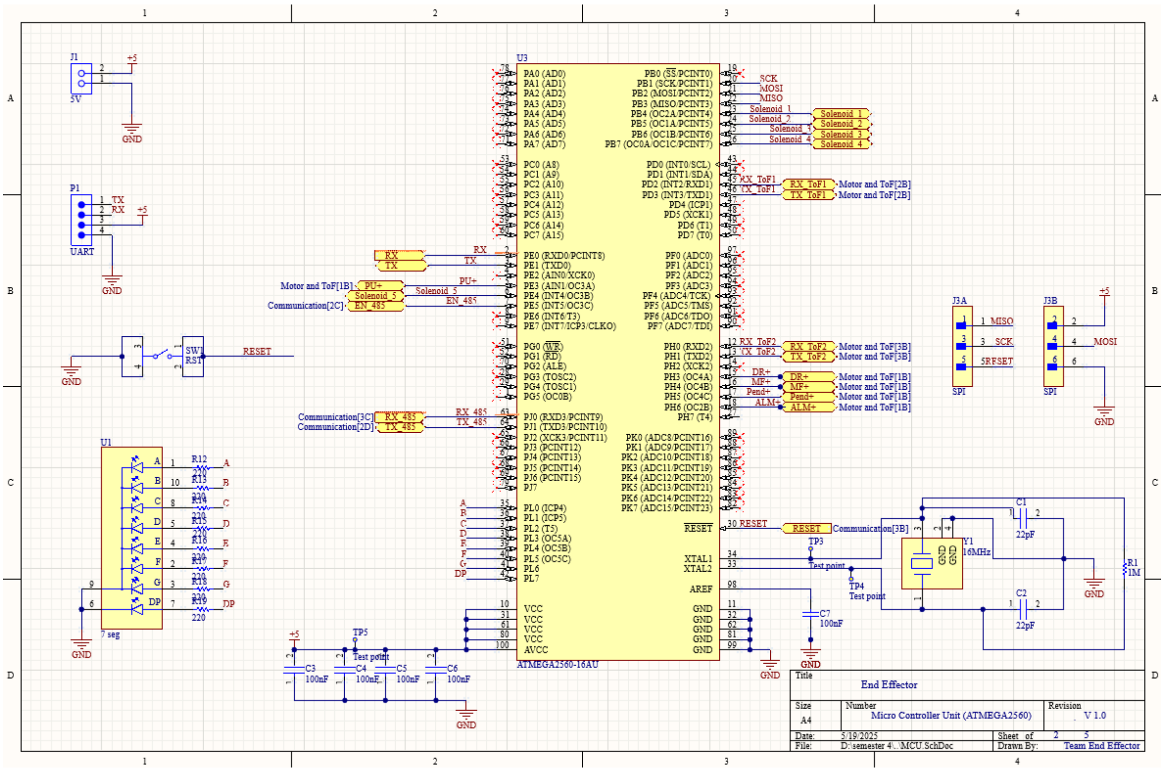


Figure 23: Micro Controller Unit (ATMEGA2560)

11.2.3 Motor and ToF headers

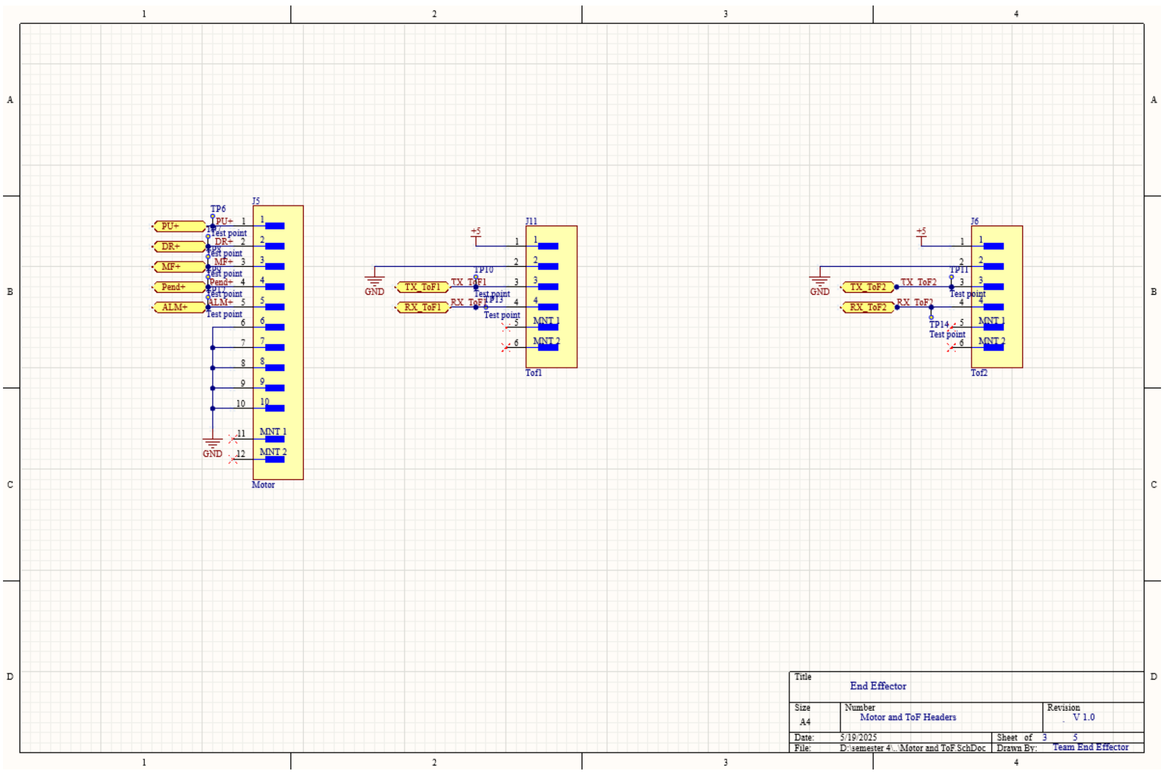


Figure 24: Motor and Tof Headers

11.2.4 Switching Circuitry for Solenoids

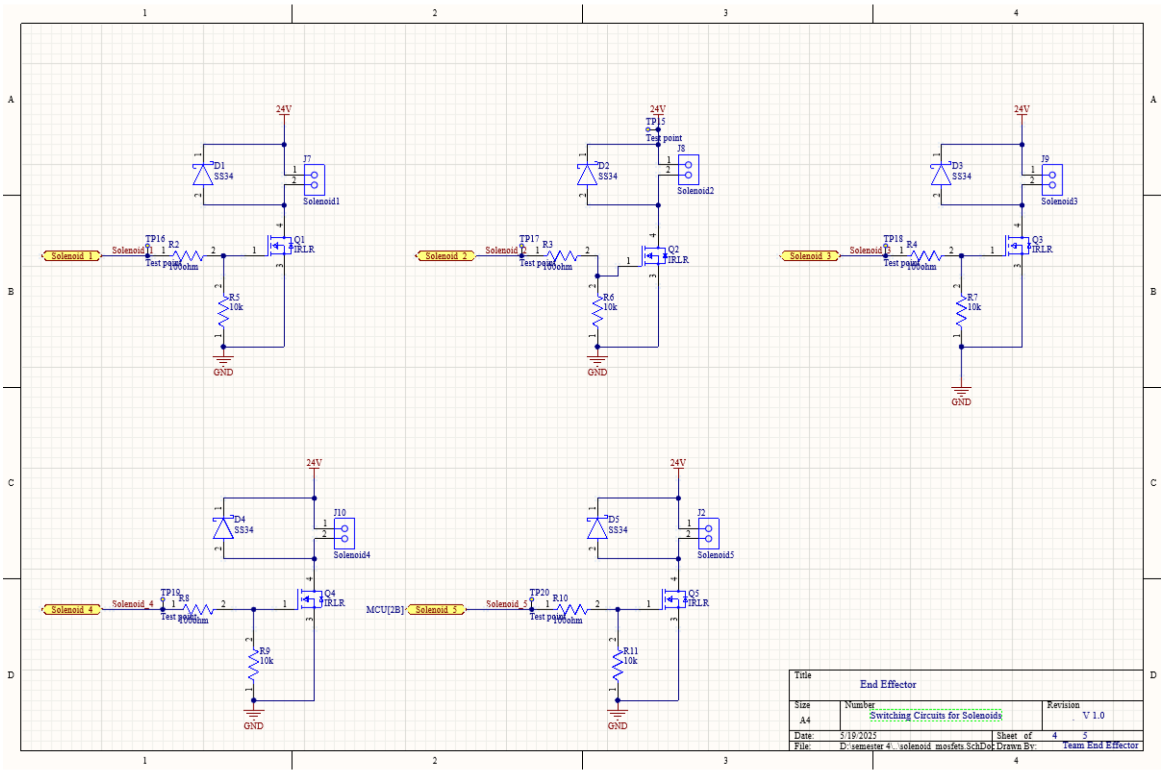


Figure 25: Switching circuitry for solenoids

11.2.5 USB-TTL and RS485-TTL Programming Interfaces

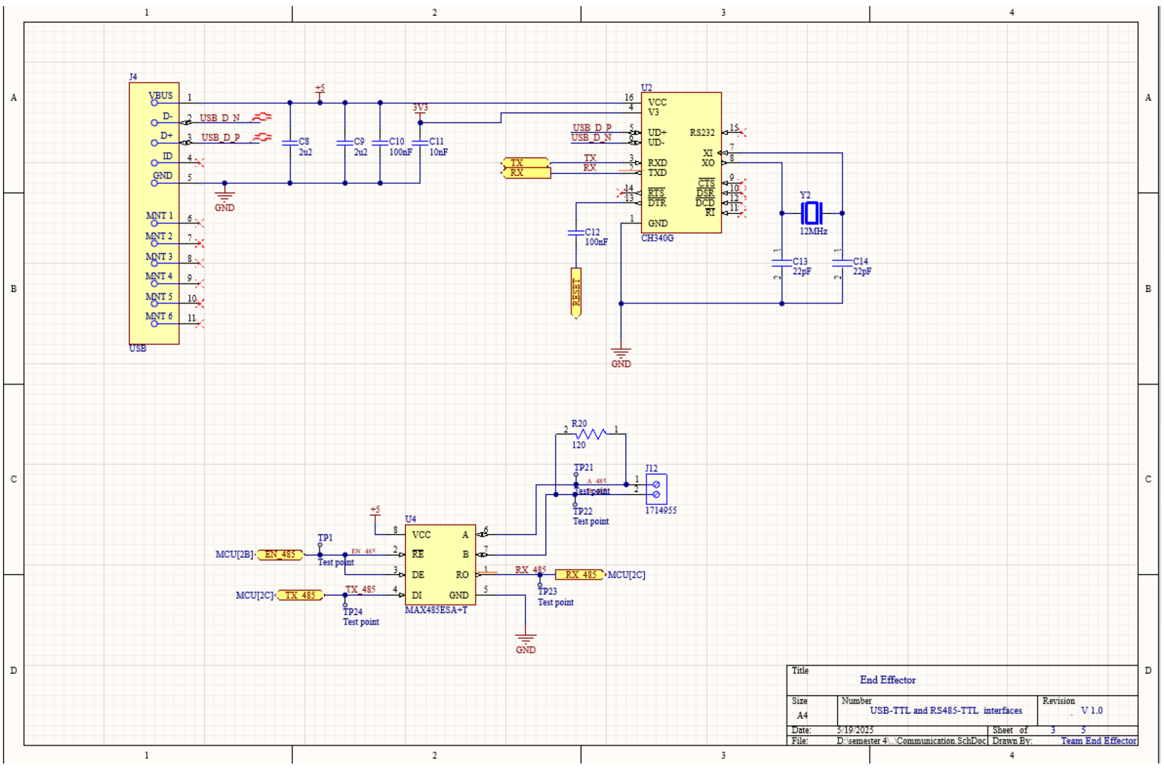


Figure 26: USB-TTL and RS485-TTL Programming Interfaces

11.2.6 24V to 5V Buck Converter

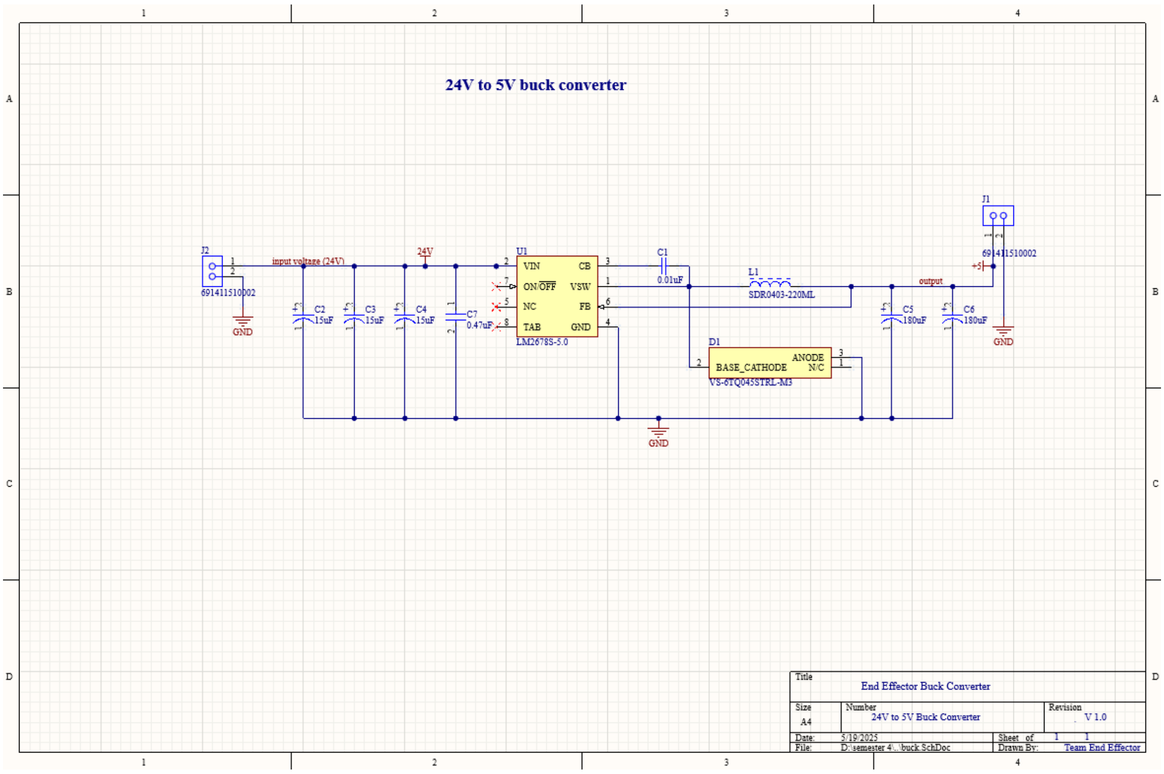


Figure 27: 24V to 5V Buck Converter

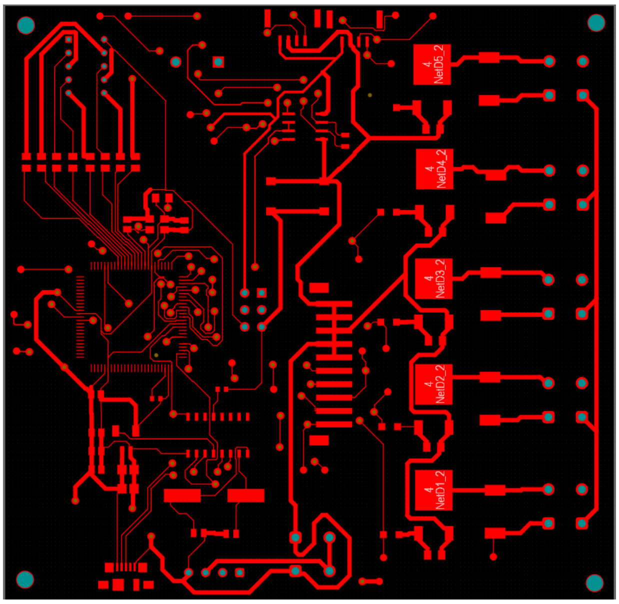
12 PCB Design

12.1 Main PCB Layout

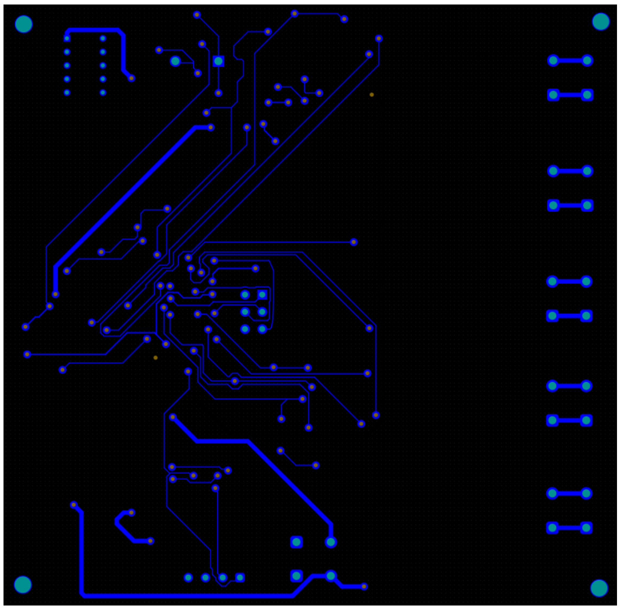
The PCB layout was guided by principles of signal integrity, power efficiency, and manufacturability, optimized for a two-layer design (top and bottom layers only, without dedicated ground or power planes). Key decisions in the component placement and routing strategy include:

- **Centralized MCU Placement:**
  The microcontroller was placed centrally to minimize trace lengths to key peripherals, enabling symmetrical routing and reducing propagation delays.
- **Peripheral Connector Positioning:**
  - **ToF sensor** and **solenoid driver connectors** were positioned at the corners of the board to streamline external wiring and minimize cross-interference.
  - **Communication interfaces** (e.g., UART, I^2C, SPI) were placed to ensure logical signal flow and ease of access during integration.
- **Power Routing Optimization:**
  - Power traces were widened to support higher current capacity and minimize resistive losses and voltage drop.
  - Routing paths were kept as short as possible to improve power delivery efficiency and reduce EMI susceptibility.
- **Via Usage for Signal Integrity:**
  Multiple closely spaced vias were introduced in key locations, particularly on power and ground nets. These serve to:
  - Provide low-impedance paths between top and bottom layers.

- Reduce ground loop area and high-frequency noise coupling.
- Support robust return paths in the absence of solid reference planes.



Top Layer



Bottom Layer

Figure 28: Top and Bottom PCB Layer Views

12.2 Buck Converter PCB Layout

12.3 Layer Stackup

	Top Overlay		Overlay				
	Top Solder	Solder Resist	Solder Mask	0.4mil	3.5		
1	Top Layer		Signal	1.4mil			1oz
	Dielectric 1	FR-4	Dielectric	12.6mil	4.8		
2	Bottom Layer		Signal	1.4mil			1oz
	Bottom Solder	Solder Resist	Solder Mask	0.4mil	3.5		
	Bottom Overlay		Overlay				

Figure 29: Used Layer stackup

The 2-layer PCB, manufactured by JLCPCB, features a FR-4 dielectric with 1 oz copper layers (1.4 mil thick) on top and bottom, flanked by 3.5 mil solder resist and overlay layers. This design balances cost and performance for low-to-medium current applications.

12.4 Test Points

To facilitate effective validation and debugging during development and production testing, test points were incorporated across all critical signal nets. These include power and control lines associated with the MCU, solenoid driver circuits, ToF sensors, and motor interfaces.

Test points were implemented as exposed copper pads manually defined on the top layer of the PCB. Rather than using dedicated test point components, standard SMT pad primitives were placed directly on the relevant nets. Each pad serves as an accessible probe point for oscilloscope tips, logic analyzers, or multimeter probes.

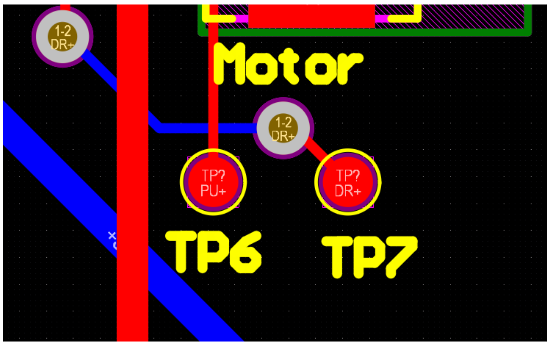


Figure 30: Test Points

12.5 Production and Manufacturing Considerations

The design was validated using the manufacturer's DRC (Design Rule Check) constraints provided in JLCPCB's Altium rule files to ensure manufacturability. Standard Gerber files and NC drill files were generated for the purpose of manufacturing the PCB.

13 Bill of Materials

Comment	Description	Designator	LibRef	Quantity
22pF	CL21 Series 0805 150nF 25V ±10% Tolerance X7R Multilayer Ceramic Chip Capacitor	C1, C2	CMP-13271-001271-1	2
100nF	CL21 Series 0805 150nF 25V ±10% Tolerance X7R Multilayer Ceramic Chip Capacitor	C3, C4, C5, C6	CMP-13271-001271-1	4
100nF		C7, C10, C12	CMP-1035-02588-2	3
2u2		C8, C9	CMP-2007-03313-1	2
10nF	CAP 10nF 500V ±10% 1206 (3216 Metric) Thickness 1.7mm SMD	C11	CMP-1037-03540-1	1
22pF	Capacitor; Ceramic; Cap; 22.0pF; Tol 5%; SMT; Vol-Rtg 50V; C0G; Tape and Reel	C13, C14	CMP-2007-00048-2	2
SS34	DIODE SCHOTTKY 40V 3A DO214AB	D1, D2, D3, D4, D5	CMP-02539-000066-1	5
5V		J1	CMP-1502-03078-2	1
Solenoid5		J2	CMP-1502-03078-2	1
SPI	CONN HEADER VERT 6POS 2.54MM	J3	CMP-04776-000468-1	1
USB	CONN RCPT USB2.0 MICRO B SMD R/A	J4	CMP-2000-05246-2	1
Motor	CONN HEADER SMD 10POS 2MM	J5	CMP-2000-05881-2	1
Tof2	CONN HEADER SMD 4POS 1.25MM	J6	CMP-17439-000062-2	1
Solenoid1		J7	CMP-1502-03078-2	1
Solenoid2		J8	CMP-1502-03078-2	1
Solenoid3		J9	CMP-1502-03078-2	1
Solenoid4		J10	CMP-1502-03078-2	1
Tof1	CONN HEADER SMD 4POS 1.25MM	J11	CMP-17439-000062-2	1

Comment	Description	Designator	LibRef	Quantity
1714955	PC Terminal Block, Pitch 6.35 mm, 1 x 2 Position, Height 21.5 mm, Tail Length 5.1 mm, RoHS, Bulk	J12	CMP-2000-05797-1	1
UART		P1	CMP-1502-00586-2	1
IRLR	IRLR110PBF Mosfet; Power; N-ch; Vdss 100V; Rds(on) 0.54 Ohm; Id 4.3A; TO-252AA; Pd 25W; Vgs +/-10V, IRLR	Q1, Q2, Q3, Q4, Q5	CMP-00030-46527327-1	5
1M		R1	CMP-2001-01491-1	1
100ohm	RES SMD 100 OHM 1% 1/8W 0805	R2, R3, R4, R8, R10	CMP-2001-04374-6	5
10k	RES Thick Film, 10k, 1%, 0.125W, 100ppm/°C, 0805	R5, R6, R7, R9, R11	CMP-2001-04908-2	5
220		R12, R13, R14, R15, R16, R17, R18, R19	CMP-2001-00044-1	8
120	RES Thick Film, 120, 1%, 0.125W, 100ppm/°C, 0805	R20	CMP-02407-007854-1	1
RST	SWITCH TACTILE SPST-NO 0.05A 12V	SW1	CMP-2000-05160-2	1
Test point		TP1–TP24	$test_{point}$	23
7 seg	Display Modules - LED Character and Numeric Red 7-Segment 1 Character Common Cathode 1.7V 5mA	U1	HDSP-U113	1
CH340G	USB Interface Integrated Circuit	U2	CH340G	1
ATMEGA2560-16AU	Atmel Microcontroller with 256 KB In-System Programmable Flash, 8-Bit , 4.5 to 5.5 V, -40 to 85°C, 100-Pin QFP, Pb-Free	U3	CMP-020-00013-3	1
MAX485ESA+T	IC TRANSCEIVER HALF 1/1 8SOIC	U4	CMP-05679-000009-1	1
16MHz	Crystal 16MHz ±20ppm (Tol) ±50ppm (Stability) 12pF FUND 70Ω Automotive 4-Pin Ultra Mini-CSMD T/R	Y1	CMP-27762-000014-2	1
12MHz	HC/49US (AT49) LOW PROFILE SURFACE MOUNT MICROPROCESSOR CRYSTAL	Y2	ABLS2-12.000MHZ-D4Y-T	1

14 Enclosure Design

Initially, we developed the first design for the enclosure in SolidWorks, focusing on structural compatibility with the end effector and robotic arm. The enclosure was modeled to securely house the pneumatic components and provide easy access for maintenance, while minimizing material usage to maintain a lightweight form. The initial design phase emphasized modularity, allowing quick adjustments based on airflow paths and vacuum line routing. SolidWorks tools were utilized to ensure spatial accuracy and to assess the physical constraints when mounted on the robotic arm, setting the foundation for further refinements through simulation and weight analysis.

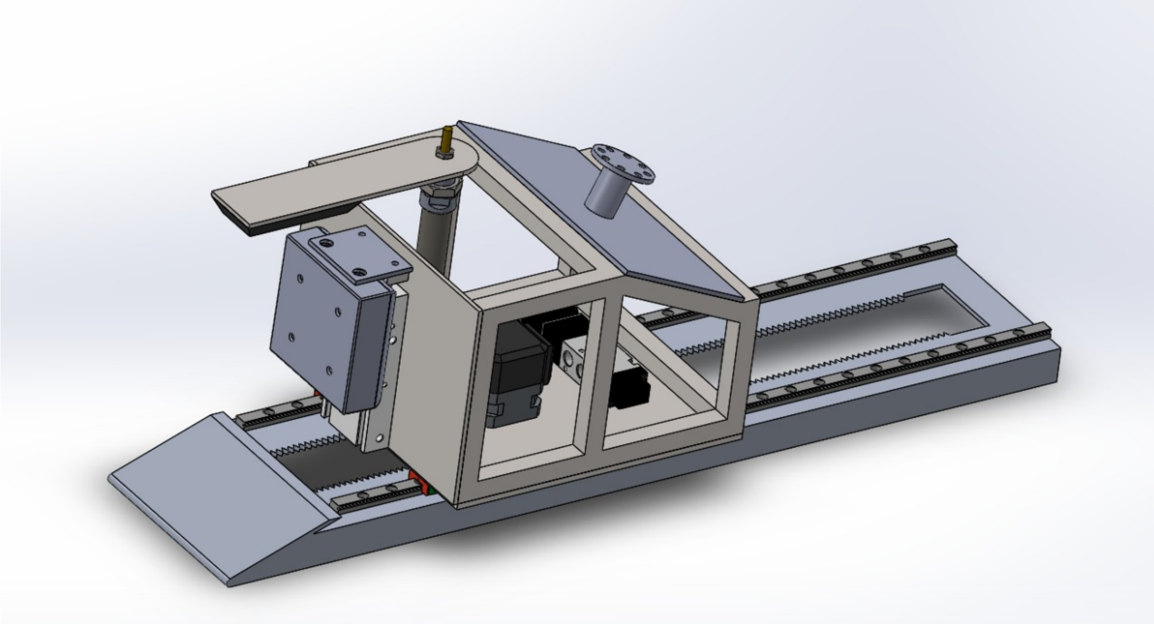


Figure 31: Initial Solidworks CAD Model for the Initial Enclosure Design

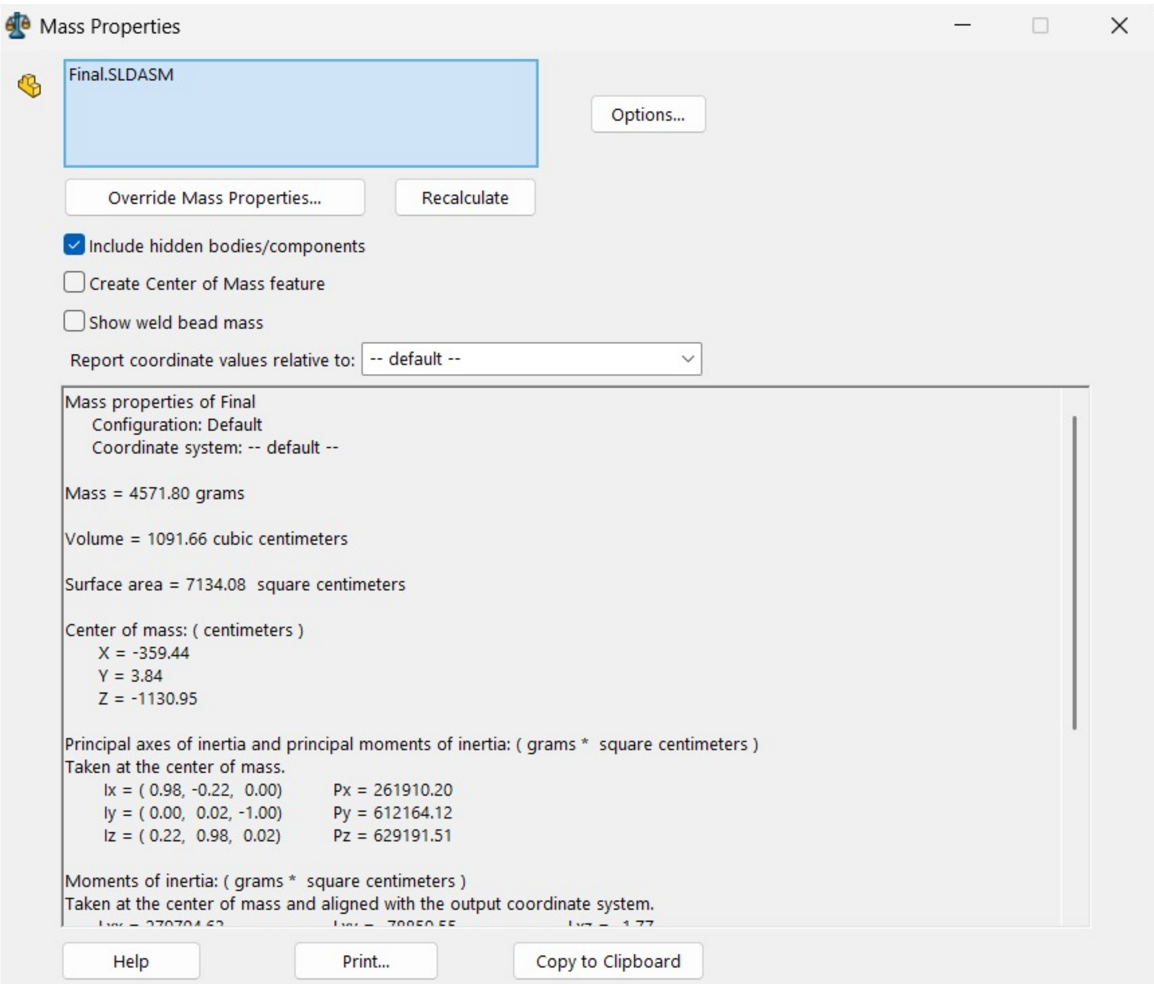


Figure 32: Weight Analysis using solidworks

Our design process evolved through three distinct cycles, each driven by the need to balance functionality, durability, and ease of assembly.

14.1 First Design Cycle – Acrylic Prototype

The first design cycle used **acrylic** for its transparency and ease of machining, allowing quick prototyping and visual inspection. However, its low strength and brittleness made it unsuitable for long-term use due to poor mechanical durability.

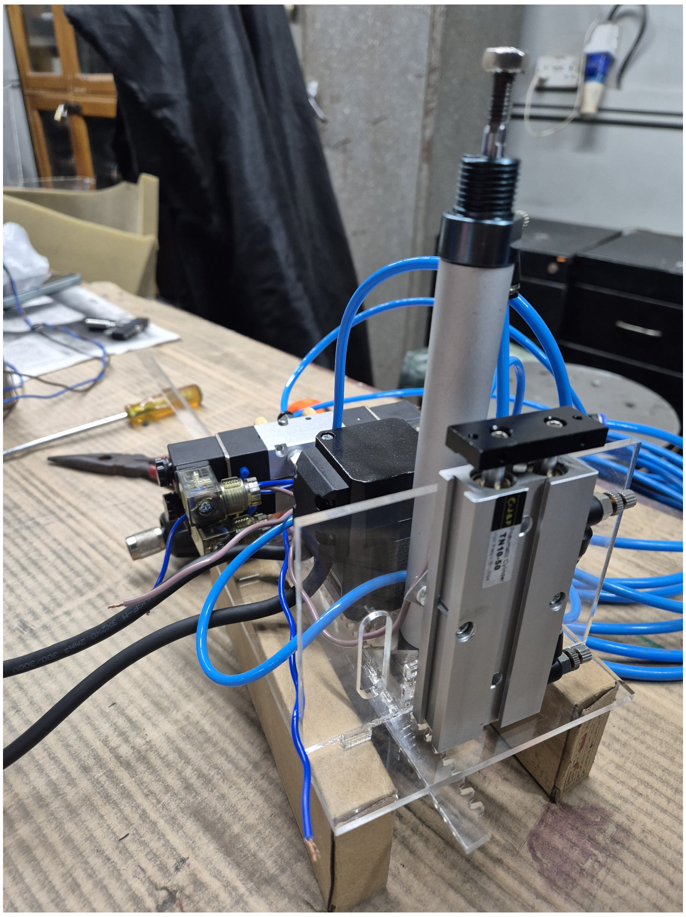


Figure 33: First Design Cycle using acrylic

14.2 Second Design Cycle – Zinc-Coated Iron Sheet Prototype

The second iteration used **zinc-coated iron sheets**, which significantly improved strength and rigidity, providing better protection for internal components. However, it introduced challenges like increased weight and complex fabrication, making assembly and maintenance difficult.

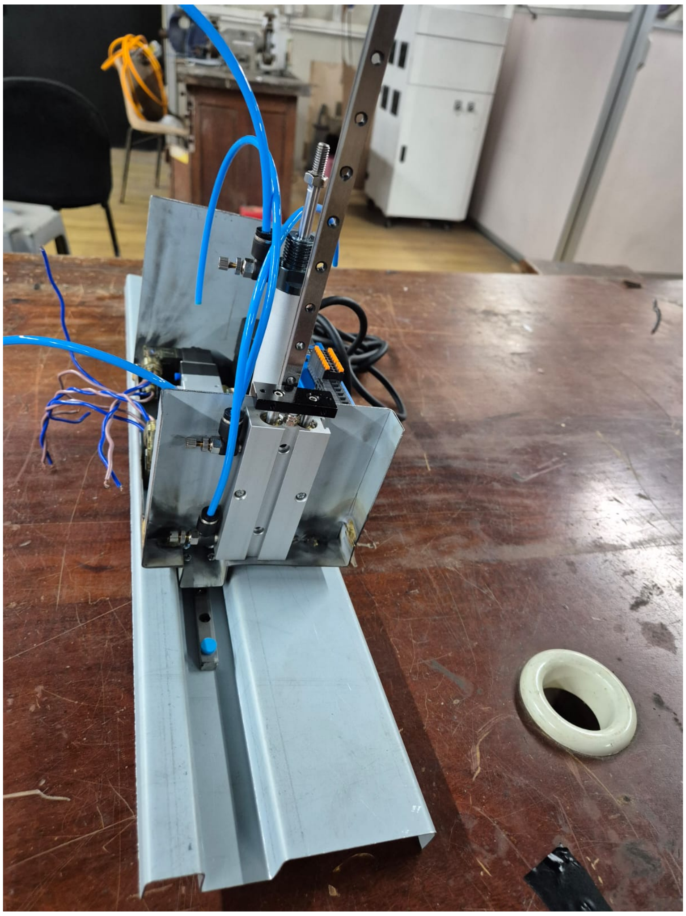


Figure 34: Second Design Cycle using zinc coated metal

14.3 Final Design Cycle – Zinc coated iron Enclosure

The final design of the end-effector enclosure utilized **zinc-coated sheet metal**, selected for its optimal balance between **structural rigidity**, **corrosion resistance**, and **ease of fabrication**. This material ensured the enclosure could withstand mechanical stresses while maintaining a relatively lightweight profile suitable for robotic arm applications.

Fabrication Process

The manufacturing workflow was carefully optimized for strength and precision:

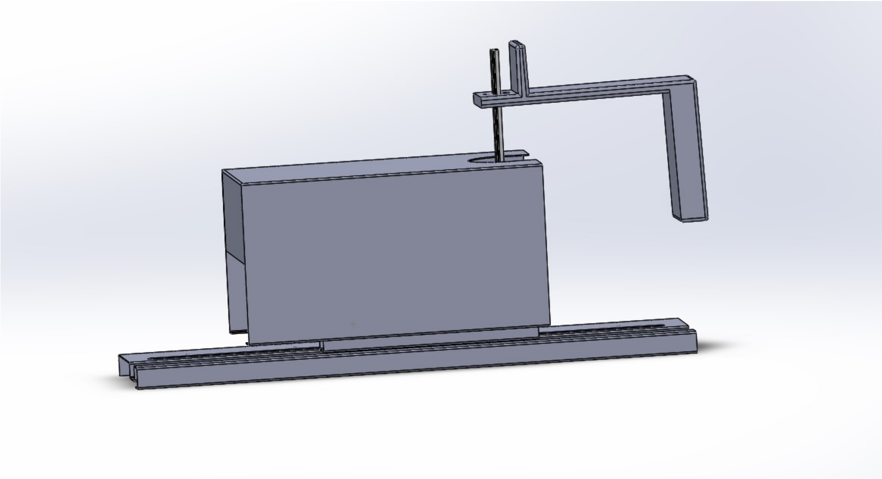
- **Laser cutting**: Used to achieve highly accurate profiles in the sheet metal
- **Bending/forming**: Critical for creating flanges and fold-based joints
- **Gas welding**: Ensured strong, reliable seams, especially at high-stress joints item **Painting**: Applied to prevent corrosion, and provide a good finish

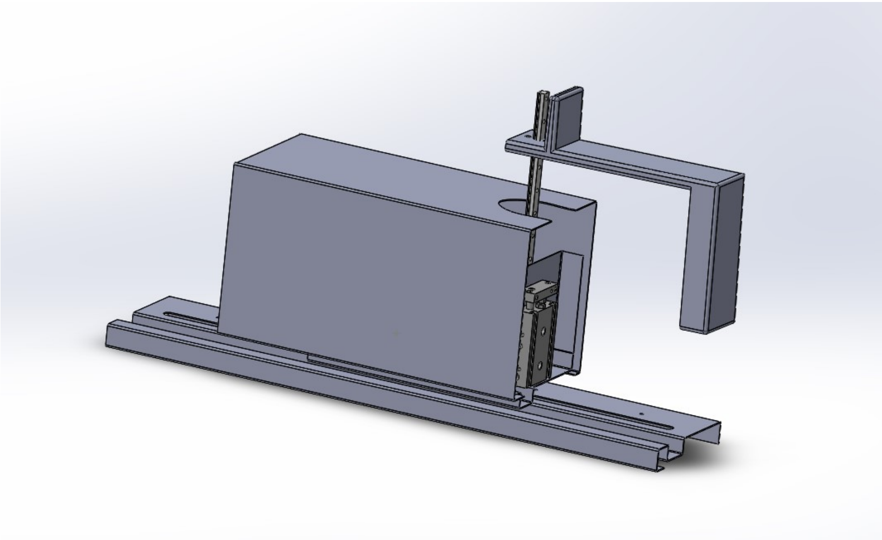
Assembly Benefits

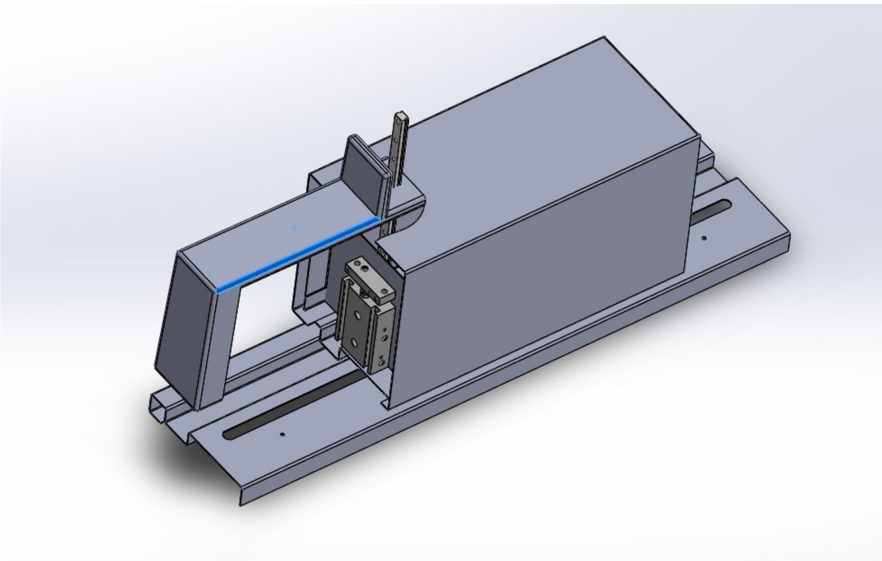
The modular and robust structure of the enclosure provided:

- **Secure mounting of components** through integrated flanges and brackets
- **Easy access to internal mechanisms**, enabling straightforward assembly and maintenance
- **Compact and protective form factor** tailored to the dynamic motion profile of the robotic arm

Images of the SolidWorks model and the assembled physical design are included below to illustrate the final enclosure layout and structural integration.







15 Final Assembly

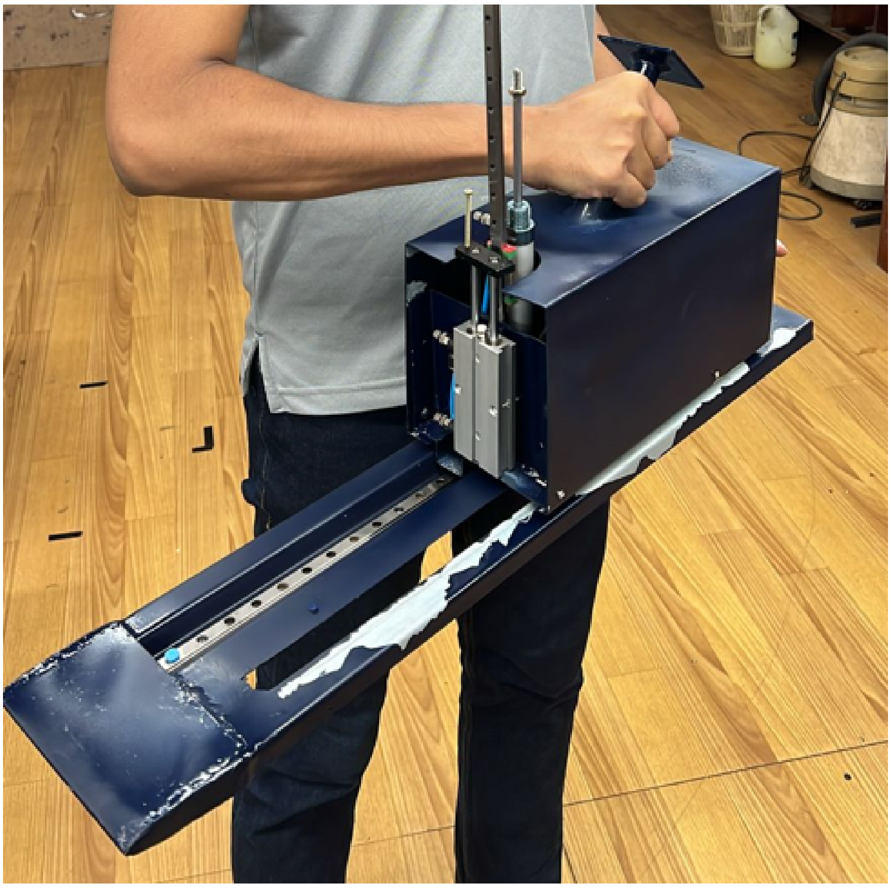


Figure 35: Fully assembled product

16 Conclusion

The development of the flexible robotic depalletizing system represents a significant advancement in automating supermarket warehouse logistics. By integrating advanced Time-of-Flight (ToF) sensors, bellows-type vacuum suction cups, and a robust microcontroller-based control system, the end effector achieves precise box detection, secure gripping, and reliable handling of diverse packages. The modular design, incorporating components such as closed-loop stepper motors, pneumatic cylinders, and a carefully engineered enclosure, ensures adaptability, durability, and ease of maintenance. The system's ability to handle varying box sizes, weights, and textures, combined with real-time responsiveness and seamless integration with robotic arms, addresses key logistical challenges. This project successfully demonstrates a cost-effective, efficient, and scalable solution, poised to enhance operational efficiency in warehouse environments while meeting stakeholder needs for flexibility, safety, and performance.

17 References

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[13] **Schmalz – FSG 20 NBE-ESD-55 M5-AG Suction Cup**
`https://www.schmalz.com/en/product/10.01.06.04345/download`