Autonomous Rover for Warehouse Rack Inventory Management

INTER IIT TECH MEET 14.0

End Term Submission Report

Team 33

1 Executive Summary

1.1 Problem Statement

The objective of this project is to develop an autonomous wheeled-mobile robot capable of navigating complex warehouse environments while performing reliable vertical scanning operations on storage racks. Modern warehouses require fast, accurate, and automated inventory monitoring across multiple rack levels; however, manual scanning is slow, error-prone, and unsafe when working at elevated heights.

To address this need, the robot must be able to:

- Autonomously traverse warehouse aisles.
- Detect and localize storage racks.
- Capture QR-based inventory information at varying elevations.

A key requirement is the ability to perform vertical scanning up to 2 meters, ensuring full coverage of typical warehouse shelving systems. The system must integrate perception, motion control, vertical actuation, and human–machine interaction while maintaining safe operation, real-time performance, and robust communication within indoor environments.

Figure 1: Inventory Scanning

1.2 Proposed Solution

We propose a robust differential-drive two-wheeled robot with a scissor lift mechanism for vertical traversal. The key elements of the solution are:

- **Compute and Control**
    - Industry-grade SBC: **Jetson AGX Xavier**.
    - Microcontroller: **ESP32 DevKit** for real-time motor control and I/O.

- Supports complex onboard computation and over-the-air software updates.

- **3D Perception**
  - **Intel RealSense D455i** RGB-D camera.
  - Generates dense depth maps to build dynamic 3D maps of the environment.
  - Enables navigation in both known and unknown warehouses.

- **Vertical Scanning**
  - **Scissor lift mechanism** mounted centrally on the chassis.
  - Provides precise vertical motion with high positional repeatability.
  - Supports QR scanning at multiple rack levels up to 2 m.

- **Integrated, Modular System**
  - Mechanical, electrical, and software components co-designed for competition constraints.
  - Modular interfaces allow future upgrades in perception, control, or lift mechanisms.

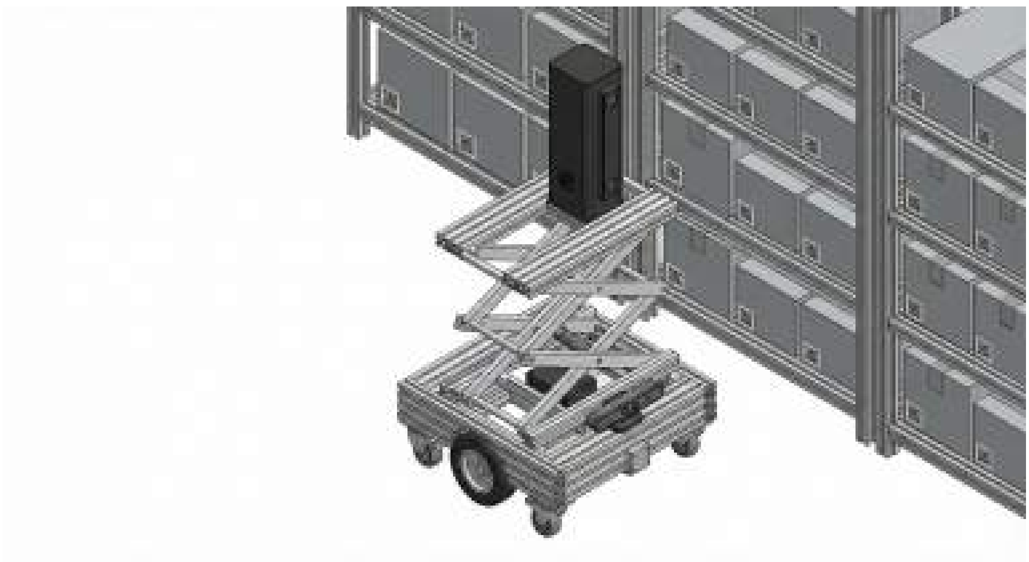

Figure 2: Proposed Solution

1.3 Metrics

Feature	Accuracy / Performance
Lateral Positional Accuracy	± 2 cm
Vertical Positional Accuracy	± 10 cm
QR Scanning Accuracy	96%
QR Scanning Time (per QR)	2 s

Table 1: System Metrics

1.4 Unique Selling Point / Innovation

- **Compact, Competition-Optimized Form Factor**
  - Rover footprint: 570×355 mm, mass ≈ 20 kg.
  - Satisfies $600 \times 450 \times 25$ kg competition limits.
  - Still accommodates a four-stage lift and dual-camera system.
- **Precision Differential Drive**
  - Two powered wheels plus front and rear ball casters form a diamond-shaped 4-point support polygon.
  - Enables zero turning radius and reliable lateral stability near racks.
- **Remote Access via Mobile App**
  - In-house mobile application for robot discovery and connection.
  - Provides teleoperation, live video, and inventory data.
- **Modular Top Plane**
  - Top plane supports multiple mounts and toolings.
  - Hardware can be reconfigured quickly for different warehouse tasks.

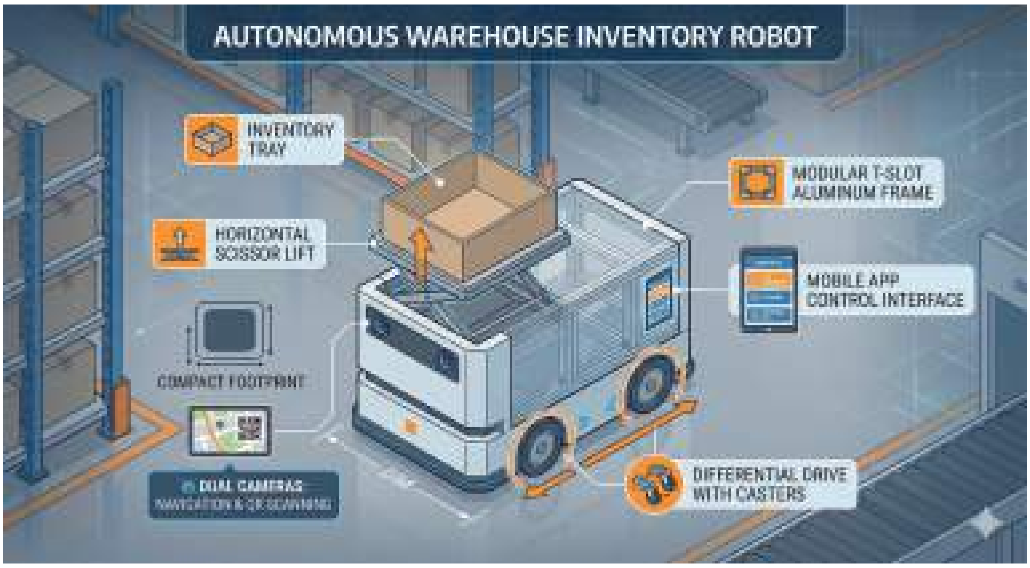

Figure 3: USPs

2 Problem Understanding and Motivation

2.1 Challenges Faced in Warehouses

- **Inventory Management**
  - Manual entry and poor tracking in large warehouses.
  - Inaccurate inventory counts leading to stockouts and overstocking.

- **Labour-Related Issues**
  - Long walking distances and repetitive tasks cause fatigue and errors.
  - Skilled human resources are underutilized on low-skill scanning tasks.
- **Large-Scale Operations**
  - Scaling manual audits across large facilities is difficult and expensive.
- **Safety Risks**
  - High-rack inspection with ladders or lifts is hazardous.
  - Interaction with heavy loads and moving equipment increases risk.
- **Limited Optimisation**
  - Human-driven workflows restrict algorithmic optimisation.
  - Difficult to systematically improve throughput, safety, and efficiency.
- **Data and Visibility Gaps**
  - No real-time visibility into stock positions.
  - Poor analytics for reorder points, KPIs, and performance tracking.

Figure 4: Warehouse Challenges

2.2 Current Solution Gaps

- **Slow and Inconsistent Inventory Checks**
  - Manual audits can take 10–15 minutes per rack.
  - Updates are infrequent and often inconsistent.
- **High Error and Mismatch Rates**
  - Human counting introduces 1–3% errors.

- This leads to 30–50% stock mismatches and incorrect replenishments.

- **No Real-Time Visibility**
  - Inventory data is only updated after audits.
  - Causes both stockouts and overstocking, hurting service levels.

- **Safety and Scalability Limits**
  - Ladder-based high-rack checks are unsafe.
  - Reliance on manual labour makes it hard to scale across warehouses.

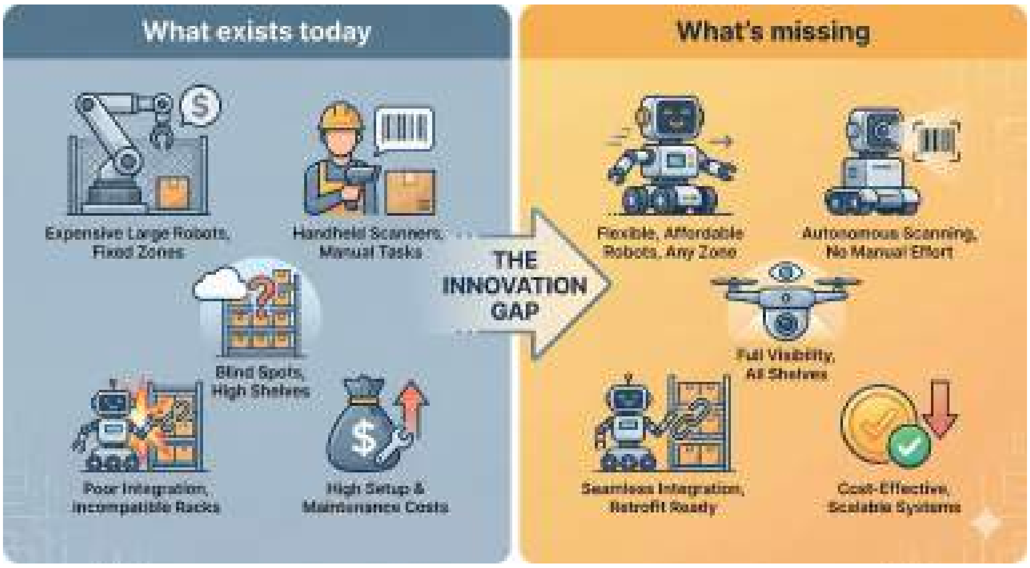

Figure 5: Solution Gaps

2.3 Value Proposition

- **80% Faster Inventory Audits**
  - Rover scans racks in under 3 minutes per aisle.
  - Reduces manual audit time from 10–15 minutes.
  - Enables continuous, near real-time visibility.

- **High Scan Accuracy**
  - $> 95\%$ consistency and $> 90\%$ QR accuracy.
  - Significantly reduces stock mismatches and missed items.

- **Operational Uplift**
  - 4–7% improvement in order fulfilment accuracy.
  - Fewer stockouts and better replenishment timing.

- **Cost Savings**
  - Estimated savings of 12–20 lakh per warehouse annually.

- Reduced labour costs, wastage, and discrepancy overheads.

- **Safe, Reliable Operation**
  - Eliminates ladder-based inspections.
  - Complies with safety constraints in the problem statement.
- **Scalable Deployment**
  - $<$ 25 kg hardware and 600 mm footprint.
  - Can be rolled out across dark stores and distribution centres.
- **Digitised Inventory Records**
  - Generates structured QR-linked logs and 1080p visual datasets.
  - Provides a rich base for downstream analytics.
- **Future-Ready Infrastructure**
  - Supports anomaly detection, demand forecasting, and autonomous stock management.
  - Aligns with long-term intelligent warehousing roadmap.

Figure 6: Value Proposition

2.4 Competition Objectives

The major competition objectives are summarised below:

- **Navigation and Positioning**
  - Horizontal positioning accuracy of ±10 cm.
  - Vertical positioning accuracy of ±2 cm.
  - Obstacle detection within a 5 m range.

- Path planning time under 3 s for real-time operation.
- Emergency stop response under 500 ms.

- **Scanning Performance**
  - Vertical scanning of each rack in less than 3 minutes.
  - Image resolution of at least 1920×1080 pixels with minimal motion blur.
  - Scanning repeatability greater than 95%.
  - Detection of 5×5 cm QR codes with more than 90% success rate.

Figure 7: Competition Objectives

3 System Architecture

Figure 8: System Architecture – HW + SW Block Diagram

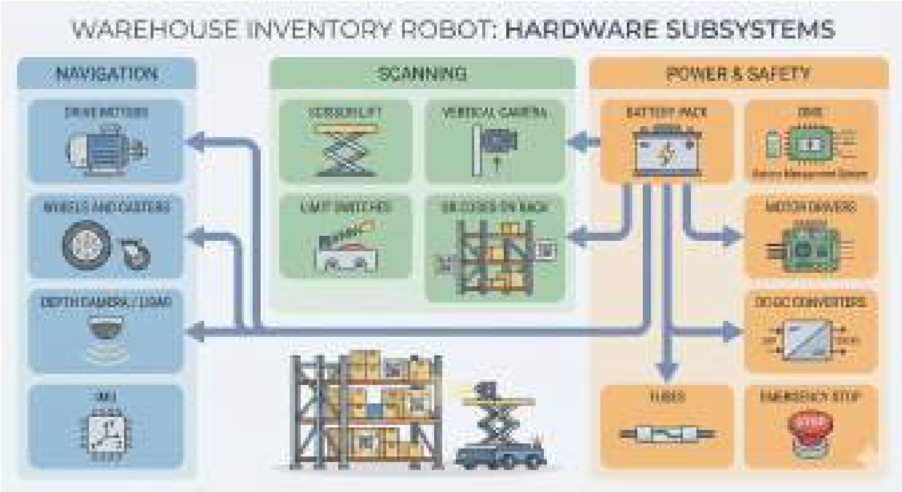

Figure 9: Hardware Subsystems – Navigation, Scanning, Power

Figure 10: Software Stack – SLAM, QR, HMI

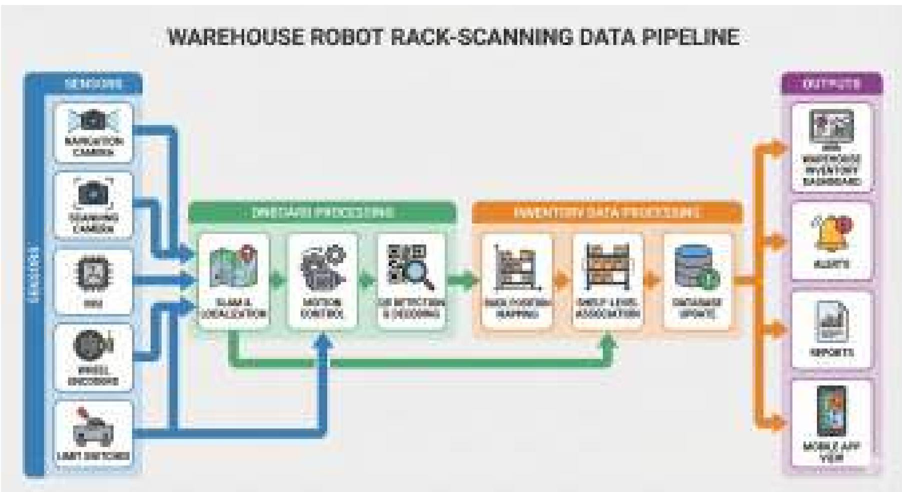

Figure 11: Data Flow Diagram – Sensing to Inventory Output

4 Hardware Design

4.1 Chassis and Overall Layout

The chassis is designed to satisfy footprint, mass, and stability constraints while providing a rigid base for the drive and lift subsystems. This ensures safe navigation in narrow aisles while supporting the full lift height.

- **Footprint and Mass**
  - Dimensions: 570 × 355 × 145 mm with 25 mm ground clearance.
  - Total mass: ≈ 20 kg, within 600 × 450 × 25 kg competition limits.
  - Compact footprint improves aisle compatibility while maintaining stability.
- **Frame Construction**
  - 20 × 20 mm anodised 6062 aluminium T-slot profiles.
  - Joints implemented using L-clamps and M4 hammer bolts.
  - T-slots support flexible mounting and rapid reconfiguration.
- **Closed-Box Topology**
  - Two structural faces (top and bottom) connected by eight vertical members.
  - Closed-box layout improves bending and torsional stiffness.
  - Avoids complex diagonal bracing and simplifies fabrication.
- **Operating Envelope and Stability**
  - Heavy components placed low and centrally to maintain a low centre of gravity.
  - Geometry tuned for anti-tip behaviour even with the lift extended.
  - Compatible with typical warehouse rack spacing and aisle widths.

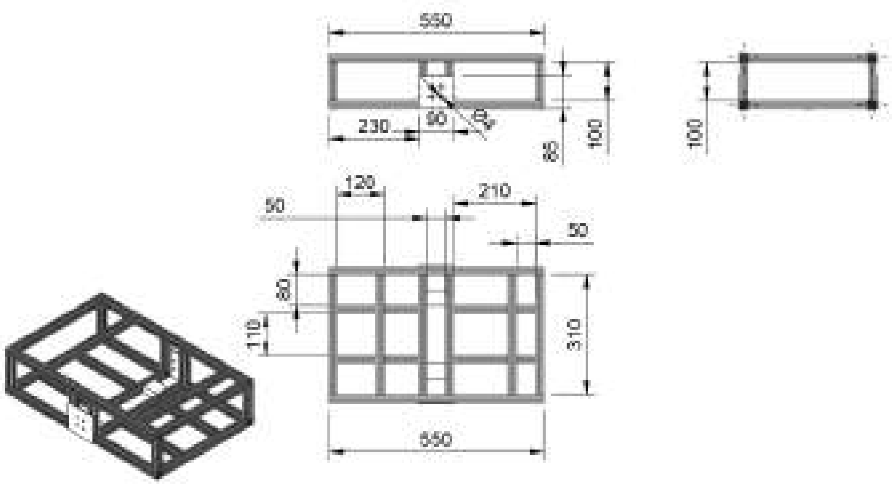

Figure 12: Chassis CAD with motor mounts

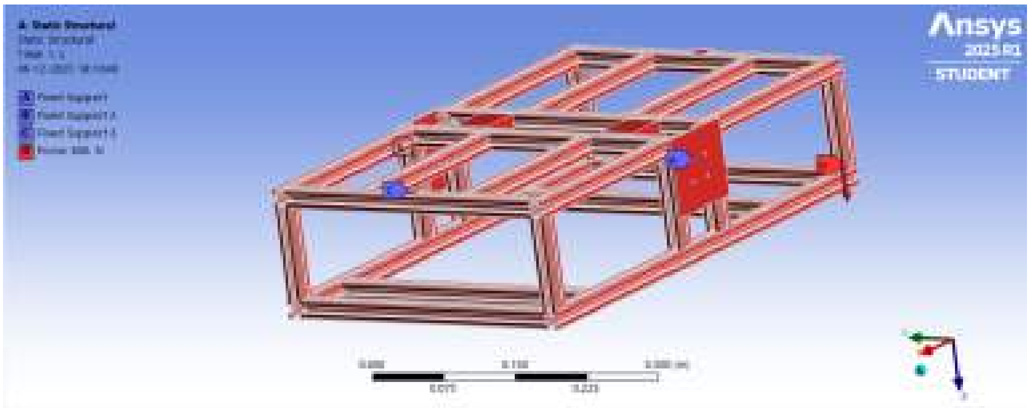

Figure 13: Uniform Vertical Loading

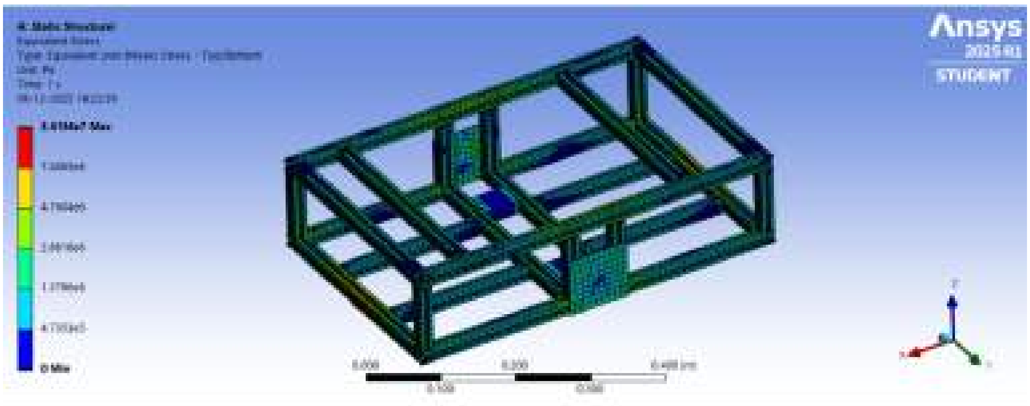

Figure 14: Stress under Load

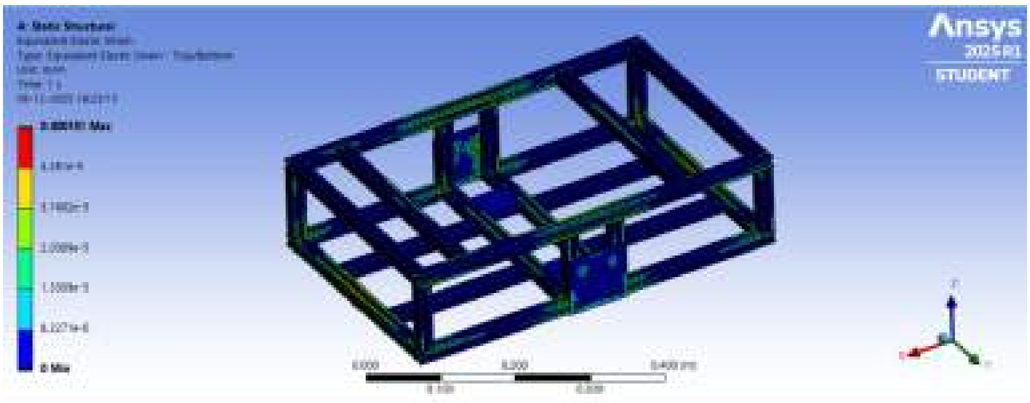

Figure 15: Strain under Load

4.2 X–Y Motion Hardware (Horizontal Locomotion)

The locomotion system is based on a 2-wheel differential drive supported by two casters. This architecture combines manoeuvrability, simplicity, and stability.

- **Locomotion Concept and Wheel Configuration**
  - Two direct-drive DC motors on the main wheels.

- Two metal ball casters (front and rear) forming a 4-point support polygon.
- Diamond support footprint supports zero turning radius and tight manoeuvres.

- **Drive Wheels**
  - Diameter: 100 mm; width: 25 mm.
  - Plastic rim with rubber tread for grip on smooth floors.
  - Smaller diameter helps manage ground clearance and chassis height.
- **Caster Wheels**
  - Metal ball casters ($49 \times 32 \times 21$ mm) mounted on the longitudinal centreline.
  - One caster at the front and one at the rear.
  - Omnidirectional behaviour eliminates need for steering linkages.
- **Why This Configuration**
  - Simplicity with fewer moving parts than Ackermann or mecanum systems.
  - Stable centre of gravity within the support polygon under dynamic conditions.
  - Uses standard COTS components for easy procurement and maintenance.
- **Drivetrain Architecture and Motor Selection**
  - Direct-drive layout with motors coupled directly to wheels via 8 mm hardened shafts and keyed/set-screw hubs.
  - Minimises backlash and transmission losses, improving positioning accuracy.
  - Motors: RMCS 2012 (18 V DC, 39 kg·cm torque, 1:25 planetary gearbox).
  - Holding torque $\sim$ 200 kg·cm with integrated encoders ($\sim$1300 CPR at wheel).
  - Adequate torque margin for small floor irregularities and controlled acceleration.
  - **Max Acceleration Without Toppling**
    - Important Parameters
      - Mass of the bot = 15 kg
      - Radius of the driving wheel $R = 50$ mm
      - Weight of the bot = $15 \times 9.81 = 147.15$ N
      - Driving system consists of two main wheels and two castor wheels for balancing.
      - Normal Reaction per wheel = $147.15/4 = 36.79$ N
    - Bot Dimensions
      - Length $l = 440$ mm
      - Breadth $b = 550$ mm

$$(b/2) \times N + m \times g = m \times a$$
$$0.275 \times 36.79 + 15 \times 9.81 = 15a$$
$$10.12 + 147.15 = 15a$$
$$a = 10.48 \text{ m/s}^2$$

- Considering factor of safety (FOS = 3), the maximum safe acceleration becomes:

$$a_{\text{safe}} = \frac{10.48}{3} = 3.49 \text{ m/s}^2$$

- **Bot Velocity Calculations**
  - **Rated angular velocity of motor:**

$$\omega = 81.68 \text{ rad/s (780 rpm)}$$

  - **Velocity of the bot:**

$$v = \omega \times R = 81.68 \times 0.05 = 4.08 \text{ m/s}$$

- **Torque Calculations**
  - Center wheel drive (Two wheels driving system)
  - Normal Reaction per wheel $N = 36.79$ N
  - Acceleration of the bot = 1.5 m/s^2
  - Wheel material: silicone rubber; surface: flat & smooth.
  - SS castor wheels support (rolling resistance negligible).
  - Coefficient of friction per document.
  - Total Force per wheel:

$$(22.5 + 73.58/2) = 48.04 \text{ N}$$

  - Torque required:

$$T = 48.04 \times 0.05 = 2.402 \text{ N} \cdot \text{m} = 24.48 \text{ kg} \cdot \text{cm}$$

  - From the calculations, the robot's maximum acceleration before toppling is 10.48 m/s^2, while a conservative design acceleration of 1.5 m/s^2 was used. Using a realistic traction coefficient for silicone rubber on smooth floors ($\mu \approx 1$), the required wheel torque is ≈ 2.402 N $\cdot$ m (≈ 24.28 kg $\cdot$ cm) per wheel. The selected motor is rated 39 kg $\cdot$ cm (≈ 3.83 N $\cdot$ m), so it comfortably satisfies this requirement. With a safety margin (FOS = 1.5), the required torque becomes ≈ 3.05 N $\cdot$ m, which the motor still meets.

- **Motor Mounting and Integration**
  - Motors mounted centrally in the bottom frame gap.
  - Brackets fixed to lower T-slot members.

  - Low and central placement reduces the centre of gravity and protects motors inside the chassis envelope.

- **Power and Control Rationale**
  - 18 V battery supply and dual H-bridge drivers per motor.
  - Independent control of left and right wheels for differential steering.
  - Current limiting ($\approx$ 80–100 A soft limit) protects against stalls.

- **Kinematics and Stability Behaviour**
  - Wheelbase: 560 mm; track width: 405 mm.
  - Minimum turning radius: 0 mm (on-the-spot rotation).
  - Supports precise docking to racks and tight turns in constrained spaces.
  - Centre of gravity intentionally placed well inside the convex footprint.

- **Closed-Loop Control with ESP32**
  - ESP32 microcontroller implements PID controllers for wheel speed.
  - Error computed as difference between desired and actual RPM from encoders.
  - PID output (sum of K_p, K_i, K_d terms) converted to integer PWM for motor drivers.
  - Motor transfer functions approximated in MATLAB.
  - PID gains tuned offline using these transfer functions for stable response.

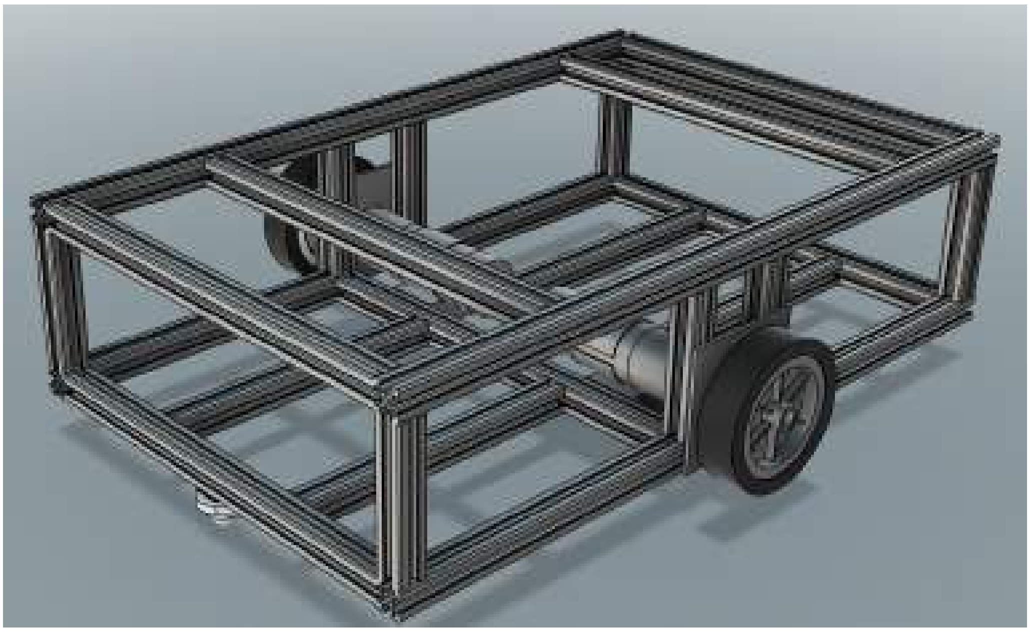

Figure 16: Drive System

4.3 Scissor Mechanism Analysis (Z Motion Hardware)

The Z-axis design uses a multi-stage scissor lift to achieve the required height while remaining within the base footprint.

- **Lift Concept and Actuation**
  - Four scissor stages, centrally mounted on the chassis.
  - Actuated by a horizontally oriented lead screw.
  - Scissor geometry provides guided vertical motion without external rails.
- **Actuation Layout**
  - A DC motor drives a horizontal lead screw.
  - Nut motion on the lead screw opens and closes the scissor linkage.
  - Actuator positioned inside the footprint to reduce collision risk and improve packaging.
- **Travel Range and Coverage**
  - Camera height range: 320 mm (min) to 1780 mm (max).
  - Covers $\approx$ 1800 mm usable rack height across multiple shelves.
  - Lead screw stroke: $\approx$ 250 mm, chosen to match required lift amplification.
- **Shelf Levels and Stand-Off**
  - Five discrete shelf levels mapped to specific camera heights.
  - $\approx$ 200 mm stand-off from racks for safe, consistent QR scanning.
- **Vertical Accuracy**
  - Vertical control uses motor feedback and known scissor kinematics.
  - Target accuracy: $\pm$20 mm, matching the $\pm$2 cm vertical requirement.
- **Structural Design**
  - Links: 6061 aluminium, 30 mm $\times$ 3 mm, across four stages.
  - Pivots: M8 bolts with 8 mm ID bearings for low-friction rotation.
  - Lift base: 1 mm 6061 aluminium plate.
  - Mounted to top T-slot members using M4 hardware to distribute loads.
- **Anti-Sway Measures**
  - Tight-fit bearings and scissor geometry limit lateral motion and tilt.
  - Central mounting maintains the centre of gravity within the support polygon, even at full height.
  - Mechanical limit switches and hard stops prevent over-extension.
- **Closed-Loop Vertical Control**

- After the rover reaches the target X–Y position, a desired camera height is computed.
- Height is converted to encoder counts using motor PPR and lead screw pitch.
- Z-axis PID controller uses encoder feedback to drive the motor with PWM.
- Real-time Z position is reported back to a ROS2 node on the Jetson.
- This allows synchronisation between vertical motion and scanning tasks.

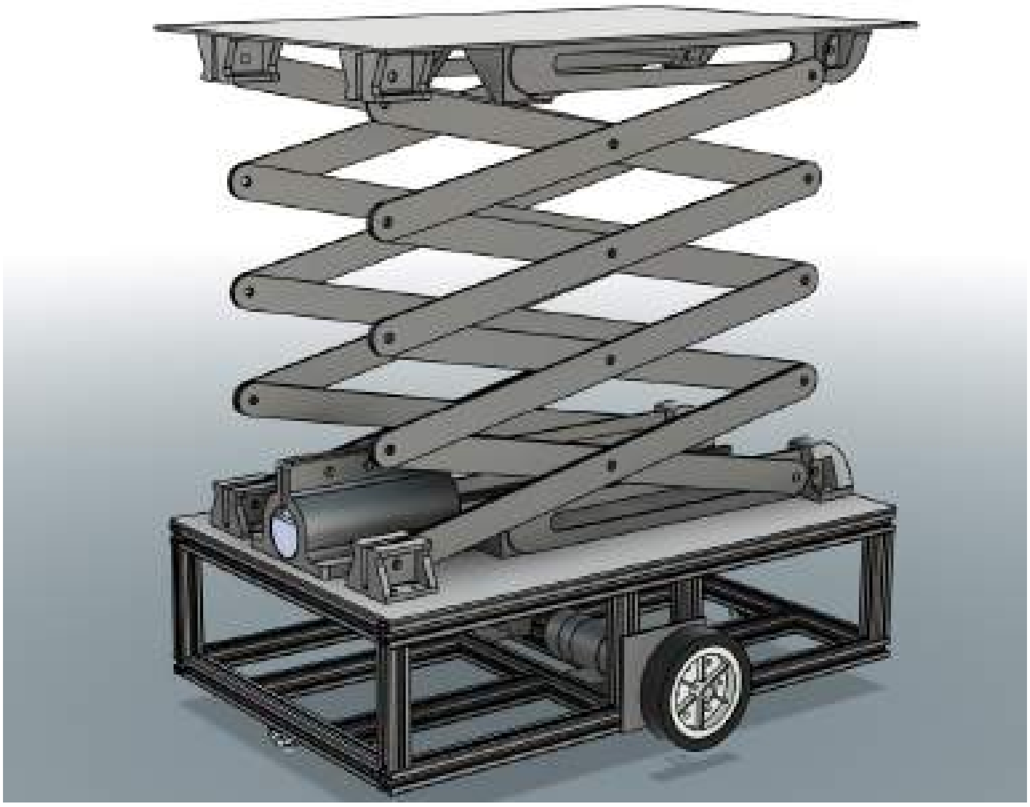

Figure 17: Scissor Mechanism

4.4 Power System

The power distribution system is designed to efficiently manage power across motors, encoders, Jetson AGX Xavier, and the Intel RealSense D455 camera, enabling fully autonomous operation.

- **Battery Architecture**
  - Three separate LiPo batteries:
    - Battery 1: Powers the Jetson AGX Xavier.
    - Battery 2: Powers the base drive motors.
    - Battery 3: Powers the Z-axis motor.
  - 25C discharge rate allows high current draw during dynamic manoeuvres.
- **Power Management Unit (PMU)**
  - Regulates and distributes 12 V DC from batteries to subsystems.

- 5 V rails supply the ESP32 and logic circuits.
- 12 V rails supply motor drivers for both base and Z-axis motors.

- **Jetson AGX Xavier Power Supply**
  - Dedicated DC power source.
  - DC–AC inversion followed by AC–DC rectification provides the required input profile.
  - Ensures stable and regulated power to the Jetson for GPU-intensive workloads.

- **Live Charging Detector**
  - Monitors charging status of each battery in real time.
  - Feeds diagnostic information to the control system and HMI.
  - Alerts on undercharging, overcharging, or disconnected states.

- **Overall Power and Control Flow**
  - Separate batteries isolate sensitive compute hardware from motor noise.
  - ESP32 sends PWM control signals to motor drivers for both XY and Z axes.
  - Encoders provide feedback to ESP32, which closes the motor control loops.
  - Jetson processes RGB-D data from RealSense, performs mapping and planning, and sends high-level commands to ESP32.

- **Motor Control Electronics and PCB Summary**
  - The rover's motor control system uses an ESP32 DEVKIT-V1 with a Cytron MDD20A driver to provide high-current PWM/DIR control of two DC motors with quadrature encoders for closed-loop PID speed and position control. The PCB is split into logic, motor/power (with a 470 µF bulk capacitor), and motor/encoder connector zones with 100 nF filters, using thick traces, a solid ground plane, and decoupling capacitors for stable, low-noise operation. Integrated over-current, thermal, and fault protection in the MDD20A helps deliver a robust and reliable motor-control platform for precise robotic actuation.

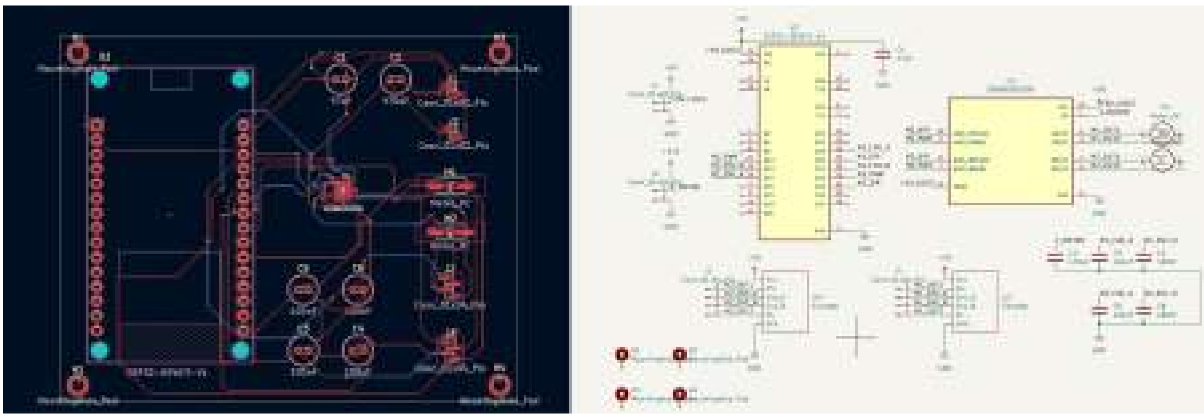

Figure 18: Power System Architecture

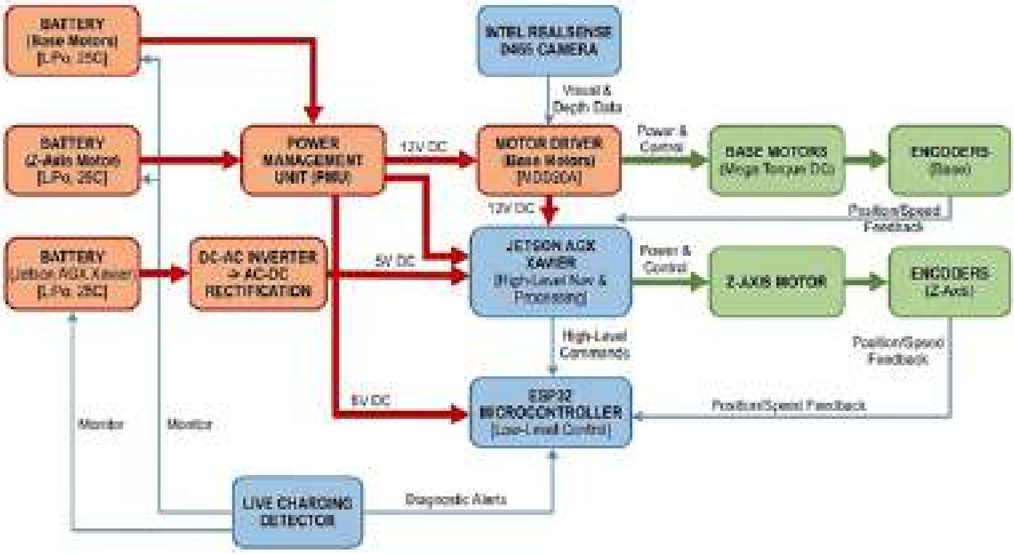

Figure 19: PCB Layout of our corresponding circuit schematic of ESP-32 DEVKIT-V1 with motor driver

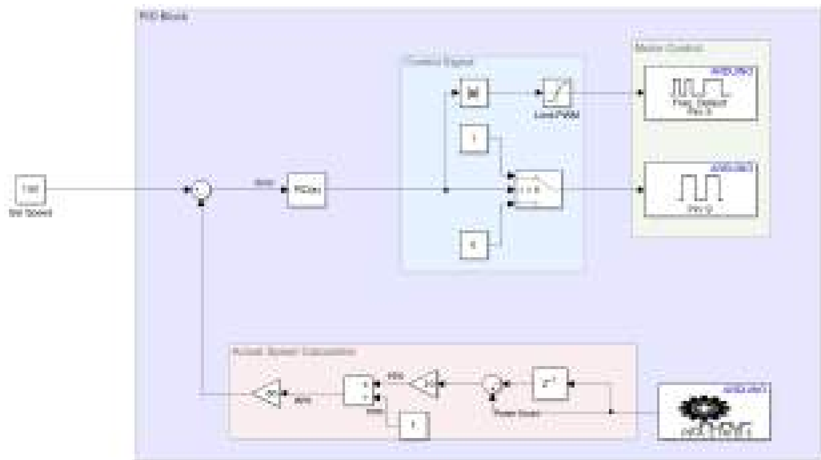
Figure 20: Speed Control Block Diagram

4.5 Safety System

The safety system combines electronic, mechanical, and human-in-the-loop mechanisms to ensure safe operation.

1. **Electronic Kill Switch (Power Cut-Off)**
   - Cuts power to motors and critical subsystems during emergencies.
   - Can be triggered manually or automatically by the ESP32.
   - Ensures immediate halt of motion in unsafe conditions.
2. **Mechanical Safety Switches for Z-Axis**
   - **Bump Switch**
     - Acts as a mechanical limit switch at maximum Z height.

- Prevents overextension of the Z-axis mechanism.

- **Limit Switches**
    - Define safe upper and lower travel limits.
    - Provide physical end stops in case of sensor or software failure.

3. **Physical Emergency Stop**

- Manual E-stop switch mounted on the rover.
- Cuts power immediately to prevent accidents.
- Independent of higher-level software.

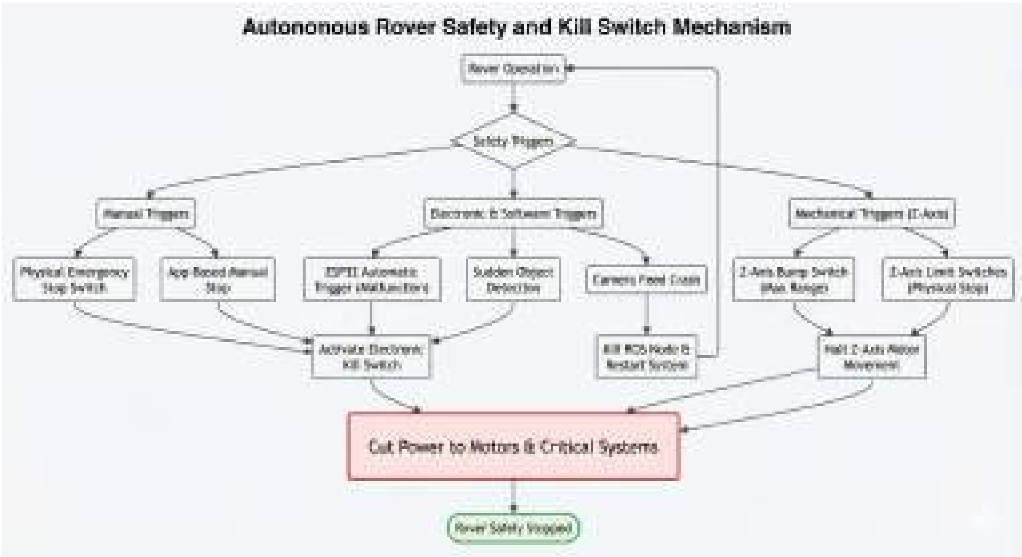

Figure 21: Safety System

5 Software Architecture

The software architecture is divided into four main subsystems:

- ROS2 control.
- 3D mapping.
- Path planning (global and local) with obstacle avoidance.
- Scanning and vision.

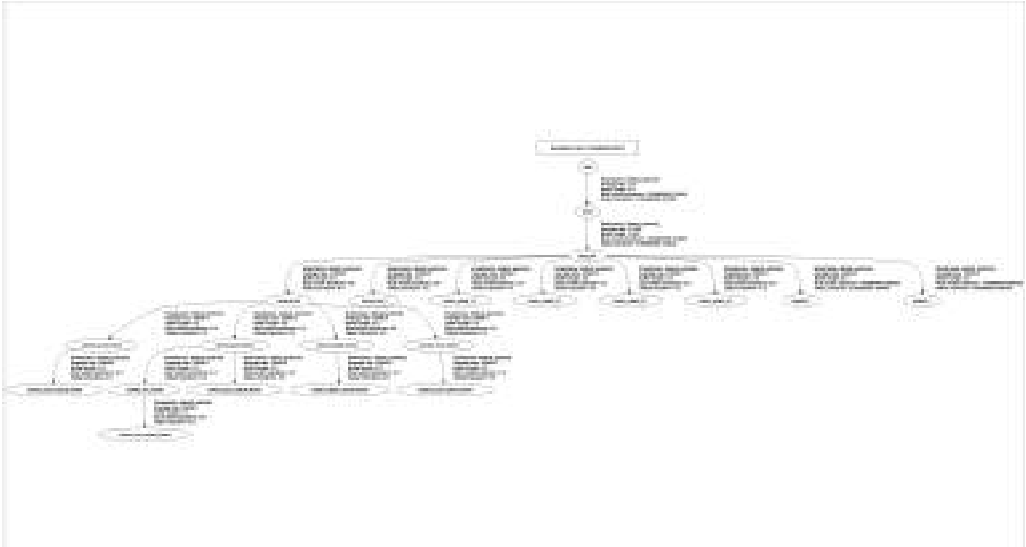

Figure 22: Overall Software Architecture

5.1 Communication Protocol

Cyclone DDS is used as the ROS2 middleware to enable fast, reliable, and scalable data exchange between nodes.

- **DDS-Based Communication**
  - Implements the Data Distribution Service (DDS) standard.
  - Supports robust publish–subscribe communication patterns.
- **Real-Time Characteristics**
  - Low-latency message delivery for sensor and control topics.
  - Deterministic behaviour suitable for real-time robotics.
- **Scalability**
  - Scales to multiple nodes and subsystems without central brokers.
  - Suitable for distributed compute across future multi-robot deployments.

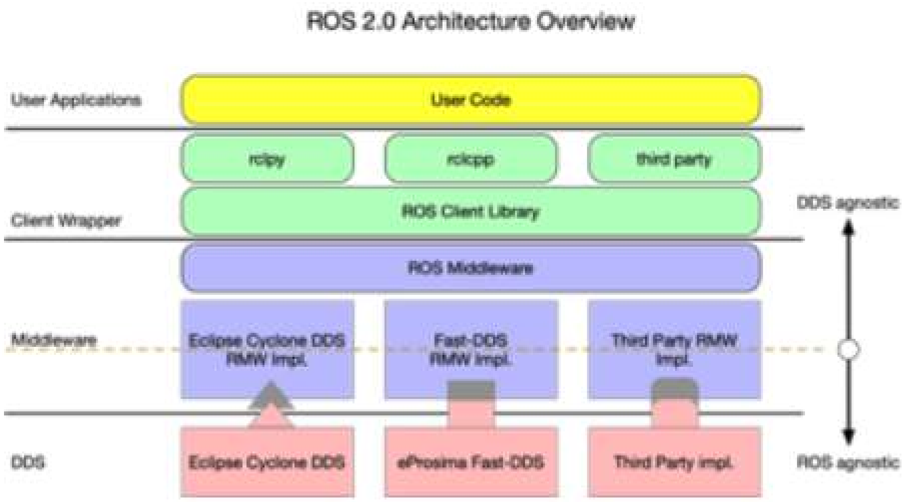

Figure 23: Cyclone DDS Communication Protocol

5.2 ROS2 Control

`ros2_control` provides a hardware abstraction layer for actuators and sensors, enabling modular and real-time control.

- **Real-Time Performance**
  - Controllers execute in-process with minimal message overhead.
  - Suitable for closed-loop control of motors and actuators.
- **Hardware Abstraction**
  - Exposes joints and actuators through standard interfaces.
  - Allows swapping or upgrading hardware without changing high-level control code.
- **Differential Drive Controller**
  - Standard ROS2 differential drive controller used.
  - Interfaces with custom `diff_drive_esp` hardware plugin.

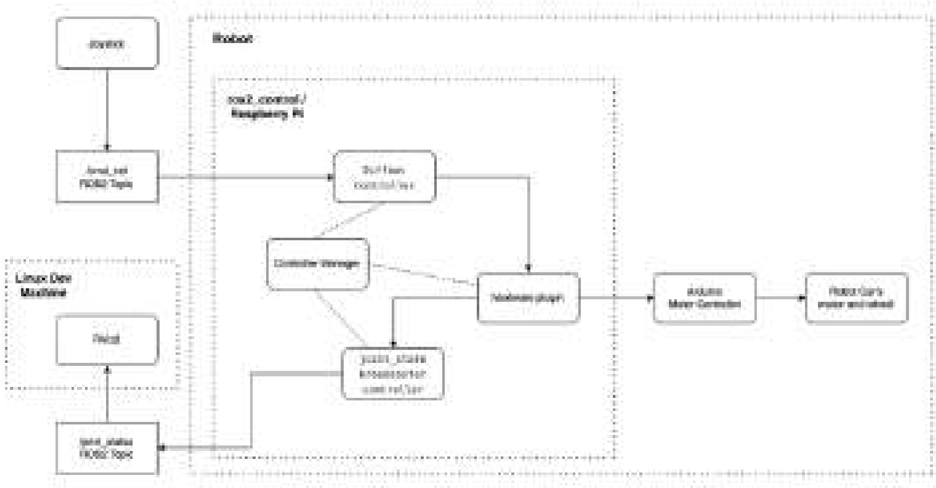

Figure 24: ROS2 Control System

5.3 3D Mapping

The robot uses RTAB-Map (Real-Time Appearance-Based Mapping) for visual SLAM with RGB-D input.

- **SLAM Principles**
  - Simultaneous localisation and mapping using camera images, point clouds, and laser scans.
  - Fuses odometry and visual features into a graph-based representation.
- **Loop Closure Detection**
  - Uses a bag-of-words approach to compare new images with past locations.
  - Adds loop closure constraints when revisiting locations to reduce drift.
- **Graph Optimisation and Memory Management**
  - Graph optimisation reduces accumulated mapping errors.
  - Memory management prunes older nodes while preserving important locations.
  - Ensures scalability and real-time operation in larger environments.

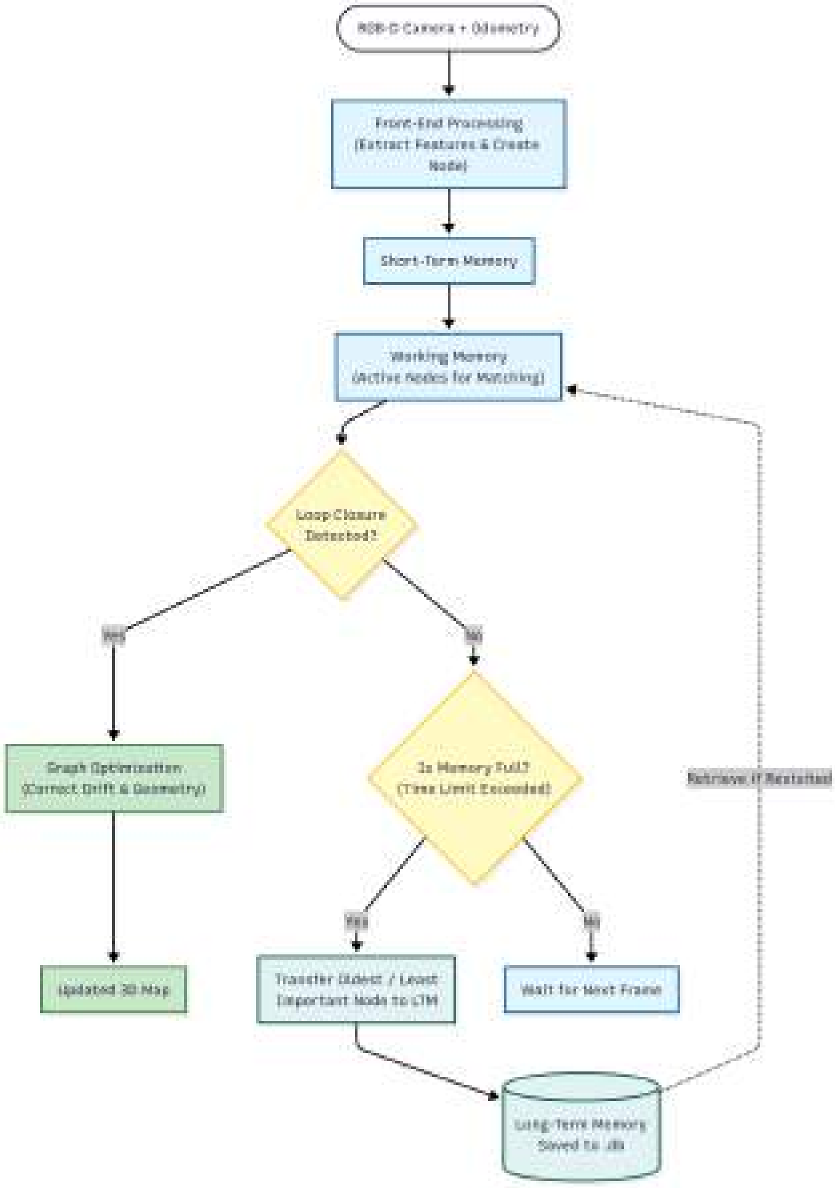

Figure 25: 3D Mapping

5.4 Path Planning

The robot's path depends on a combination of the environment map and the desired start–goal trajectory.

- **Global Cost Map**
  - Serves as a high-level map for long-distance planning.
  - Static layer loads pre-computed warehouse layout.
  - Obstacle layer subscribes to live RGB-D data for dynamic obstacles.
- **Local Cost Map**
  - Safety-critical rolling window around the robot.
  - Uses a voxel layer to represent 3D geometry.

- Handles overhanging shelves, table edges, and nearby obstacles.

- **Navigation Pipeline**
  - **Global Planner**
    - Uses the A* algorithm on the global cost map.
    - Computes the primary path between source and goal.
  - **Path Smoothing**
    - Eliminates sharp turns induced by grid-based planning.
    - Produces smooth, dynamically feasible reference trajectories.
  - **Local Planner**
    - Ensures the robot footprint does not intersect 3D obstacles.
    - Enforces speed and acceleration limits tuned for tight spaces.
    - Reacts to dynamic obstacles and modifies the trajectory as required.

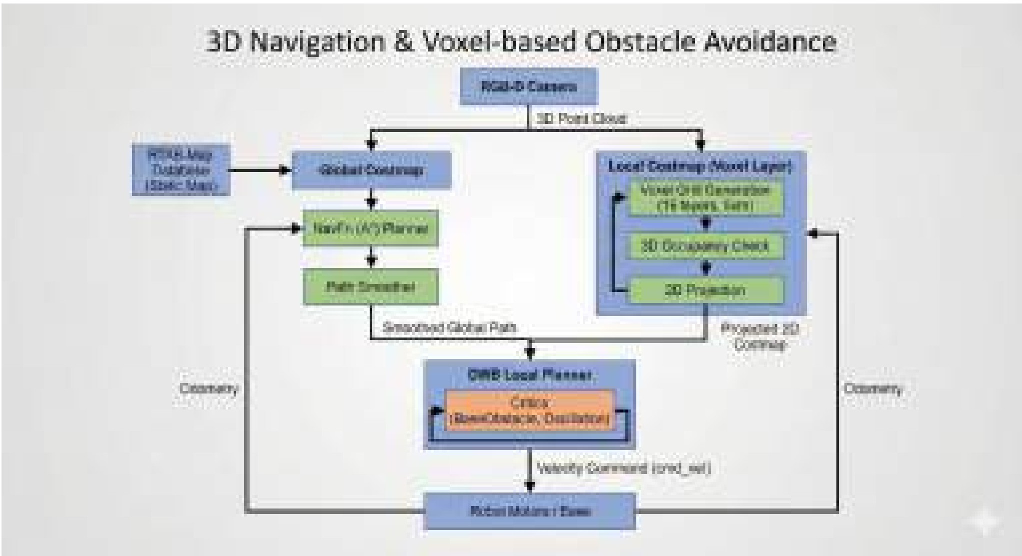

Figure 26: Path Planning System

5.5 Scanning Vision

Each camera provides 640×480 frames that may contain noise, uneven lighting, or motion blur. A two-stage QR detection pipeline is used to ensure reliable decoding.

- **Stage 1: Direct Detection**
  - Raw frames are passed to ZXing-CPP for fast decoding.
  - Works well under good lighting and contrast conditions.
- **Stage 2: Preprocessing-Based Detection**
  - Triggered if direct decoding fails.

- Preprocessing steps:
    - Grayscale conversion.
    - Gaussian blur (3×3) to reduce noise.
    - Adaptive thresholding to stabilise black–white QR patterns.
    - Contrast scaling (e.g., $\alpha = 1.5$) to sharpen boundaries.
- Preprocessed image is then re-submitted to ZXing-CPP.

- **ZXing-CPP Decoding Steps**
  - Finder pattern detection for the three main QR corner markers.
  - Perspective correction using homography to rectify tilt.
  - Module sampling to extract the QR's binary grid.
  - Reed–Solomon error correction to recover corrupted bits.
  - Payload extraction to obtain the decoded text and QR boundaries.

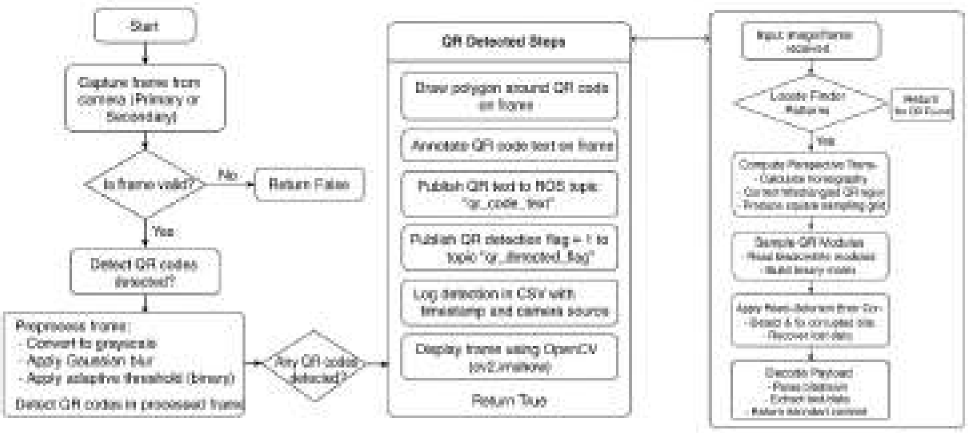

Figure 27: Scanning Vision Pipeline

5.6 Docker Containerization

The entire software stack is encapsulated in a Docker-based deployment on the NVIDIA Jetson AGX Xavier.

- **Reproducibility**
  - All dependencies and versions are specified within the container.
  - Behaviour is consistent across development and deployment devices.
- **Isolation**
  - Perception, navigation, and control can run in separate containers.
  - Library conflicts and host system differences are isolated.
- **Hardware Acceleration**

- NVIDIA Docker runtime exposes CUDA, cuDNN, and TensorRT.
- Enables GPU-accelerated perception and planning pipelines.

- **Modularity and Deployment**
  - Individual components can be updated without rebuilding the entire image.
  - Container image can be pulled and run on any compatible Jetson device.

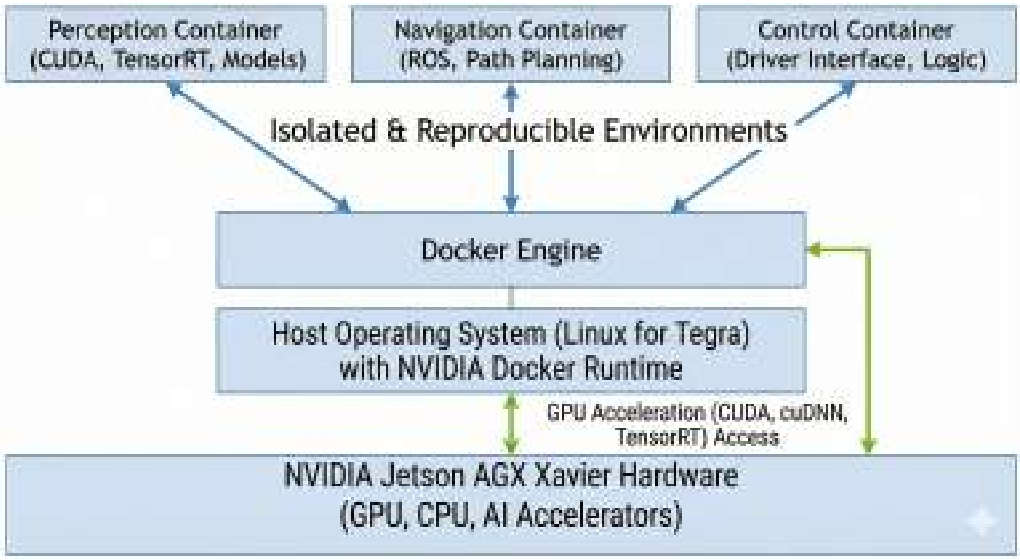

Figure 28: Docker Architecture

6 Human–Machine Interface

The human–machine interface (HMI) consists of two main components:

1. Mobile application.
2. Capacitive screen.

6.1 Mobile Application

The mobile application provides remote access and supervision capabilities:

- **Connectivity**
  - Automatically discovers and connects to the rover over the network.
  - Ensures secure communication with the onboard systems.
- **Control and Monitoring**
  - Allows operators to issue motion commands and high-level tasks.
  - Displays live video feed from onboard cameras.
  - Shows inventory scan results and associated QR information.
- **Alerts and Status**

- Highlights high-priority alerts (e.g., obstacles, low battery).
- Shows system health indicators for quick decision-making.

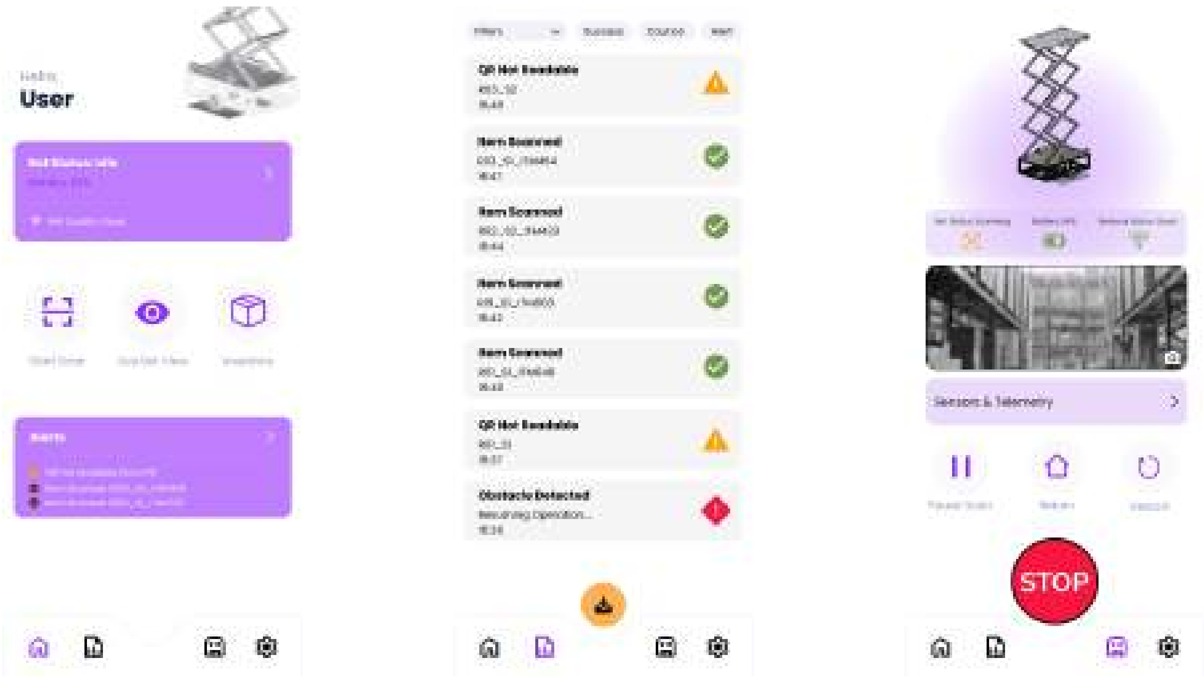

Figure 29: Mobile Application UI Screens

6.2 Capacitive Screen

The capacitive display serves as an onboard monitoring and interaction interface.

- **Real-Time System Status**
  - Displays voltage, current, and battery percentage.
  - Shows thermal conditions of key components.
- **Visual Indicators**
  - Uses graphical gauges and icons to convey state information.
  - Enables rapid assessment by on-site operators.
- **Local Interaction**
  - Supports basic controls and acknowledgements.
  - Acts as a fallback interface if the mobile app is unavailable.

Figure 30: Capacitive Monitoring Screen Interface

7 Integration Control

Hardware–software integration is achieved through custom ROS2 hardware interfaces, primarily the `diff_drive_esp` and `z_axis_esp` plugins.

7.1 Differential Drive Integration

The `diff_drive_esp` plugin connects ROS2 control with the ESP-based motor controller.

- **Responsibilities**
  - Maps ROS2 `cmd_vel` commands to left and right wheel velocities.
  - Sends wheel speed commands to ESP over UART.
  - Receives encoder feedback and publishes joint states and odometry.
- **Data Flow**
  - ROS2 controllers output target linear and angular velocities.
  - `diff_drive_esp` converts these into wheel-specific speeds.
  - ESP drives motors using PWM signals derived from these targets.
  - Encoders report actual velocities and distances back to ROS2.

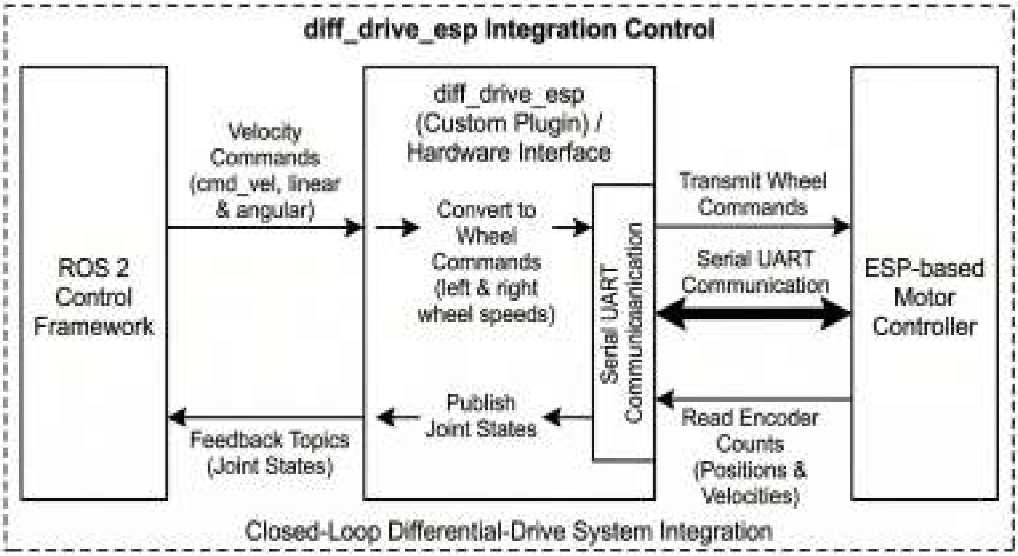

Figure 31: Integration Control Diagram

7.2 Z-Axis Interaction

The `z_axis_esp` plugin handles integration of the vertical lift mechanism.

- **Height Feedback**
  - ESP reads Z-axis encoder or height sensor signals.
  - Reports position and status to a ROS2 node running on the Jetson.
- **Command Interface**
  - ROS2 node computes the required height for scanning.
  - Sends target encoder counts or height commands to ESP.
  - ESP executes Z-axis motion using its local PID controller.
- **Modular Integration**
  - Reuses patterns and communication logic from `diff_drive_esp`.
  - Keeps XY and Z-axis integrations consistent and maintainable.

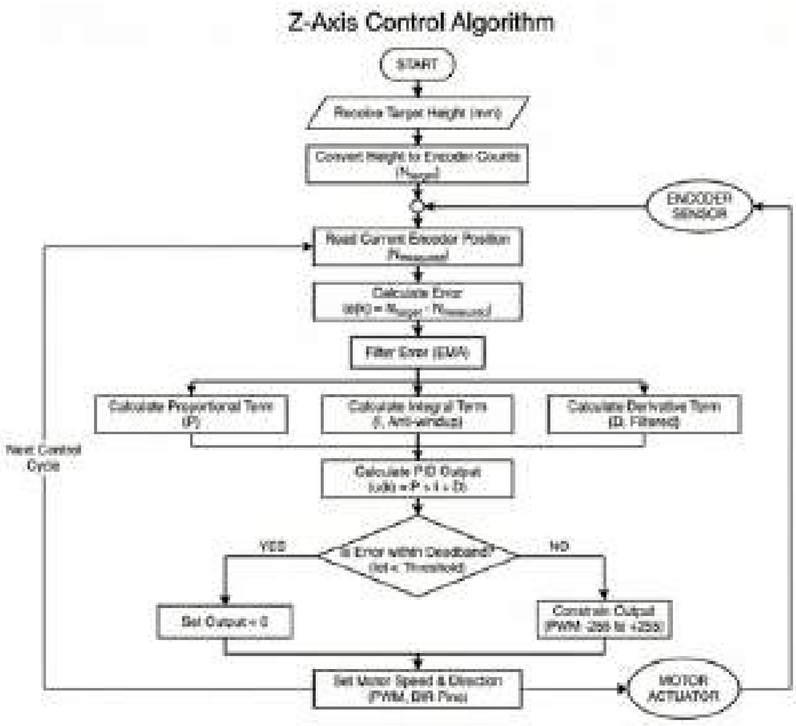

Figure 32: Z-Axis Interaction

7.3 Control Flow Feedback Loop

The closed-loop control flow between sensors, controllers, and actuators is summarised below:

1. **Sensor and Encoder Data Acquisition**
    - Wheel encoders and other sensors measure velocity, orientation, and motor states.
    - ESP-based controllers aggregate readings into structured serial messages.
2. **Transmission to Jetson (via `diff_drive_esp`)**
    - Encoder and status data are transmitted over UART.
    - `diff_drive_esp` parses messages and publishes:
        - `/odom`.
        - `/joint_states`.
        - Motor state feedback topics.
3. **ROS2 Control Processing**
    - ROS2 controllers use feedback to compute new wheel velocity commands.
    - Commands are generated at a fixed control frequency.
4. **Command Transmission to Electronics**
    - Updated left and right wheel commands are sent back to the ESP.

- ESP converts these into PWM outputs for the motor drivers.

5. **Motor Actuation**

- Motor drivers execute the PWM signals to rotate the wheels.
- Encoders update their readings, completing the physical feedback loop.

6. **HMI Interaction (Mobile App and Capacitive Display)**

- Mobile app connects to the rover and streams high-level status and video.
- Operators can issue manual override commands or emergency stops.
- Capacitive screen shows on-board status and allows local control.

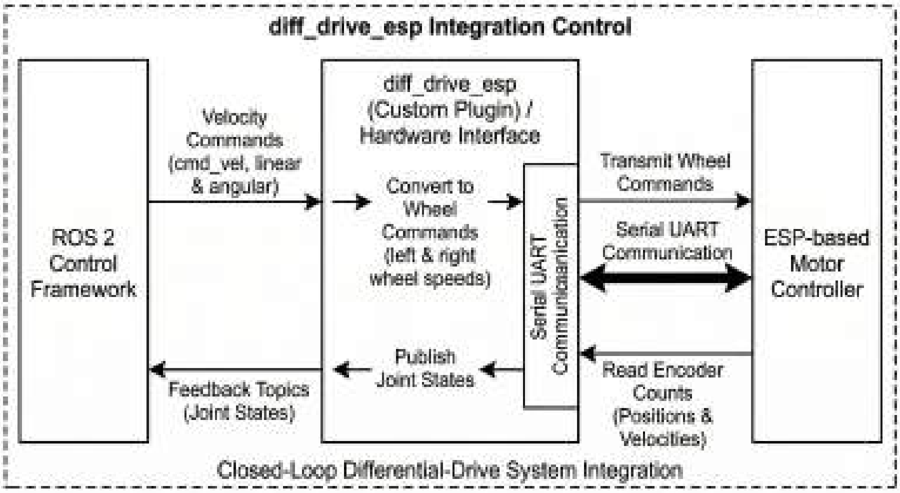

Figure 33: Control Flow Feedback Loop

8 Fail-Safe Mechanism

1. **Outlier Detection**

- Commands that would result in excessive speed or out-of-bounds positions are checked at the firmware level.
- Out-of-range commands are clamped or discarded.
- Such events are reported to the HMI for operator awareness.

2. **Self-Diagnosis and Software Safety**

- **Sudden Object Appearance**
  - If a new obstacle appears unexpectedly, software triggers an emergency stop.
  - Prevents potential collisions and allows the operator to re-evaluate the situation.
- **Camera Feed Failure**
  - If the camera feed crashes, the corresponding ROS2 node is killed and restarted.

    - The rover re-localises with the existing map and resumes safe operation.
- **App-Based Manual Control**
    - Operators can command a stop or override via the mobile application.
    - Provides a human-in-the-loop fail-safe in unforeseen scenarios.

9 Testing and Validation Summary

9.1 Methodology Overview

The system was developed and validated using a multi-stage testing workflow:

- Simulation-based testing in Gazebo.
- Controlled physical arena testing.
- Integrated system tests combining navigation, scanning, and HMI.

9.2 Simulation-Based Testing (Gazebo)

The initial testing phase used a Gazebo simulation environment.

- **Objectives**
    - Validate navigation, perception, and control algorithms without risking hardware.
    - Verify ROS2 graph, transforms, and sensor workflows.
- **Parameters Tuned**
    - Velocity limits and acceleration profiles.
    - PID controller gains.
    - Obstacle thresholds and planner settings.
- **Test Scenarios**
    - Different warehouse layouts and aisle configurations.
    - Varying lighting conditions.
    - Dynamic obstacles to simulate real-world activity.

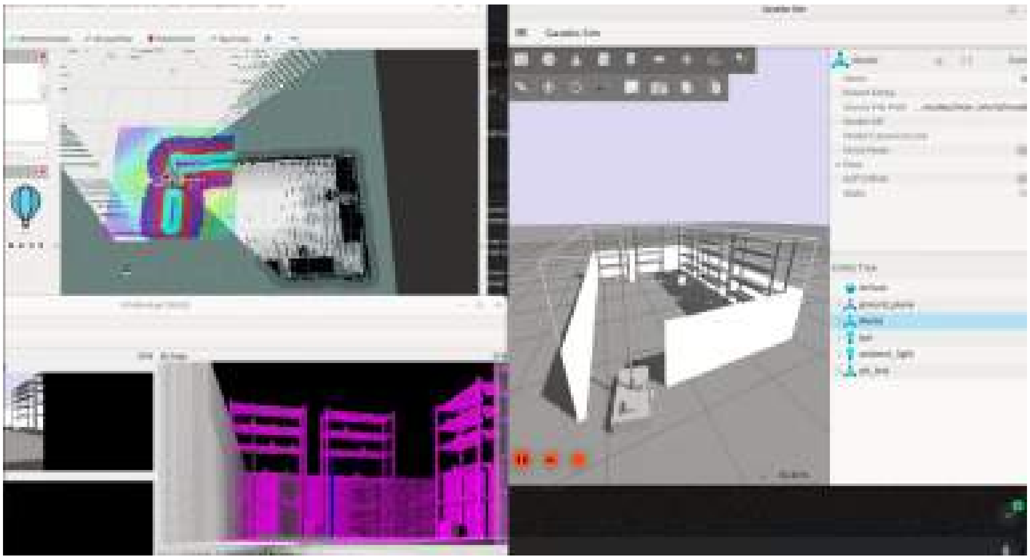

Figure 34: Simulation Testing

9.3 Controlled Physical Testing Arena

After achieving stable behaviour in simulation, a scaled physical test arena was built to replicate key warehouse conditions.

- **Arena Features**
  - Marked lanes and turn sections.
  - Shelving racks for perception and scanning tests.
  - Known obstacles for detection and avoidance evaluation.
  - Defined navigation paths for repeatable experiments.
- **Performance Validated**
  - Wheel odometry accuracy.
  - QR detection robustness under real lighting and motion.
  - Sensor fusion behaviour and mapping consistency.
  - Motor response, control stability, and tracking performance.
  - Communication reliability between electronics, Jetson AGX Xavier, and the HMI.

Figure 35: Testing Arena

10 Innovation and Novel Contributions

10.1 Unique Design Choices

- **Horizontally Actuated Scissor Lift**
  - The Z-axis uses a four-stage scissor lift driven by a horizontal lead screw.
  - The entire actuator is kept within the base footprint instead of using tall vertical screws or rails.
  - This reduces the risk of rack collisions, simplifies packaging in narrow aisles, and still achieves full rack height coverage.
- **Modular T-Slot Chassis**
  - The chassis is built from 20 $\times$ 20 aluminium T-slot profiles.
  - Every face effectively acts as a mounting backplane for drive, lift, battery, and electronics.
  - Subsystems can be repositioned and redesigned quickly with only basic tools, which is very practical for a B.Tech team iterating based on test feedback.
- **3D-Printed Camera Mounts with Damping**
  - Camera brackets are 3D printed in PLA with local stiffening ribs.
  - Thin damping pads are placed at metal interfaces to reduce vibration transmission.
  - This combines low-cost, easy fabrication with basic vibration control, supporting stable vision performance without precision machined parts.

10.2 Algorithm / Control Linked Mechanical Choices

- **Mechanics Aligned with Simple Control**
  - A 2-wheel differential drive with casters and direct-drive planetary motors with encoders provides a kinematically simple platform.

- This simplicity aligns well with basic closed-loop control and odometry.
- The approach enables the software team to achieve ±10 cm navigation accuracy using relatively straightforward algorithms, which is realistic for an undergraduate team.

10.3 Cost and Efficiency Innovations

- **COTS-Heavy Architecture**
  - The robot relies heavily on off-the-shelf motors, casters, profiles, and fasteners.
  - This reduces fabrication effort and lead times and keeps costs predictable.
  - Spares are easy to source, and other teams can replicate or extend the design without specialised manufacturing.
- **Serviceable, Student-Friendly Design**
  - Subsystems such as wheels, casters, lift pivots, and camera mounts are designed to be field-replaceable with common tools.
  - This saves time during integration and competition.
  - Overall uptime per rupee spent on the platform is improved by simplifying maintenance and repairs.

11 Limitations and Future Scope

11.1 Known Limitations

- **Camera Mount Adjustability**
  - The current camera mounts are mostly fixed, with only minor adjustment via slots or shims.
  - This is sufficient for a first prototype but can make fine calibration slower if rack layouts or camera models change.
- **Lift Stability Dependency**
  - Z-axis stability relies mainly on scissor stiffness and bearing quality, without extra side guides or rails.
  - While this meets basic requirements, it may limit performance if the payload increases or if higher scanning speeds are required.
- **Manual, Checklist-Based Maintenance**
  - The maintenance strategy is largely manual (bolt torque checks, visual inspections, lubrication).
  - There is no onboard structural health sensing.
  - This is manageable for a competition setting but would need to be strengthened for continuous industrial operation.

11.2 Commercialization Path (Mechanical Perspective)

- **From Student Build to Pilot Unit**
  - For commercial or pilot warehouse deployment, the mechanical design would require:
    - Industrial-grade guards.
    - More robust enclosures.
    - A formalised maintenance schedule aligned with industry standards.
  - The current T-slot and COTS-based architecture already makes component sourcing and assembly straightforward, which is a strong starting point for early pilot units.
- **Design for Manufacturability (DfM)**
  - Over time, some 3D-printed or multi-part bracket assemblies can be replaced with simplified sheet metal or machined parts.
  - This reduces assembly time and improves repeatability while preserving the geometry developed in this project.
  - Such evolution is feasible for a B.Tech team working with basic fabrication vendors.

11.3 Scalability

- **Scaling to More Units and Variants**
  - The modular T-slot frame and COTS component choices make it straightforward to adapt the design to different rack heights or payloads.
  - Changes can be made by adjusting link lengths, motor sizes, or camera mounts without redesigning the entire robot.
- **Path to Higher Performance**
  - Future iterations can add:
    - Side rollers or linear guides to the lift.
    - More adjustable and quick-release camera mounts.
    - Simple health sensors (e.g., limit switch counters, temperature or vibration tags).
  - These upgrades support larger fleets and longer duty cycles.
  - All improvements are mechanically incremental and achievable by student teams in follow-up cycles.

12 Innovation Highlights

12.1 Innovative Approaches in Mechanical Design

- **Horizontally actuated scissor lift inside the footprint**
  A four-stage scissor lift driven by a horizontal lead screw keeps all Z-axis hardware within the base footprint while still reaching 1.8 m rack height. This reduces collision risk in narrow aisles and is buildable with standard plates, profiles, and bearings for a B.Tech-level team.

- **Modular T-slot chassis as a mechanical backplane**
  The T-slot aluminium frame doubles as a structural skeleton and a universal mounting grid for drive, lift, battery, and electronics. Subsystems can be re-positioned or upgraded using only bolts and brackets, enabling fast iterations without cutting or welding.

- **Differential drive tuned for stability and control simplicity**
  A 2-wheel differential drive plus front–rear casters creates a diamond 4-point support polygon that offers zero-radius turning with good lateral stability. Its simple kinematics work well with standard differential-drive control, making it friendly for student-level navigation algorithms.

- **Camera layout driven by mechanics and FOV planning**
  A fixed navigation depth camera is paired with a lift-mounted scanning camera, and the lift stroke and stand-off are chosen so five shelf levels fall within the scanning camera's FOV. This makes full rack coverage a geometric guarantee, not just a software patch.

12.2 Innovative Approaches in Fabrication and Integration

- **3D-printed camera mounts with built-in damping**
  PLA camera brackets with stiffening ribs and thin damping pads provide both low-cost rapid prototyping and basic vibration isolation. This keeps the mounts student-fabricable while still supporting stable images at maximum lift height.

- **COTS-centric component strategy for a replicable platform**
  The robot relies heavily on off-the-shelf motors, casters, profiles, and bearings, reducing custom machining and sourcing risk. This makes the design easy to rebuild, repair, and extend by other student teams or labs.

- **Design decisions explicitly tied to safety and testing**
  Features such as anti-tip mass layout, hard lift stops, and accessible E-stop placement were chosen with specific tipping, bump, and stop-distance tests in mind. Treating these tests as design inputs, not afterthoughts, is a notable process innovation at the B.Tech project level.

13 Testing & Validation

13.1 The testing and validation strategy

- **Manual mapping**
  The rover was first teleoperated to verify basic drive behaviour, sensor calibration, and to generate initial maps of the test environment for baseline reference.

- **Autonomous mapping (SLAM)**
  Next, SLAM was enabled so the robot could self-explore and build a complete 2D/3D map of the arena, validating simultaneous localization and mapping performance.

- **Autonomous navigation**
  Using the generated map, path-planning and localization were tested by commanding the rover to follow planned routes and reach target poses without collision.

- **Z-axis control**
  The scissor-lift mechanism was exercised across all five shelf levels to check vertical positioning accuracy, repeatability, and stability of the camera at height.

- **QR scanning in motion**
  Finally, tests combined navigation and lift motion while the vision stack detected, tracked, and decoded QR codes on racks, confirming end-to-end scan reliability under realistic movement.

13.2 Results

- **Manual Mapping (Teleoperation)**
  - **Test description:** Teleoperated laps along a 6 m aisle with one 90° turn while logging odometry and map overlap.
  - **Key results:**
    - Average endpoint drift over 6 m: 0.11 m (RMS), within the ±0.10–0.15 m design target.
    - Map overlap between successive teleop runs: >95% occupied cell consistency in the main aisle region (RViz comparison).
- **Autonomous Mapping (SLAM)**
  - **Test description:** Three full SLAM runs in an 4 m $\times$ 3 m test arena with racks and obstacles.
  - **Key results:**
    - Map completion: 97–99% valid occupancy grid coverage across runs.
    - Loop closure correction: final pose error after a full loop of the perimeter ≤ 0.12 m and $\leq 3°$ orientation error.
    - Runtime per mapping session: 3–4 minutes.
    - No SLAM crashes or lost-track events in the final configuration.
- **Autonomous Navigation**
  - **Test description:** 20 autonomous point-to-point runs between two rack faces 8 m apart with obstacles placed mid-aisle.
  - **Key results:**
    - Goal reach success rate: 19/20 runs (95%), with 1 aborted due to a conservative safety stop near an unexpected obstacle.
    - Final pose error at goal markers: mean 6.8 cm, max 11.9 cm — within the ±10 cm target for most trials.
    - Mean path-following speed: 0.18 m/s; peak speed capped at 0.25 m/s on straight segments.
    - Minimum clearance to mapped obstacles: > 15 cm in all successful runs.
- **Z-Axis Control (Lift Performance)**
  - **Test description:** 10 full-stroke cycles and repeated positioning at 5 predefined shelf heights.
  - **Key results:**
    - Full stroke time (bottom to top): 12.4 s average, ±0.6 s variation across 10 cycles.
    - Vertical repeatability (5 heights $\times$ 5 trials): mean error 9–14 mm, max error 18 mm — within the ±20 mm design spec.

    - Platform tilt at maximum extension: $\leq 1.3°$; camera FOV remained valid at top shelf.
    - No jamming or over-current events; limit switches triggered reliably at both extremes.

- **QR Scanning in Motion**
  - **Test description:** Robot traverses a 6 m rack face while the lift cycles through 5 shelf levels, each with 2 QR codes.
  - **Key results:**
    - Total QR codes presented: 100 (5 shelves $\times$ 2 codes $\times$ 10 passes).
    - First-pass successful decode rate: 96%; remaining 4% recovered on automatic rescan $\rightarrow$ **100% final registration**.
    - Average QR detection distance: 0.20–0.23 m stand-off; decode time < 120 ms per code.
    - No missed codes due to mechanical vibration; all failures were from intentionally induced occlusions or extreme lighting.

14 User Manual

14.1 Overview

- This manual describes how to operate and assemble the robot safely and correctly.
- The robot includes the following user-accessible inputs and interfaces:
  - Main ON/OFF switch.
  - Two kill switches (drive system + Z-axis scissors lift).
  - Touchscreen LCD display.

14.2 Operating the Robot

- **Safety Requirements**
  - Ensure both kill switches are not pressed before startup.
  - Keep hands, clothing, hair, and accessories away from wheels and the scissors lift.
- **Starting the Robot**
  - Turn ON the machine using the main switch.
  - A welcome message appears on the touchscreen.
  - Select a nearby Wi-Fi network when prompted.
  - After connecting, the touchscreen displays an IP address.
  - Enter this IP address into the mobile app to establish connection.
  - Once connected, the following options become available:

        - Mapping.
        - Scanning.
        - Stop.
        - Live feed (mobile only).
        - Inventory data.

- **Operating from the Robot Touchscreen**
    - The robot can be operated without the mobile app.
    - An additional option available only on the touchscreen:
        - **Machine Jogging**: manual movement of the robot and Z-axis.
- **Emergency Stop**
    - The robot includes two kill switches:
        - **Drive Kill Switch**: immediately stops all wheel motion.
        - **Z-Axis Kill Switch**: immediately stops the scissors lift.
    - Pressing any kill switch overrides all commands.

14.3 Assembly Manual

- **Included Parts**
    - Pre-assembled components:
        - Chassis with electronics.
        - Mounts.
        - Z-axis baseplate with lead screw mechanism.
    - Loose components:
        - Drive motors.
        - Wheels.
        - Castor wheels.
        - Four pairs of scissor linkage units.
        - Z-axis top plate with slider mechanism.
        - Batteries.
        - Camera modules.
- **Assembling the Drive System**
    - Mount each motor into its designated motor holder.
    - Attach wheels to each motor shaft and tighten securely.

- Connect motor wires to the correct PCB ports.
- Attach castor wheels to the marked locations on the chassis underside.

- **Assembling the Scissors Lift**
  - Mount the Z-axis motor into its holder and connect wiring to the PCB.
  - Insert the lead screw into the motor coupler and tighten the Allen screw.
  - Assemble the four scissor layers sequentially:
    - Attach the bolt side to the fixed support.
    - Attach the bearing side to the sliding mechanism.
    - Stack the next layer and secure with provided hardware.
  - Attach the top plate, ensuring symmetry with the bottom plate.
  - Install horizontal support members at designated mounting points.
- **Installing the Cameras**
  - Position each camera on its mount.
  - Secure with the appropriate fasteners.
- **Installing the Batteries**
  - Insert each battery into its labeled slot.
  - Connect wires to PCB ports ensuring correct polarity.

14.4 Final Checklist Before Use

- All motors, cameras, and mechanical components securely mounted.
- All wiring connected to correct PCB ports.
- Batteries installed properly.
- Kill switches functioning as expected.
- Scissors mechanism moves freely in jogging mode.
- Wheels rotate smoothly without obstruction.

15 Maintenance

15.1 Preventive Maintenance

- The maintenance plan is intentionally simple so it can be executed reliably by a student team during development and competition. It focuses on detecting loosening, wear, and friction-related issues before they cause failures.
- **Routine Checks**
  - Perform regular bolt re-torque on chassis connections and lift joints to counter loosening from vibration and transport.

- Inspect wheels and casters for wear, wobble, or looseness.
- Verify that lift pivots and bearings do not show excessive play or unusual noise.
- These routine checks help prevent unexpected mechanical failures during runs.

- **Lubrication and Pre-Run Safety Checks**
  - Apply light lubrication to the lead screw and pivot bearings at defined intervals to reduce friction and extend component life.
  - Keep lubricant away from cameras, sensors, and electronic components.
  - Use a pre-run safety checklist before every session:
    - Test emergency stop functionality.
    - Confirm free motion of casters and drive wheels.
    - Check actuation of limit switches at both ends of the lift stroke.
    - Inspect cables and connectors for visible damage or looseness.
  - These steps verify that critical safety and motion subsystems are functioning properly before operation.

15.2 Replacement Parts and Transport

- The robot is designed so that common wear parts can be replaced quickly, and the form factor allows easy transport to testing and competition venues.
- **Critical Spares**
  - Maintain a small stock of spare drive wheels and casters.
  - Keep extra lift pivot bolts and bearings.
  - Store at least one backup 3D-printed camera bracket.
  - These parts cover the most common minor failures, enabling fast repairs using basic tools and minimizing downtime.
- **Transport Considerations**
  - The robot fits inside a standard car or van when the lift is fully retracted.
  - The lift can be strapped or locked down to prevent bouncing during transit.
  - Removable guards or covers may be detached for transport to reduce risk of damage and simplify packing.
  - These design choices make the platform practical to move between the lab, testing zones, and competition venues.

16 References

16.1 Differential Drive Kinematics and Control

- Columbia University. “Differential Drive Kinematics.” Department of Computer Science.
- Aleksandar Haber. “Clear and Detailed Explanation of Kinematics, Equations, and Geometry of Motion of a Differential Wheeled Robot.”
- “Kinematics of Differential Drive Robots and Odometry.” YouTube Tutorial.
- “Position Control of Differential Drive Mobile Robot – Complete Tutorial with Simulation.” YouTube Tutorial.
- “Mobile Robot Kinematics.” Course Notes, Carnegie Mellon University.

16.2 Warehouse Robots and Autonomous Systems

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- “Mobile Robot for Automated Storage & Retrieval System (AS/RS).” IJRTE Journal.
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16.3 Scissor Lift Mechanisms and Vertical Motion Systems

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- “Final Year Project Report on Scissor Lift.” SlideShare Technical Report.
- IRJET. “Scissor Lift Automation Study” (Mechanical analysis, stability, limit switches).
- Manufacturer Application Notes: “Limit Switches, Hard Stops, and Lock-Out Mechanisms in Elevating Work Platforms.”

16.4 Chassis, T-Slot Frame Design, and Mechanical Components

- Bosch Rexroth. “Aluminum Profile Kit – Structural Components for Automation.”
- PTSMAKE. “Ultimate Guide to T-Slot Aluminum Profiles for Engineering.”
- YAJIA Aluminum. “Universal Robots Aluminum Extrusions – Standard T-Slot Profiles.”
- JLCMC. “T-Slot Aluminum Explained – Modular Framing for Robotics.”
- Robotunits. “Extrusion & Fastening Technology – Engineering Profiles and Connectors.”
- Planetary DC Gear Motor Datasheets (e.g., RMCS 2012): torque–speed curves, encoder CPR, gearbox ratio.
- Ball Caster Component Datasheet: load ratings, dimensions, mounting specifications.

- 6061 / 6062 Aluminium Alloy Data Sheets: material properties used for stiffness and strength estimation.

16.5 Vision, Sensors, and Depth Cameras

- Intel Corporation. “Intel RealSense Depth Camera D455 – Product Brief.”
- Intel RealSense. “D400 Series Datasheet,” Document No. 337029 016.
- Intel RealSense. “D455 Mechanical Integration Guidelines.”
- Mouser Electronics. “Intel RealSense D455 – Feature Overview.”

16.6 Maintenance, Safety Standards, and Human Factors

- ISO 3691-4. “Industrial Trucks – Safety Requirements and Verification – Driverless Industrial Trucks.”
- Vendor Manuals for AGVs/AMRs: lubrication schedules, bolt re-torque intervals, and pre-run safety inspections.
- Application Notes for Scissor Lifts: safe limit switch placement, hard stops, and emergency lockout mechanisms.

16.7 Additional Warehouse Automation and Benchmarking Sources

- AGILOX. “AMR Robot: Scissor Free & AI Powered.” Product benchmark for compact warehouse AMRs.
- Modula / SRS-i. “Warehouse Robotics – Types and Use Cases for Modern Warehousing.”
- “Design and Development of Warehouse Robot.” Scribd Technical Slides.

17 Bill of Materials (BOM)

Part ID	Part Name	Manufacturer	Quantity
1	PCB	PCB Power	2
2	Power Management system	buck boost , DC AC , live battery indicator ,	
3	RealSense D455	Intel	1
4	Lenovo 300 FHD Camera	Lenovo	2
5	Jetson AGX Xavier Developer Kit	NVIDIA	1
6	Data Cables	various	2
7	RMCS 2016	Rhino Motion Controls	1
8	RMCS 2012	Rhino Motion Controls	2
9	USB Hub	Honeywell	1
10	wheels	Easymech	2
11	wheel coupler	Easymech	2
12	flexible coupler	Astro	1
13	caster wheel	Easymech	1
14	Lead Screw		1
15	Batteries	ProRange	3
16	3D Printed Parts	in house	22
17	Aluminium T links		24
18	Aluminium Sheet (Parts)	in house cutting	25
19	L clamps	local market	40
20	Bearings 688	ARB	30
21	kill switch	Yokins	2
22	limit Kill Switch	RC Hobby	2

Table 2: Bill of Materials (Full Parts List)

18 CAD Models

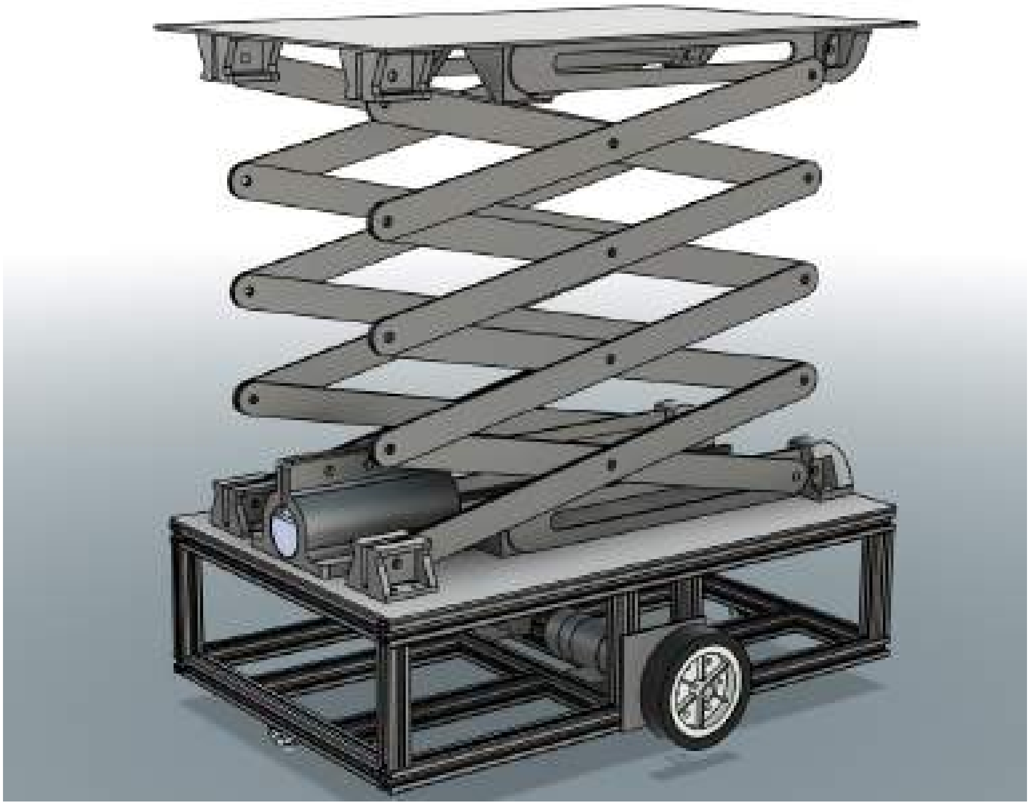

Figure 36: Full Model

Figure 37: Scissors Extended

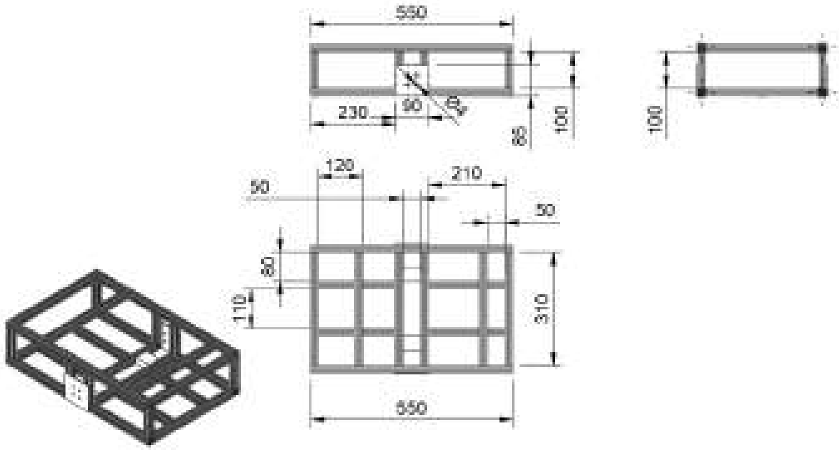

Figure 38: Chassis

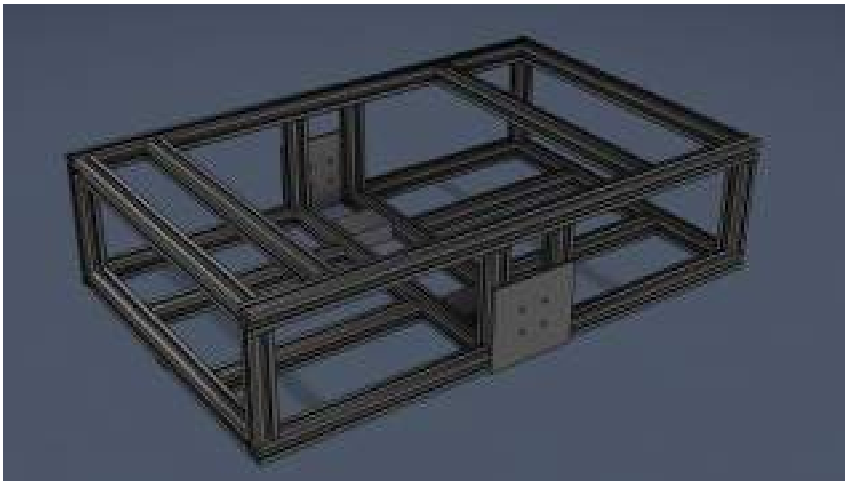

Figure 39: Chassis

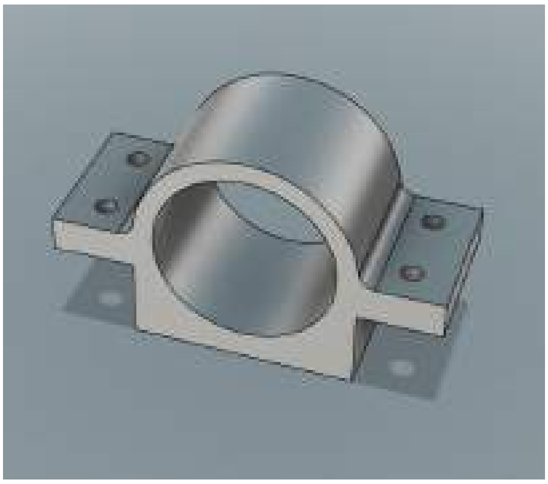

Figure 40: Wheel Motor Support Mount

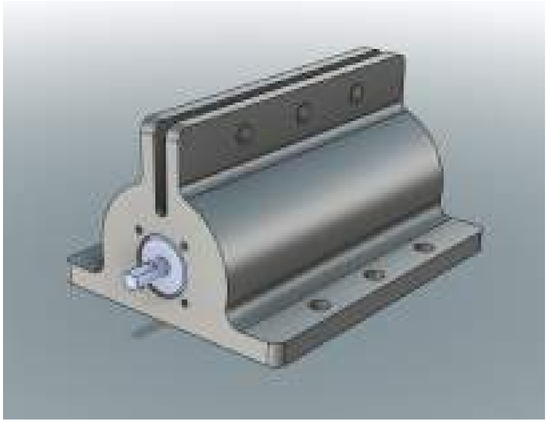

Figure 41: Z axis actuator motor mount

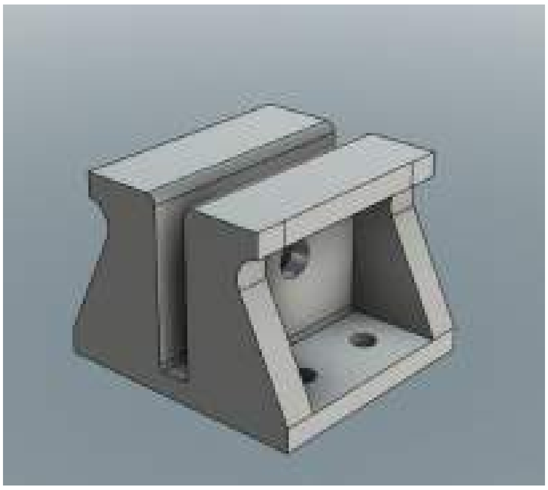

Figure 42: Fixed scissors mounting bottom

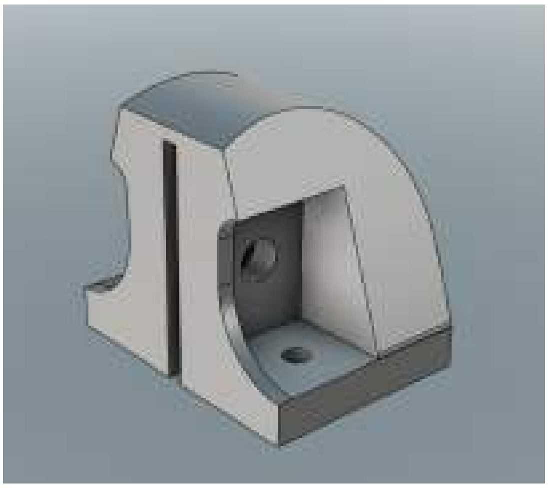

Figure 43: Slider mount type 1

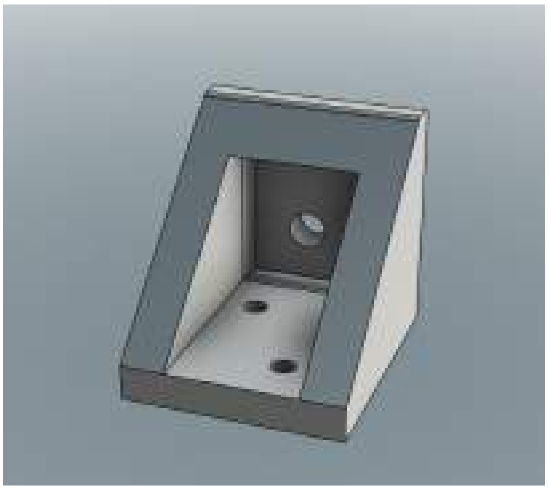

Figure 44: Slider mount type 2

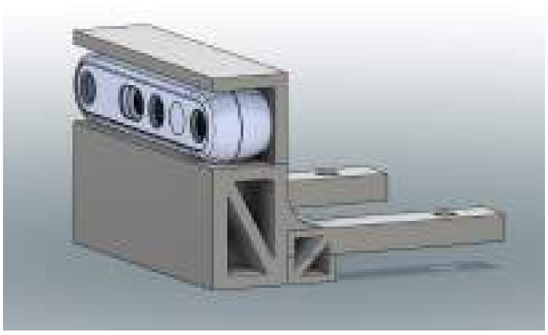

Figure 45: Camera Mount