Design of a Cartesian Robot for AOI of PCBs (PPP)

Leonardo Barrios	F11303103
Giuliana Brizuela	F11303106
Demian Escurra	F11303108
Luis Maria Prieto	F11303116
Luis Eduardo Vazquez	F11303117

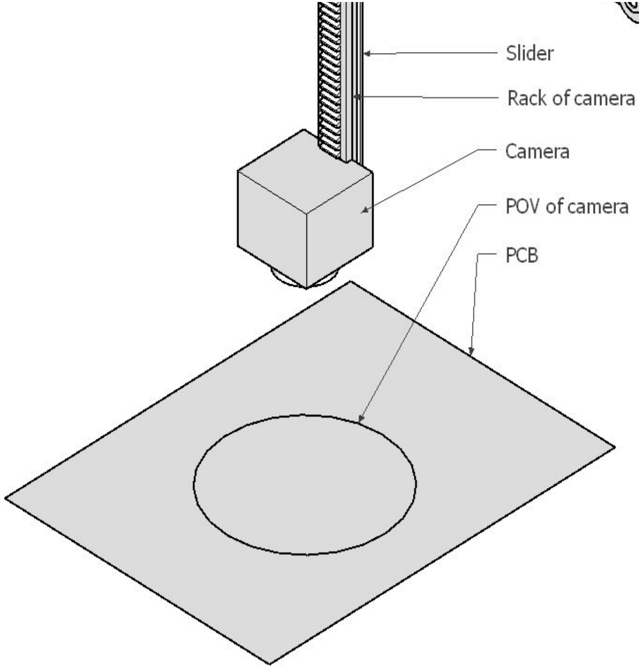
Application: Automatic Optical Inspection (AOI)

- Task:
  - Capture high-resolution images of PCB samples
  - Move camera in X–Y–Z directions
- End-effector: **Industrial camera**

Key points

- Capture high-resolution images
- Precise camera positioning
- Repeatable inspection

The robot provides precise and repeatable positioning for image acquisition. Th
rather than force interaction



Motivation

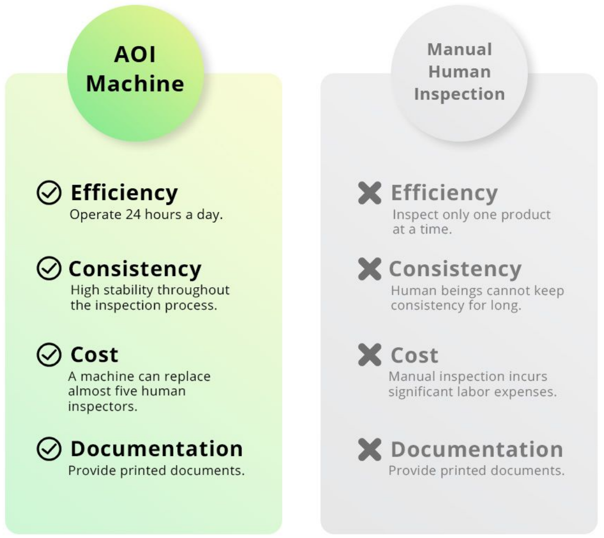
Manual inspection is:

- slow
- error-prone
- inconsistent

AOI robot allows:

- repeatability
- high precision
- automation

Accurate positioning is required to fully exploit the camera resolution.

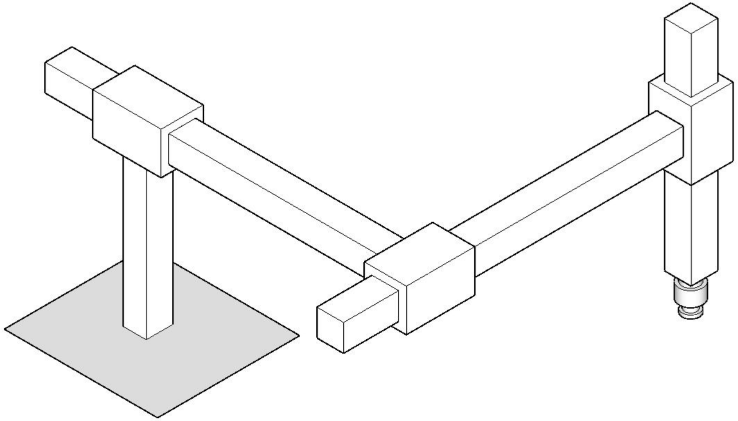


Robot Type: Cartesian Robot (PPP)

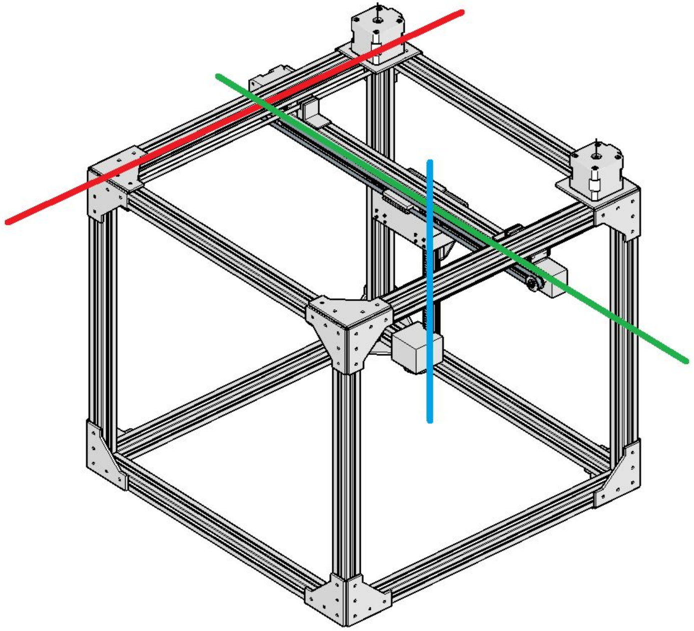
- Joint configuration:
  - Joint 1: Prismatic (X)
  - Joint 2: Prismatic (Y)
  - Joint 3: Prismatic (Z)
- DOF = 3

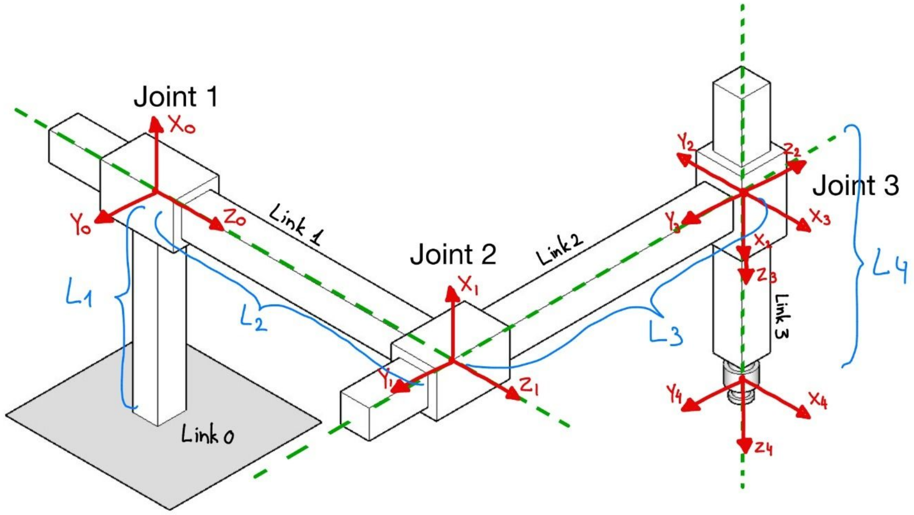
- Simple kinematics
- Decoupled motion
- Ideal for planar inspection

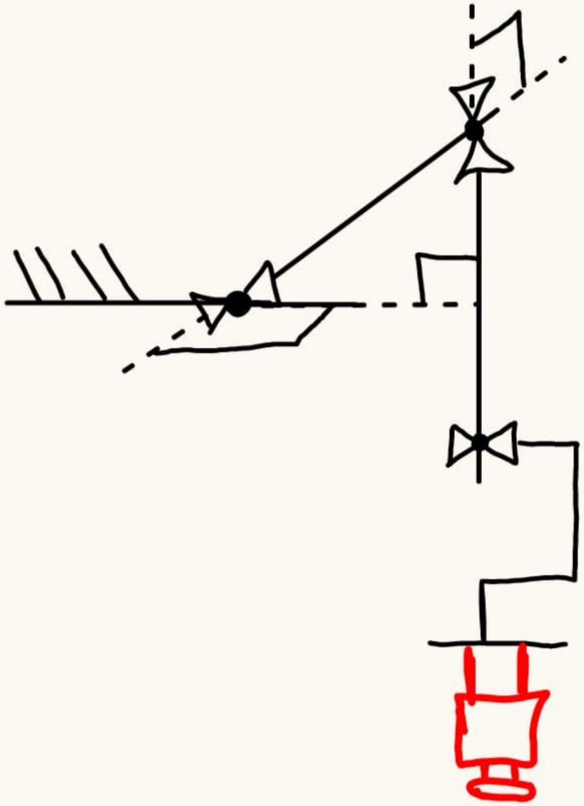
This configuration simplifies control and inverse



Robot Diagram

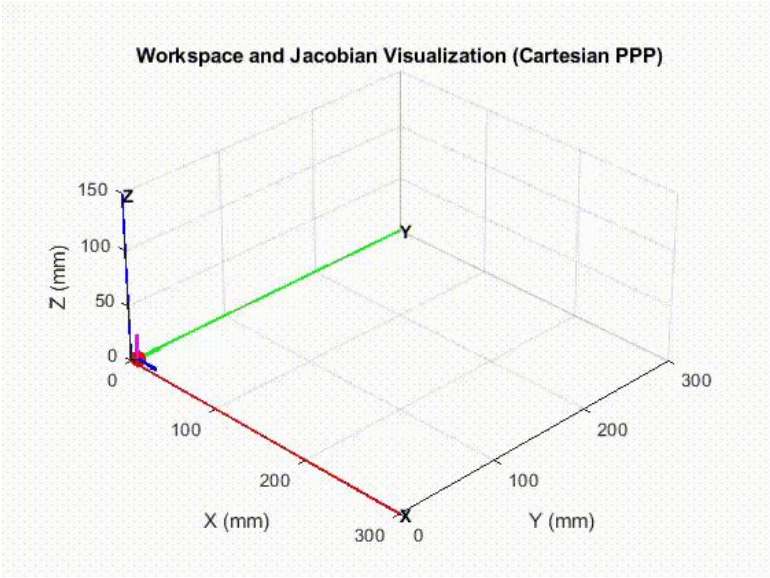


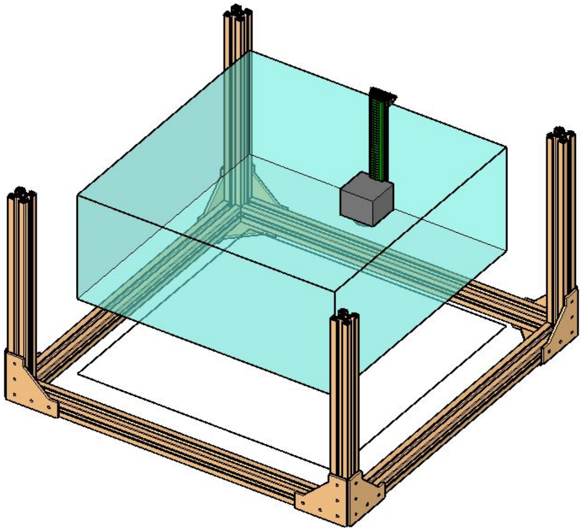




Workspace

For a PPP robot, reachable and dexterous workspace are identical.





$$X_{min} \leq x \leq X_{max}, \quad Y_{min} \leq y \leq Y_{max}, \quad Z_{min} \leq z \leq Z_{max}$$

Mathematical Model

Denavit–Hartenberg Parameters

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	d_1	0
2	-90	0	d_2	180
3	-90	0	d_3	-90
4	0	0	L_4	0

Where a_{i-1}, α_{i-1}, d_i and θ_i are the standard Denavit–Hartenberg parameters. The variables d1, d2 and d3 correspond to the prismatic joint displacements, while L4 represents the fixed end-effector offset.

Forward Kinematics

1. **Input variables**
   - q1: Displacement along the X-axis
   - q2: Displacement along the Y-axis
   - q3: Displacement along the Z-axis

2. **End-Effector Position**

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix}$$

3. **Homogeneous Transformation Matrix**

$$T_0^E = \begin{bmatrix} 1 & 0 & 0 & q_1 \\ 0 & 1 & 0 & q_2 \\ 0 & 0 & 1 & q_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Inverse Kinematics

For a desired end-effector position:

$$\mathbf{q} = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} = \begin{bmatrix} x_d \\ y_d \\ z_d \end{bmatrix} = \mathbf{p}_d$$

Due to the Cartesian structure, the inverse kinematics admit a unique analytical solution.

Differential Kinematics

$$\mathbf{J} = \frac{\partial \mathbf{x}}{\partial \mathbf{q}} = \mathbf{I}_3$$

The Cartesian structure results in a decoupled system with an identity Jacobian.

Camera-Resolution Relationship

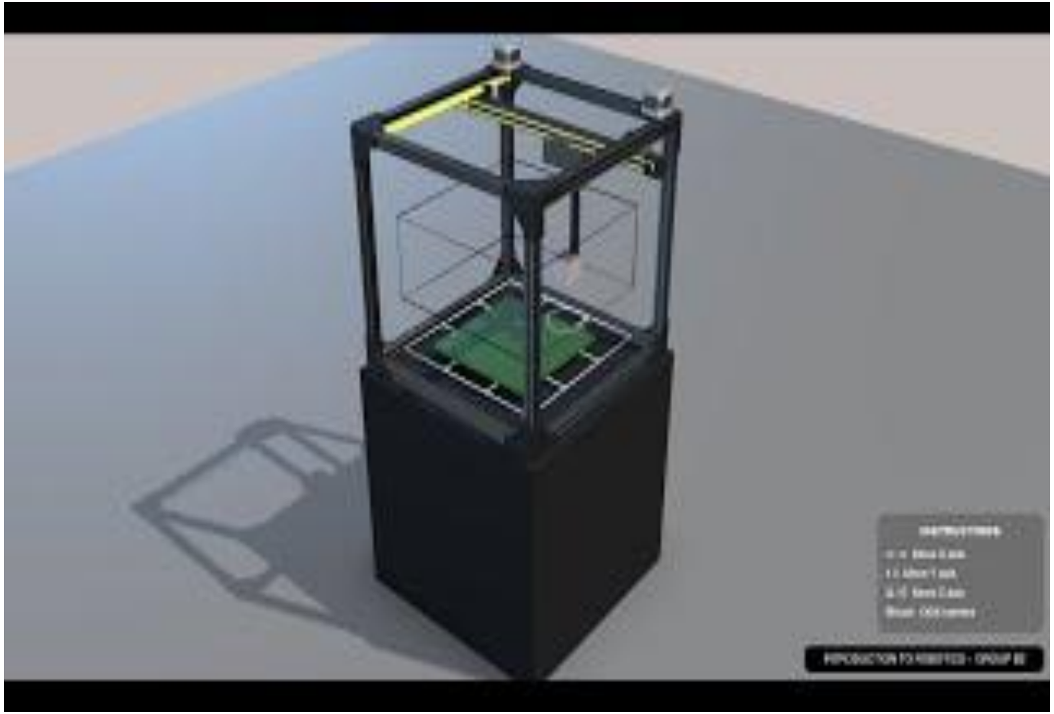
The camera field of view (FOV) defines a conical vision volume whose footprint on the PCB surface increases with the working distance zzz. The width of the imaged area is given by:

$$\mathbf{W(z) = 2z\ tan(FOV2)}$$

The spatial resolution is given by:

$$\mathbf{Resolution\ in\ mm/pixel = W(z)/Nx}$$

where Nxis the horizontal pixel resolution of the camera. This relationship highlights the trade-off between working distance and inspection resolution.



Precision Requirements

Camera resolution

- 0.05 mm / pixel

Robot positioning requirement

- Repeatability ≤ **0.03 mm**

Design consideration

- Camera FOV forms a **conical volume**
- Image footprint **increases with working distance**
- PCB size may exceed **single image footprint**
  (even within XY workspace)

Implications

- Raster scan required
- Image overlap required
- Trade-off: **resolution vs coverage**

Dynamic Considerations

Robot function: **precision positioning of a lightweight camera**

Operating conditions: **low speed, low acceleration (AOI scanning)**

Dominant external load: **gravity on Z-axis (camera payload)**

X–Y axes: friction and small inertial effects

Actuator sizing driven by:

- static load
- positioning accuracy
- repeatability

Quasi-static analysis is sufficient at this design stage

Dynamic Load Analysis (Z-axis dominant)

Decoupled Dynamics (axis-by-axis equations):

X and Y axes:

$$m_x x'' + B_x x' + F_{cx} sgn(x') = Fx$$

Z axis:

$$m_z z'' + B_z z' + F_{cz} sgn(z') + m_z g = Fz$$

Where:

• F_i is the linear actuation force on each axis

• m_i is the effective moving mass on each axis (for Y, this usually includes the X-axis carriage)

• B_i is viscous friction

• F_{ci} is Coulomb friction

• g is gravitational acceleration

Required Force / Torque

Required Force and Torque

This analysis determines the minimum actuator requirements for the Z-axis. The X and Y axes are dominated by friction and inertial effects and are treated similarly.

camera mass: $m_c = 0.30$ kg
motor mass: $m_m = 0.35$ kg (standard value)

$$m_{total} = m_c + m_m$$
$$m_{total} = 0.65\text{kg}$$

Force in the z-axis:

$$F_z = m_{total} * g$$
$$F_z = 0.65 * 9.81 = 6.38 \text{ N}$$

Relationship force-torque in a belt system:

$$T = F_z * r \quad \text{where} \quad r = 8\text{mm} = 0.008\text{m}$$
$$T = 6.38 * 0.008$$
$$T = 0.051 \text{ N.m} \quad \text{(Theoretical minimum torque)}$$

Required Force / Torque

Safety Factor

An appropriate safety factor is applied to account for uncertainties such as friction variation and manufacturing tolerances.

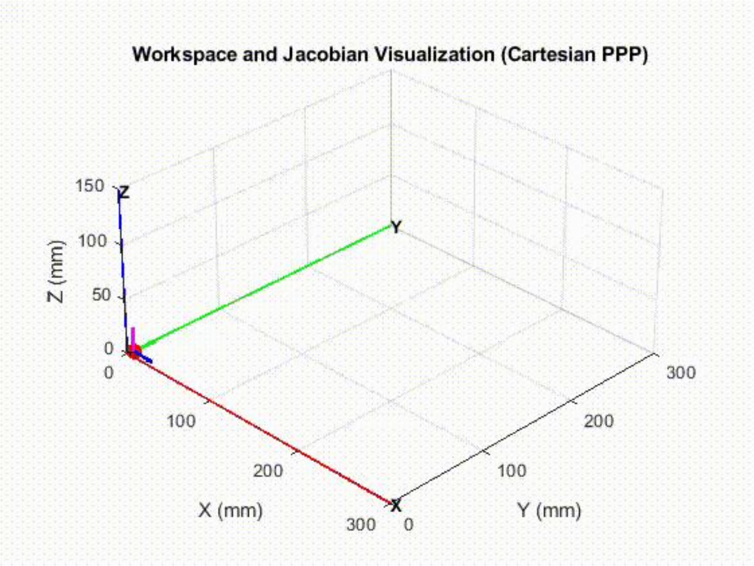
Typically for light industrial robotics we use SF = 2.

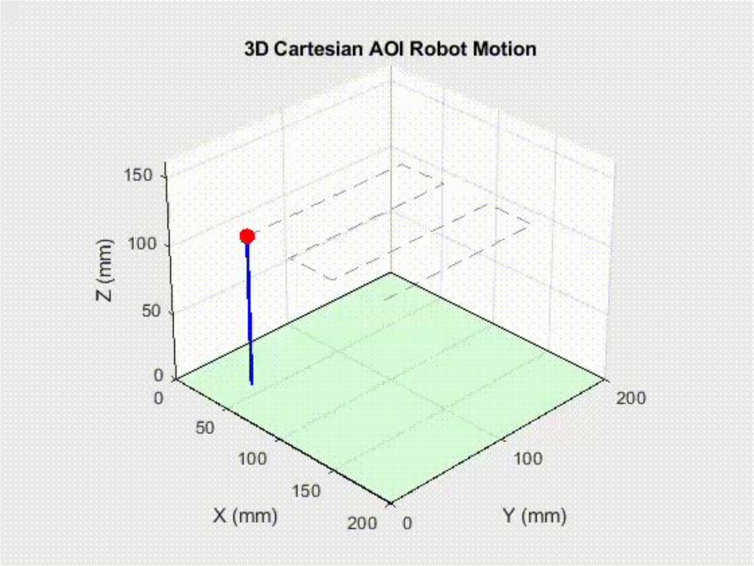
Tdesign = 20.051 = 0.10 N.m

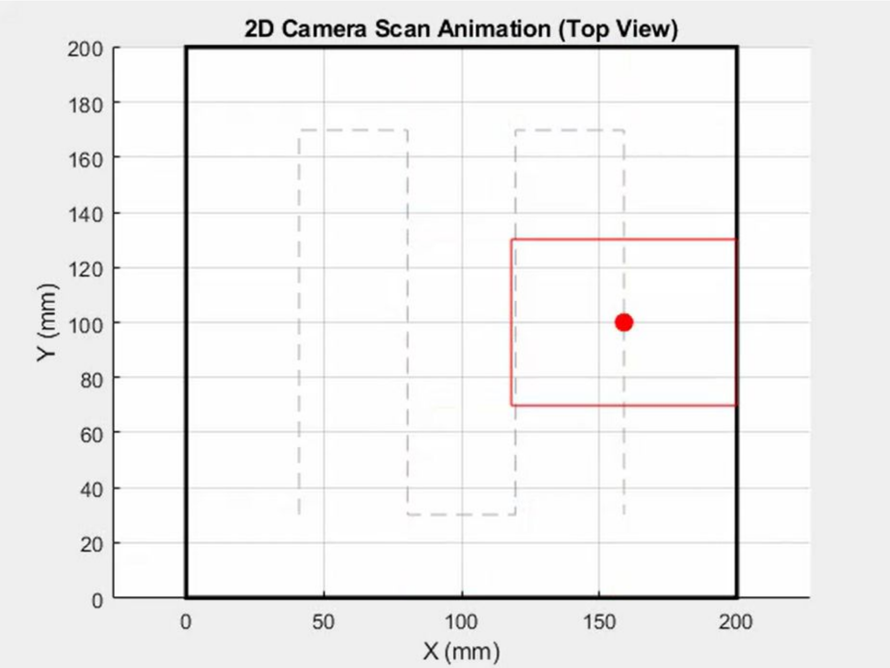
Tmotor is higher than the Tdesign and the nominal torque is between 0.4 N.m to 0.5 N.m

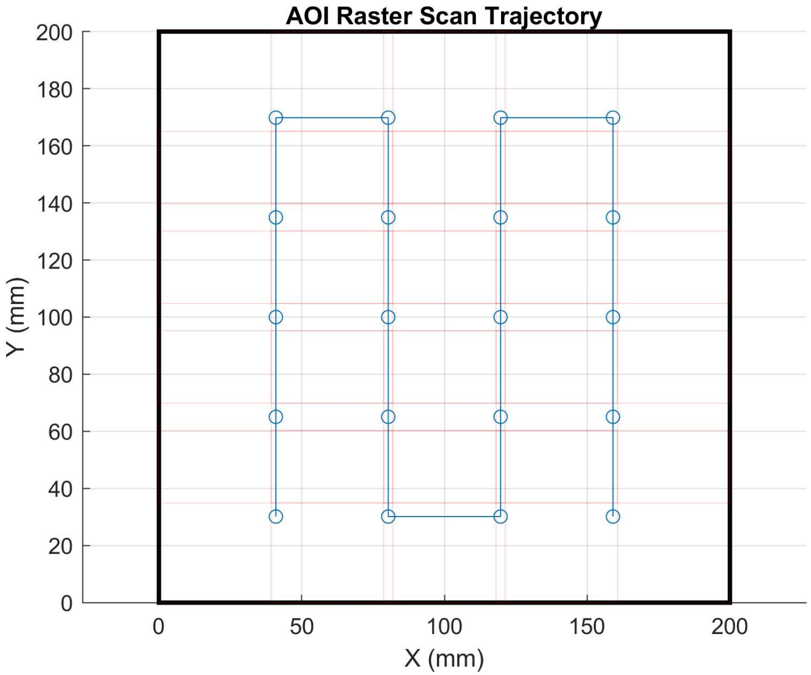
The resulting torque requirement is well below the nominal torque of a standard NEMA 17 stepper motor, confirming its suitability for the proposed AOI application.

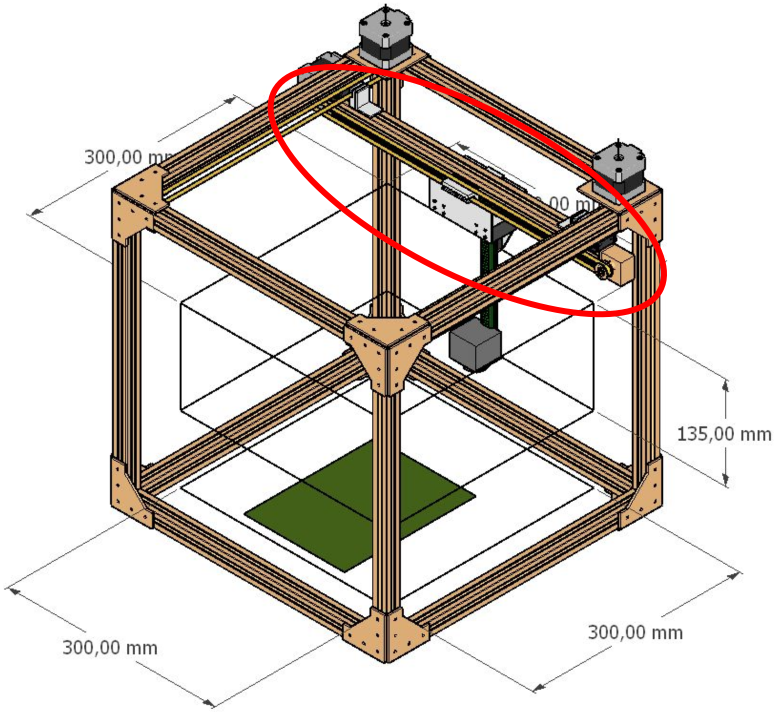
Simulations

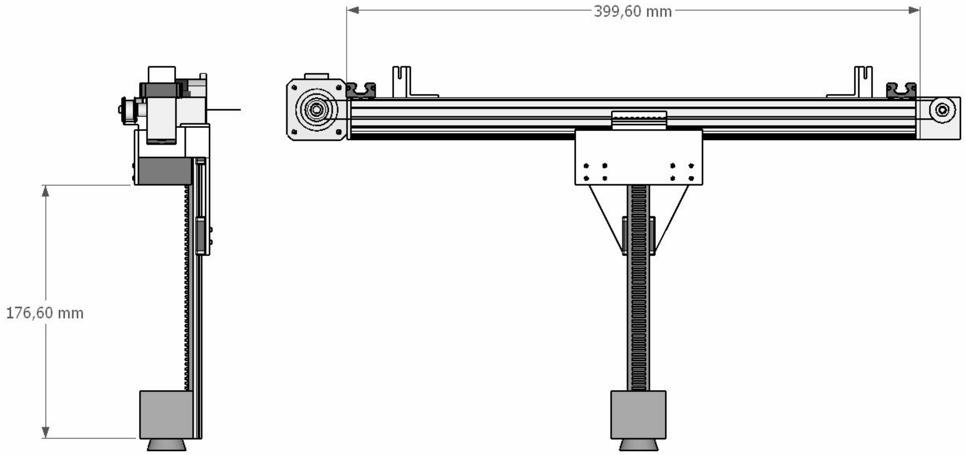


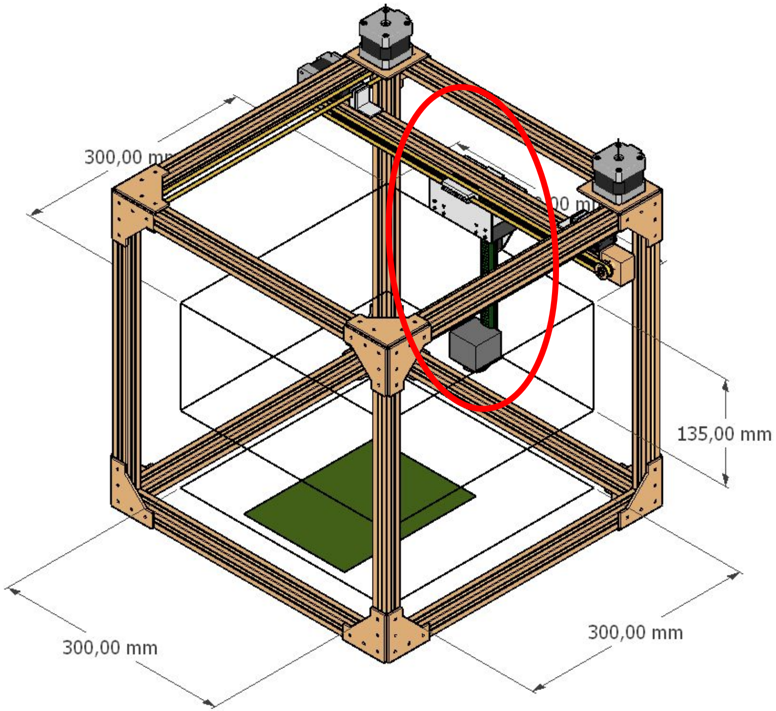


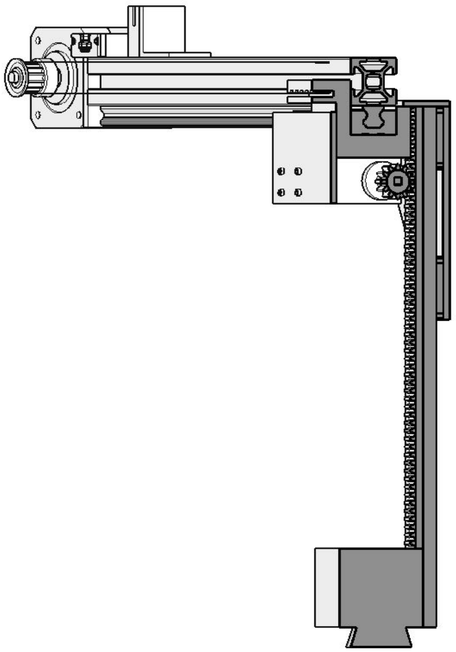

2D Camera Scan Animation (Top View)
Y (mm)
X (mm)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200

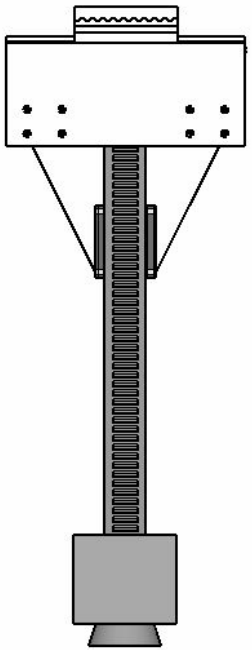

AOI Raster Scan Trajectory
Y (mm)
X (mm)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200


300,00 mm
135,00 mm
300,00 mm
300,00 mm

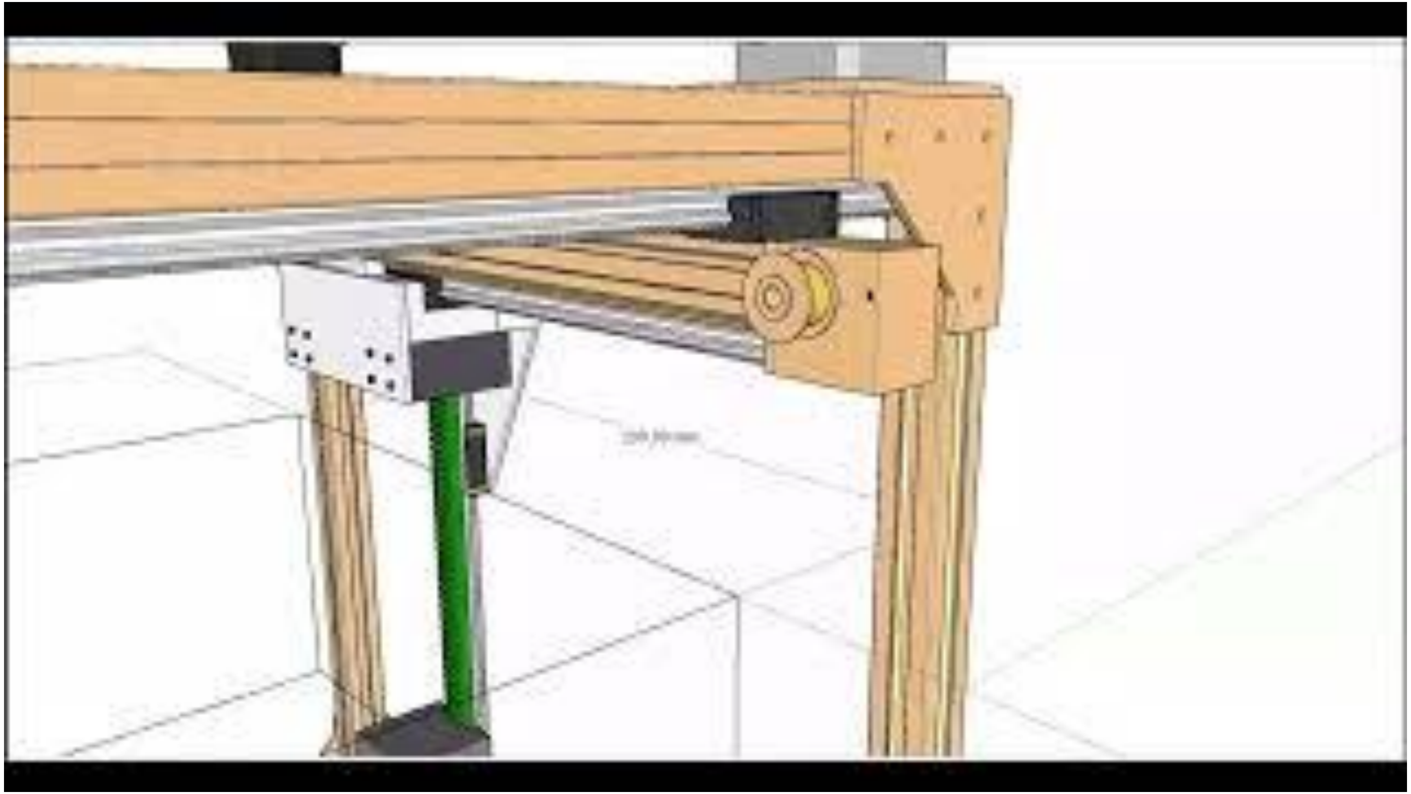

399,60 mm
176,60 mm


135,00 mm
300,00 mm
300,00 mm

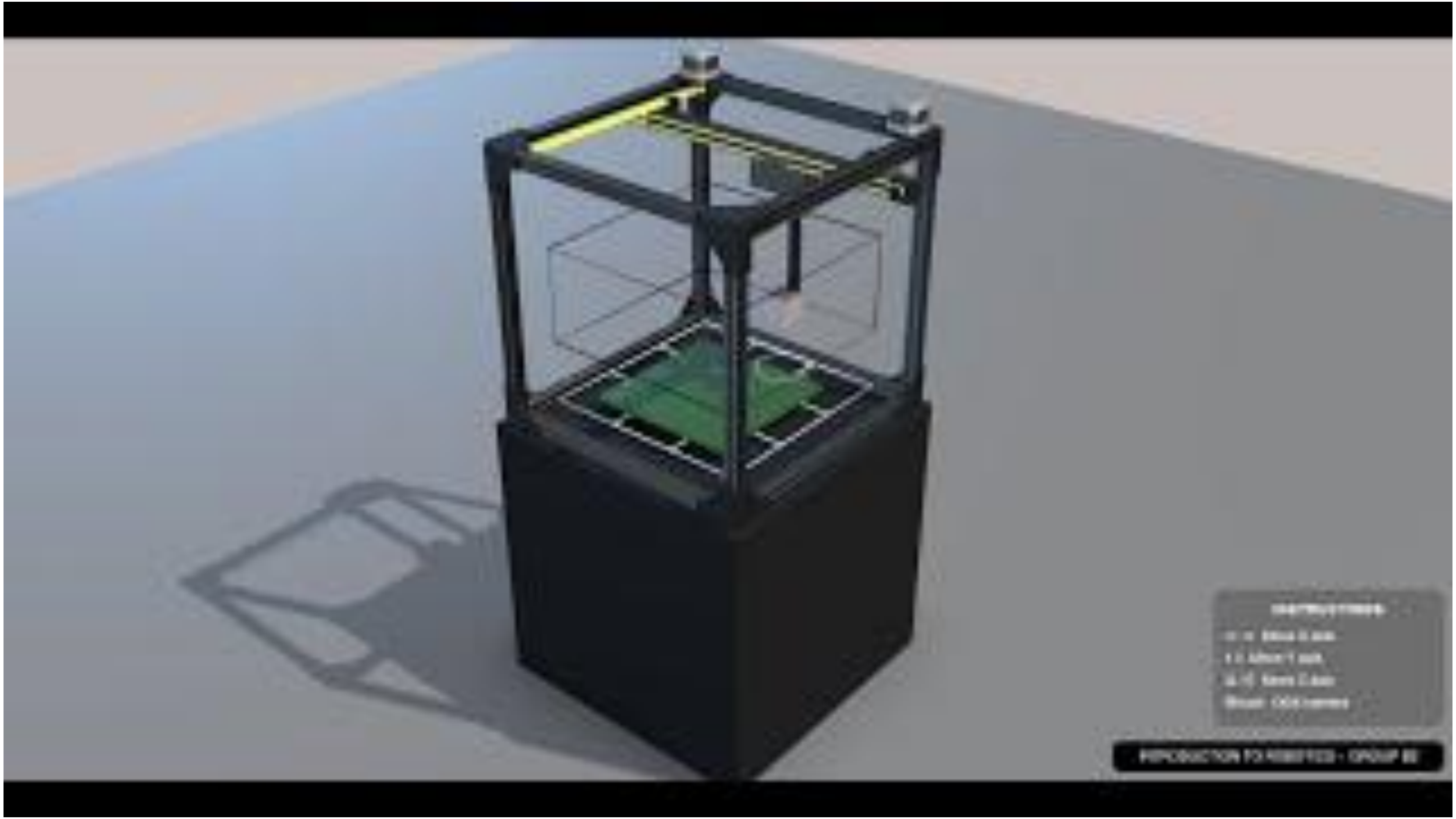




Simulations

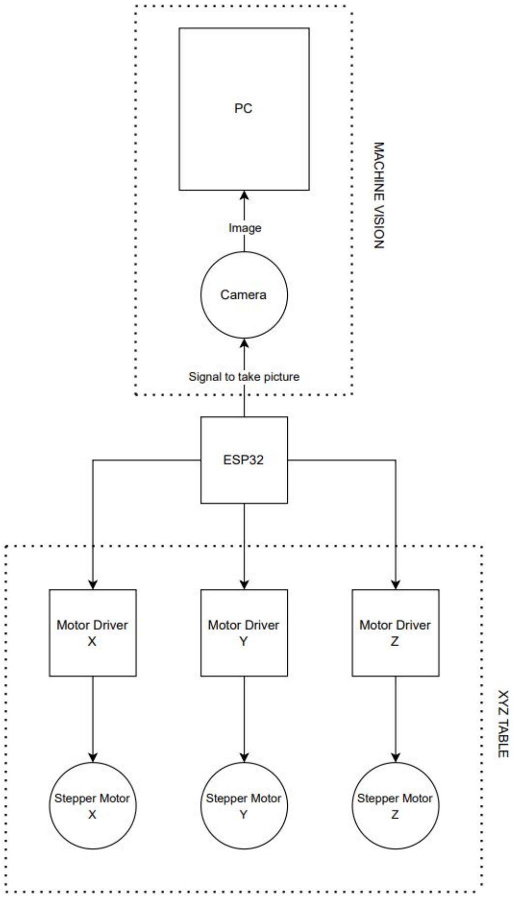


https://app.sketchup.com/share/tc/northAmerica/B7akIYUKGKA?source=web&stoken=DIPzc3P_IHAjUP8_VQ-jXvMQ23hpMmH2cTKifSW8coMmIl9sq8aC43QSrYKBZa2u

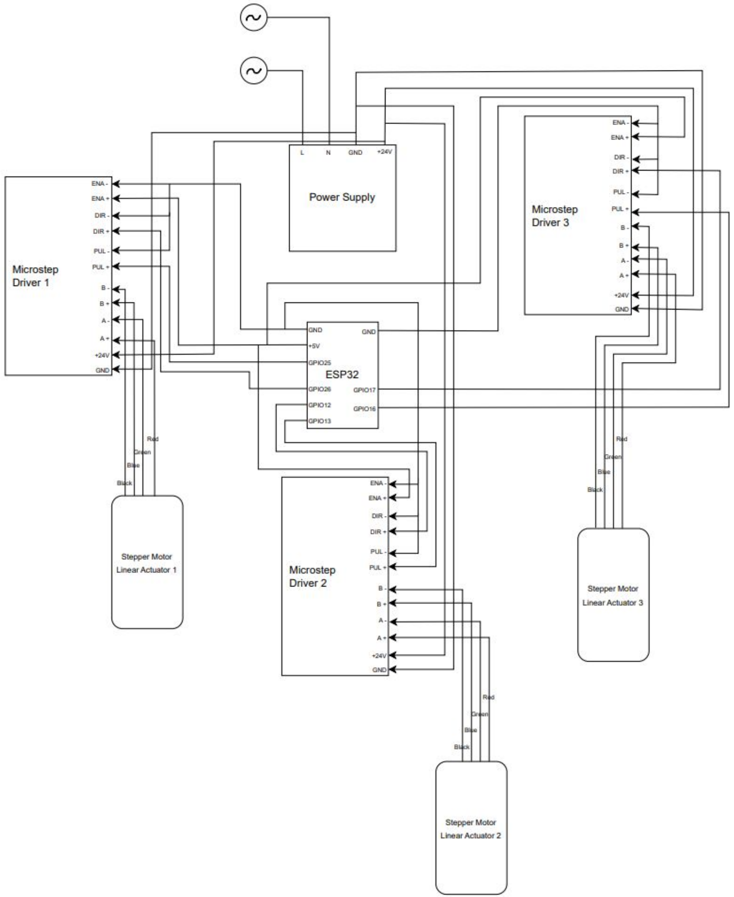


https://v3d.net/1e10

Connection Diagram



Electrical diagram



Components used and purpose

Category	Component	Purpose
Actuation	NEMA 17 Stepper	Linear motion generation
Drive	TB6600	Stepper motor control
Power	24 V DC Supply	System power
Transmission	GT2 Belt + Tensioner	Torque transmission
Guidance	MGN12 Linear Rail	Precision linear guidance
Structure	Aluminum Profiles 25×25	Robot frame
Custom Parts	3D Printed Components	Mounts and brackets
Control	ESP32	System controller

The system consists of an **ESP32** microcontroller and a **24V DC power supply**. It includes three **NEMA 17 stepper motors** with **59 Ncm** torque, accompanied by three **TB6600** drivers. The mechanical hardware comprises **25x25 mm aluminum profiles**, **3D printed components**, six **300 mm MGN12 linear guides**, as well as **6mm GT2 belts** and belt tensioners.

Github & Implementation

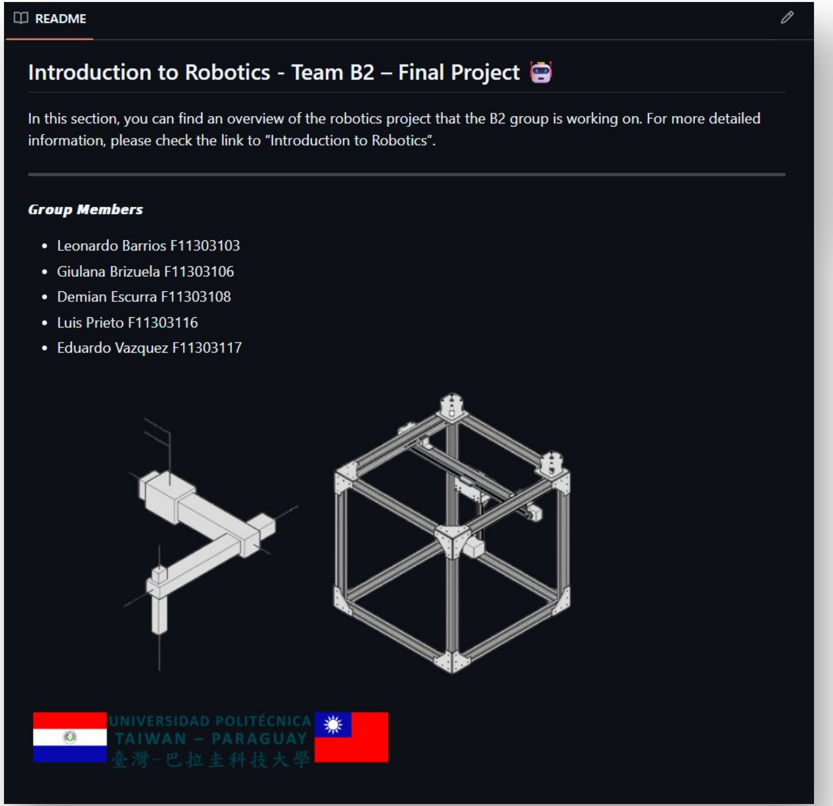
Qué mostrar

- Repo structure
- Scripts

Mensaje

All models and simulations are reproducible via the GitHub repository.

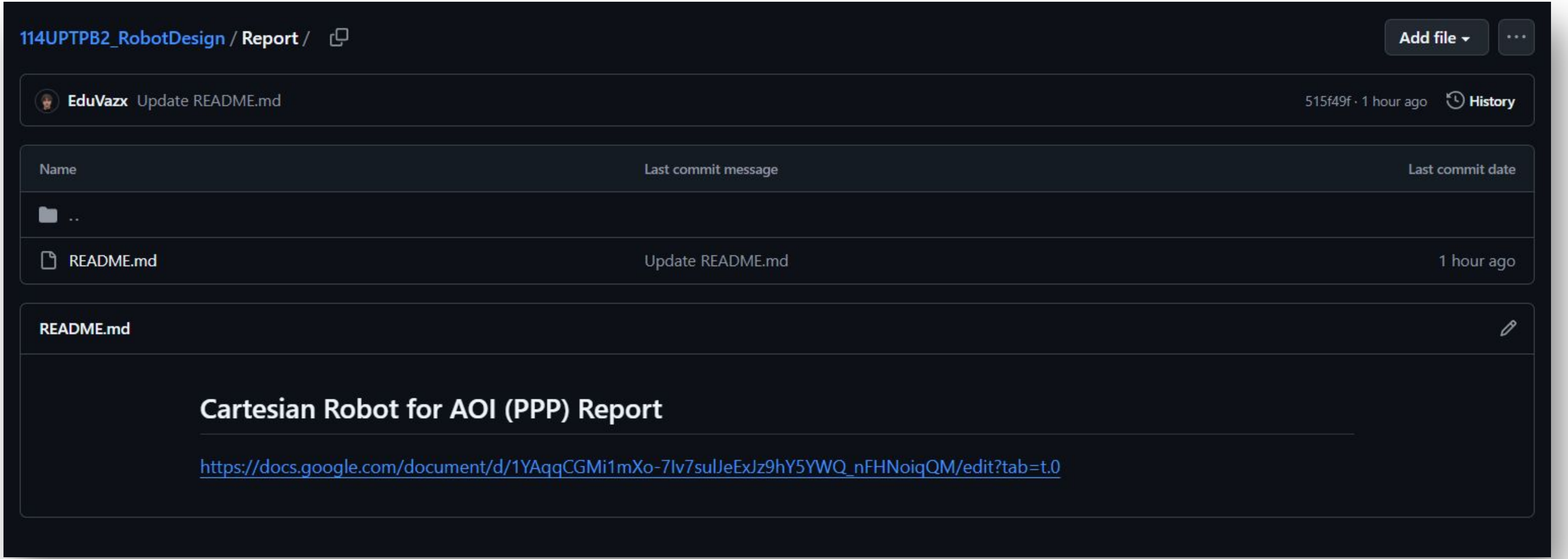
Github & Implementation



This is our project's centralized GitHub repository, titled: **114UPTPB2_RobotDesign**

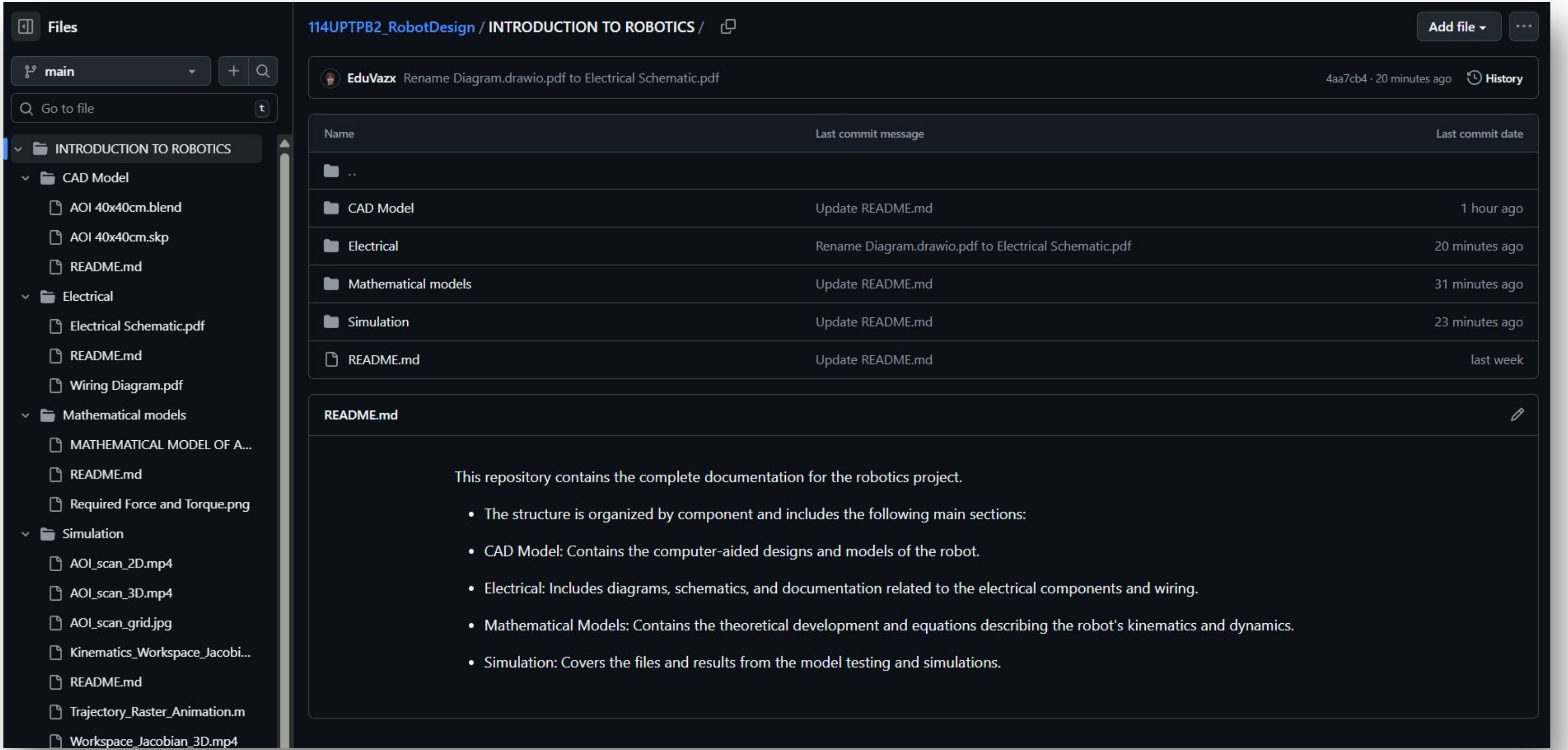
- **FOLDERS**
  - **INTRODUCTION TO ROBOTICS**
  - **Report**
- **README.md**

Report folder

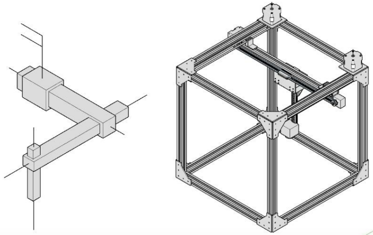


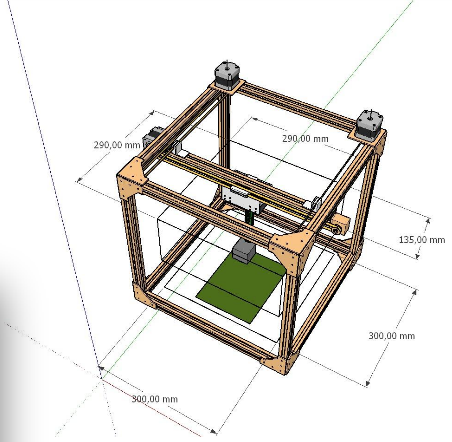
Formal report and the direct link for the Cartesian robot for AOI (PPP) Report

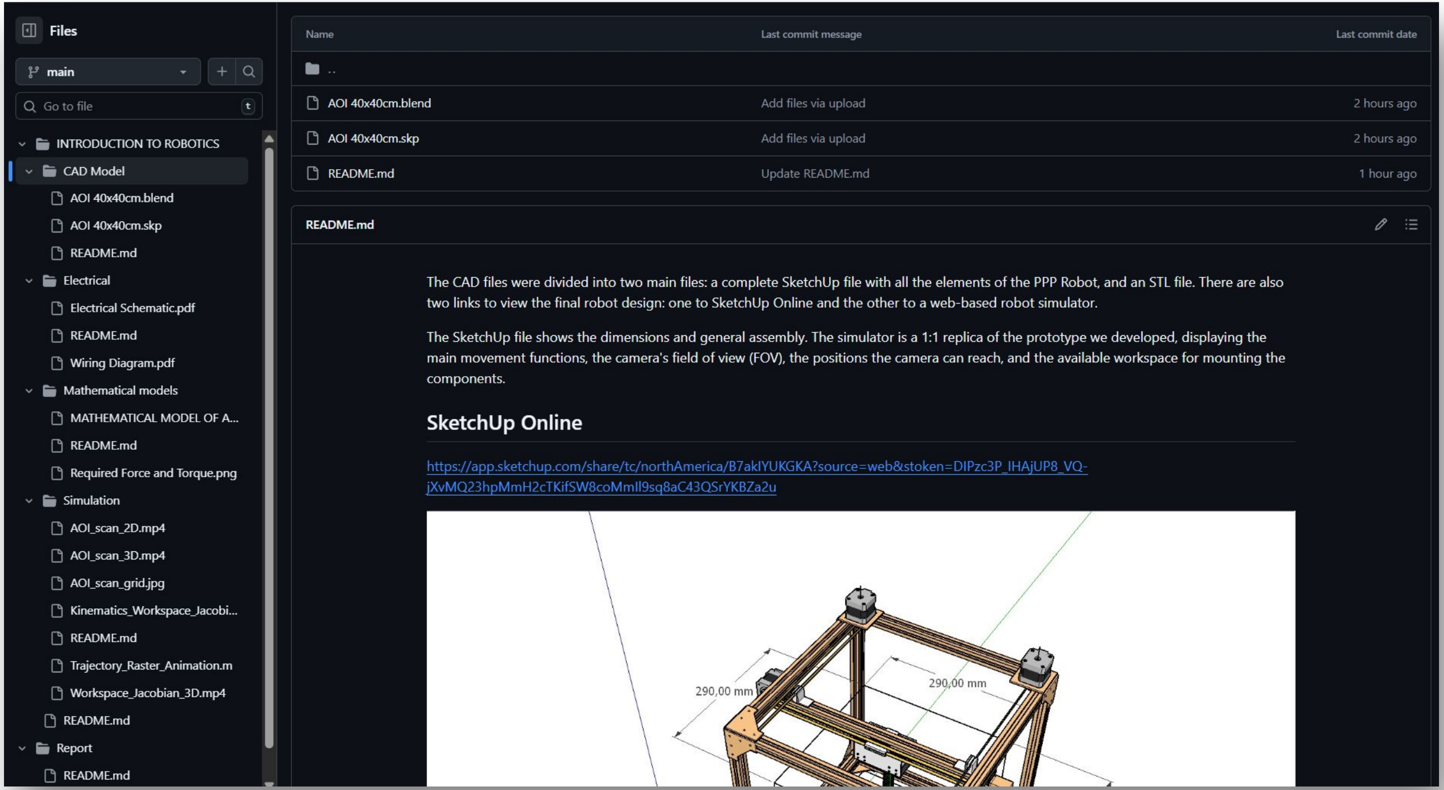
INTRODUCTIONS TO ROBOTICS folder

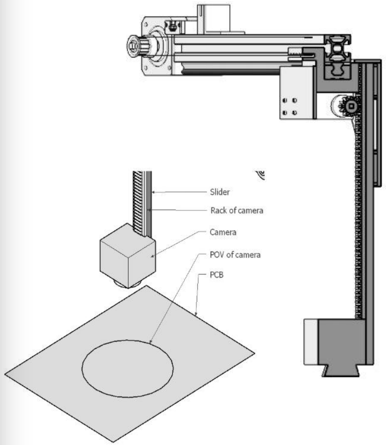


CAD Model

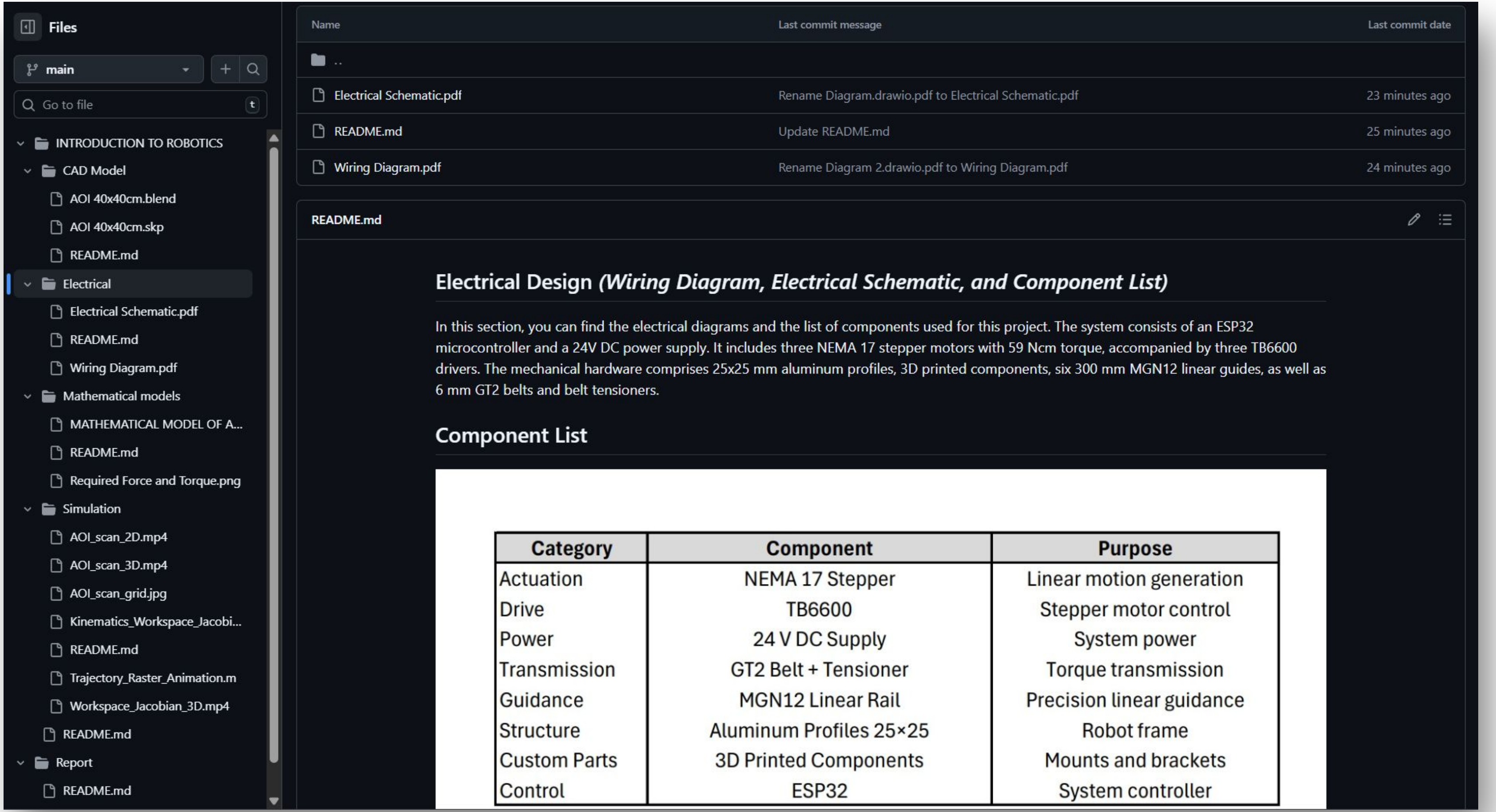



290,00 mm
290,00 mm
135,00 mm
300,00 mm
300,00 mm


Files
main
Go to file
INTRODUCTION TO ROBOTICS
CAD Model
AOI 40x40cm.blend
AOI 40x40cm.skp
README.md
Electrical
Electrical Schematic.pdf
README.md
Wiring Diagram.pdf
Mathematical models
MATHEMATICAL MODEL OF A...
README.md
Required Force and Torque.png
Simulation
AOI_scan_2D.mp4
AOI_scan_3D.mp4
AOI_scan_grid.jpg
Kinematics_Workspace_Jacobi...
README.md
Trajectory_Raster_Animation.m
Workspace_Jacobian_3D.mp4
README.md
Report
README.md
Name
Last commit message
Last commit date
..
AOI 40x40cm.blend
Add files via upload
2 hours ago
AOI 40x40cm.skp
Add files via upload
2 hours ago
README.md
Update README.md
1 hour ago
README.md
The CAD files were divided into two main files: a complete SketchUp file with all the elements of the PPP Robot, and an STL file. There are also two links to view the final robot design: one to SketchUp Online and the other to a web-based robot simulator.
The SketchUp file shows the dimensions and general assembly. The simulator is a 1:1 replica of the prototype we developed, displaying the main movement functions, the camera's field of view (FOV), the positions the camera can reach, and the available workspace for mounting the components.
SketchUp Online
https://app.sketchup.com/share/tc/northAmerica/B7akIYUKGKA?source=web&stoken=DIPzc3P_IHAjUP8_VQ-jXvMQ23hpMmH2cTKifSW8coMmIl9sq8aC43QSrYKBZa2u
290,00 mm
290,00 mm


Slider
Rack of camera
Camera
POV of camera
PCB

Electrical



Files

main

Go to file

- INTRODUCTION TO ROBOTICS
  - CAD Model
    - AOI 40x40cm.blend
    - AOI 40x40cm.skp
    - README.md
  - Electrical
    - Electrical Schematic.pdf
    - README.md
    - Wiring Diagram.pdf
  - Mathematical models
    - MATHEMATICAL MODEL OF A...
    - README.md
    - Required Force and Torque.png
  - Simulation
    - AOI_scan_2D.mp4
    - AOI_scan_3D.mp4
    - AOI_scan_grid.jpg
    - Kinematics_Workspace_Jacobi...
    - README.md
    - Trajectory_Raster_Animation.m
    - Workspace_Jacobian_3D.mp4
  - README.md
- Report
  - README.md

Name	Last commit message	Last commit date
..		
Electrical Schematic.pdf	Rename Diagram.drawio.pdf to Electrical Schematic.pdf	23 minutes ago
README.md	Update README.md	25 minutes ago
Wiring Diagram.pdf	Rename Diagram 2.drawio.pdf to Wiring Diagram.pdf	24 minutes ago

README.md

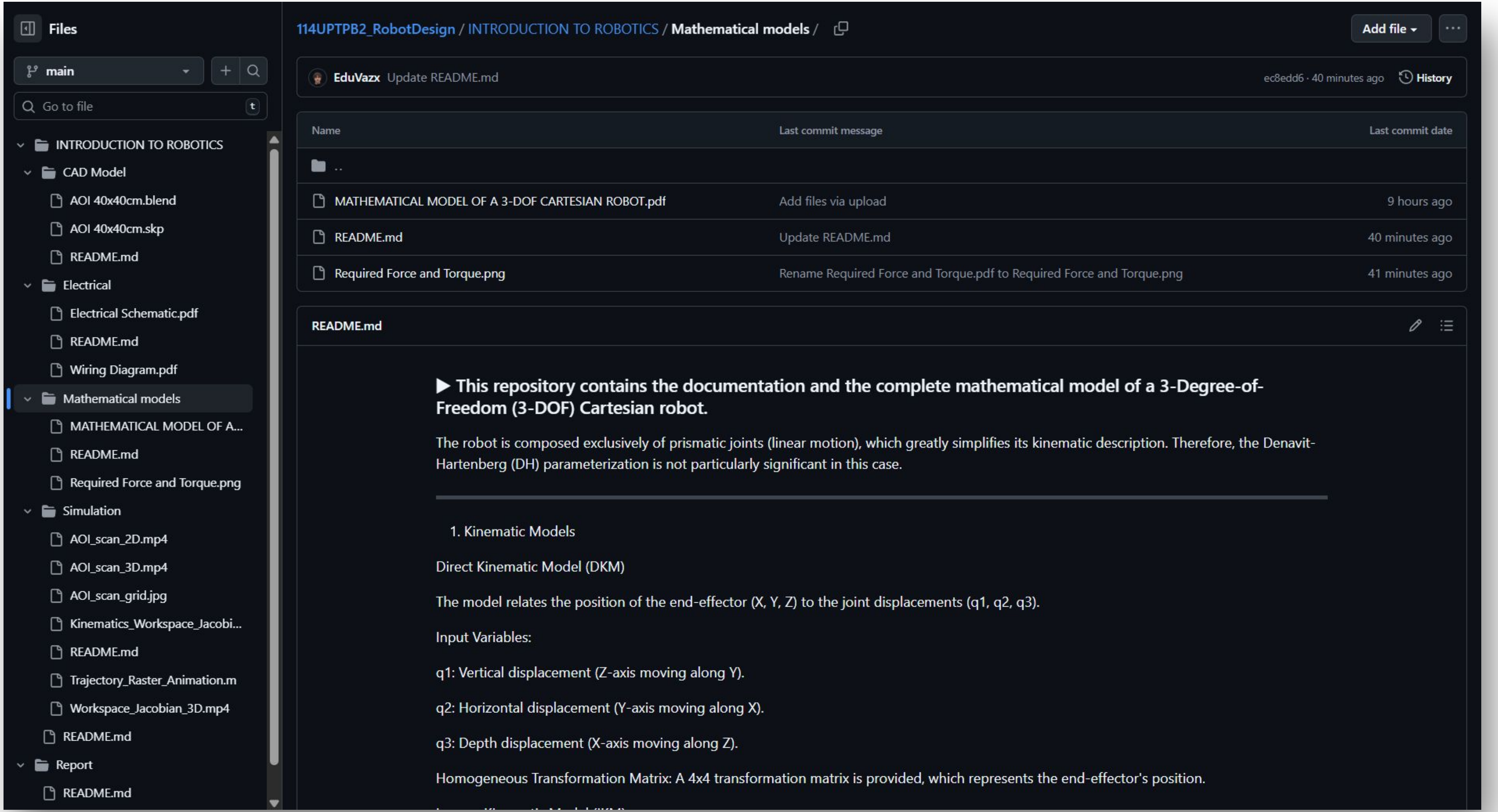
Electrical Design *(Wiring Diagram, Electrical Schematic, and Component List)*

In this section, you can find the electrical diagrams and the list of components used for this project. The system consists of an ESP32 microcontroller and a 24V DC power supply. It includes three NEMA 17 stepper motors with 59 Ncm torque, accompanied by three TB6600 drivers. The mechanical hardware comprises 25x25 mm aluminum profiles, 3D printed components, six 300 mm MGN12 linear guides, as well as 6 mm GT2 belts and belt tensioners.

Component List

Category	Component	Purpose
Actuation	NEMA 17 Stepper	Linear motion generation
Drive	TB6600	Stepper motor control
Power	24 V DC Supply	System power
Transmission	GT2 Belt + Tensioner	Torque transmission
Guidance	MGN12 Linear Rail	Precision linear guidance
Structure	Aluminum Profiles 25×25	Robot frame
Custom Parts	3D Printed Components	Mounts and brackets
Control	ESP32	System controller

Mathematical models

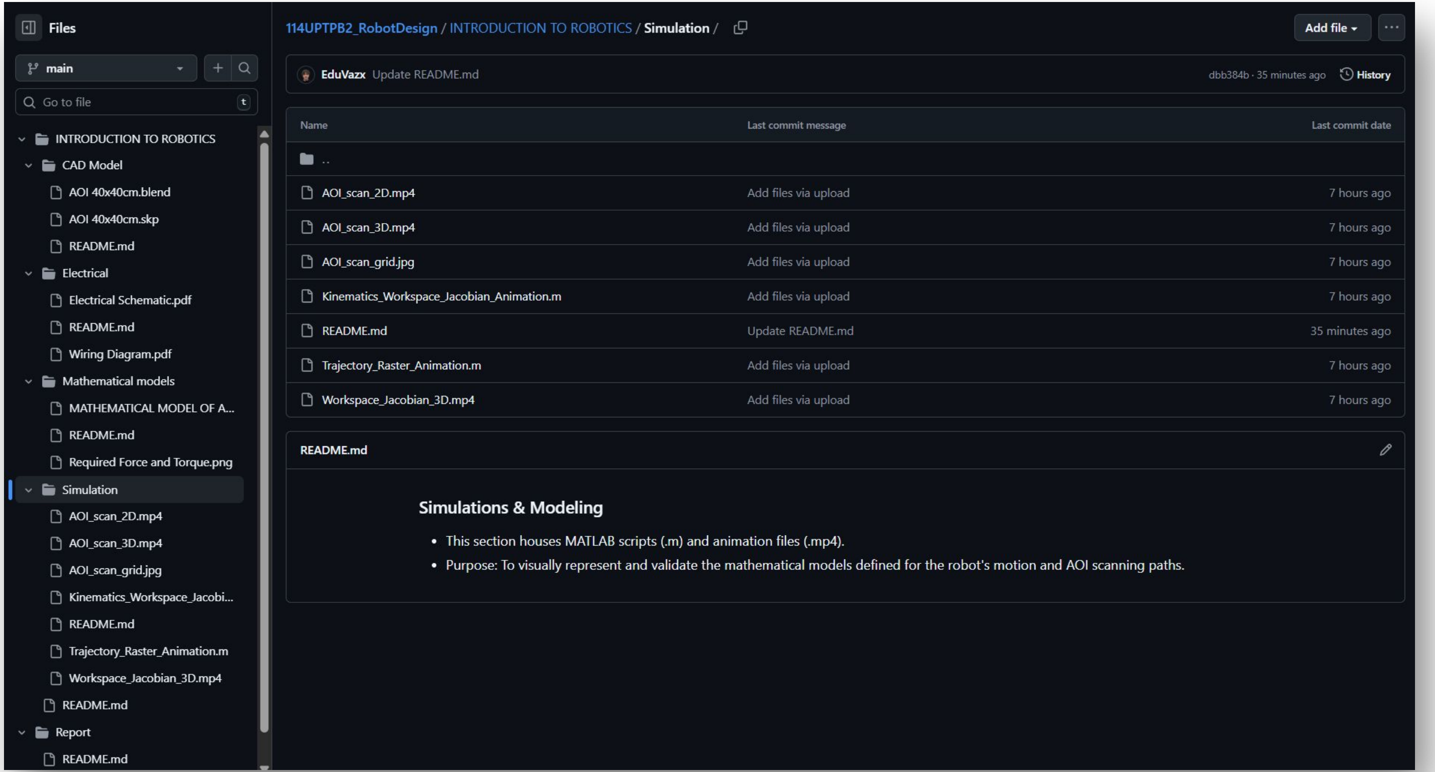


Simulation

Simulations & Modeling

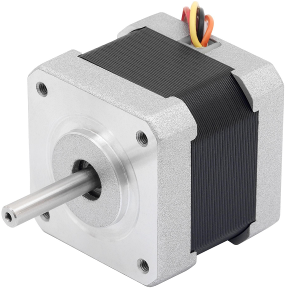
- This section houses MATLAB scripts (.m) and animation files (.mp4).

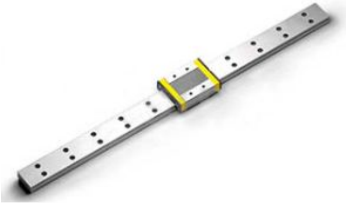
- Purpose: To visually represent and validate the mathematical models defined for the robot's motion and AOI scanning paths.



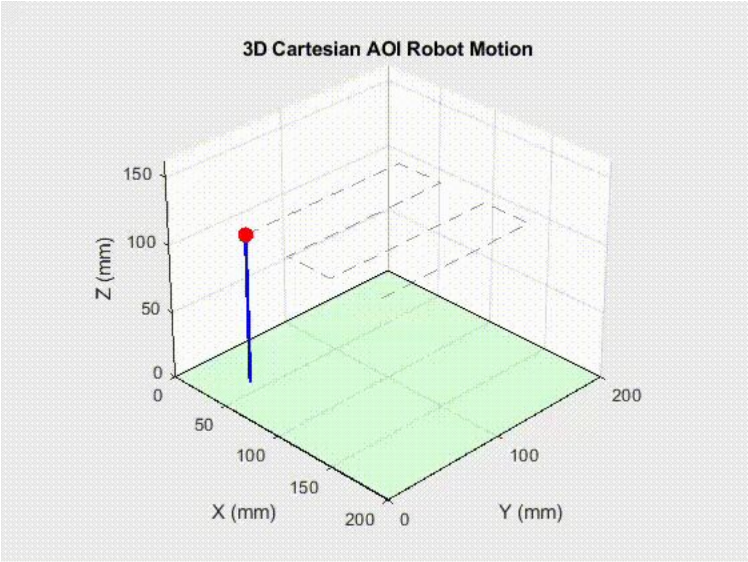
Conclusion

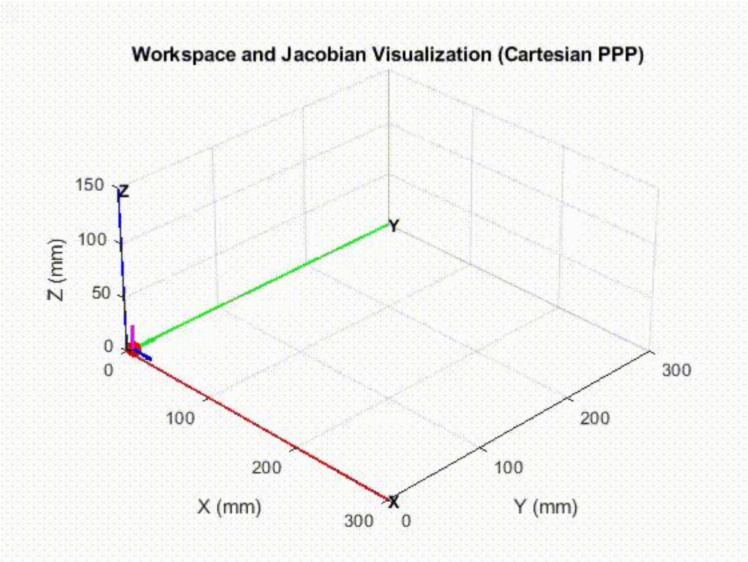
- A Cartesian PPP robot is suitable for AOI
- Simple kinematics and control
- Camera resolution directly defines positioning requirements
- Design meets inspection task requirements

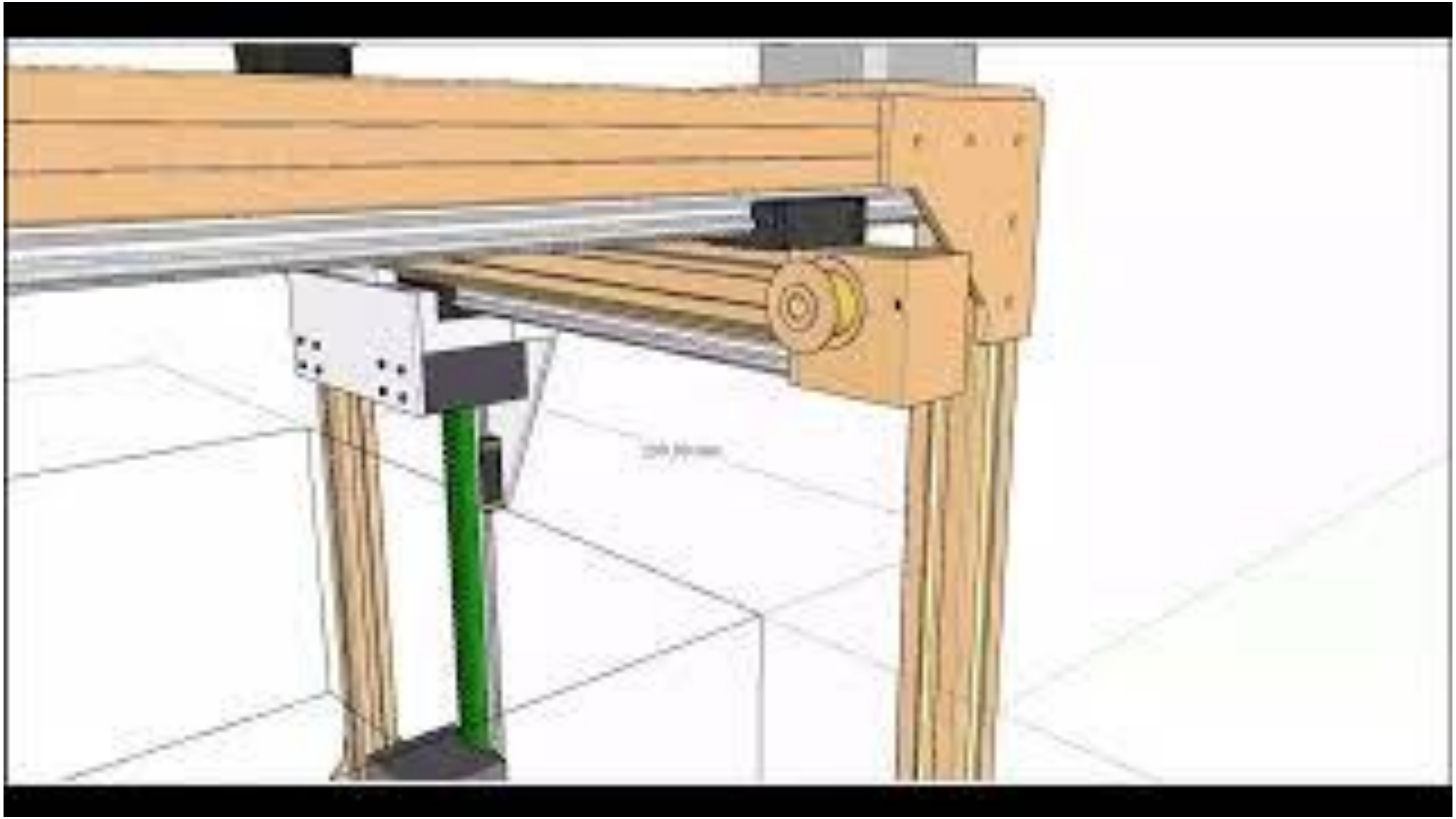




Feature	Description
Robot Type	Cartesian PPP
Application	AOI for PCB inspection
Degrees of Freedom	3 (X, Y, Z)
End-effector	Industrial Camera
Forward Kinematics	Linear, decoupled
Inverse Kinematics	Analytical, unique solution
Jacobian	Identity matrix, no singularities
Workspace	Rectangular prism
Trajectory	Raster scan in task space
Camera Consideration	Conical FOV, Resolution-driven accuracy
Dynamic Model	Quasi-static, gravity dominated
Industrial Feasibility	High (modular components, MISUMI)


3D Cartesian AOI Robot Motion
Z (mm)
X (mm)
Y (mm)


Workspace and Jacobian Visualization (Cartesian PPP)
Z (mm)
X (mm)
Y (mm)
X
Y
Z



https://app.sketchup.com/share/tc/northAmerica/B7akIYUKGKA?source=web&stoken=DIPzc3P_IHAjUP8_VQ-jXvMQ23hpMmH2cTKifSW8coMmIl9sq8aC43QSrYKBZa2u

Thank you for your attention!