

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

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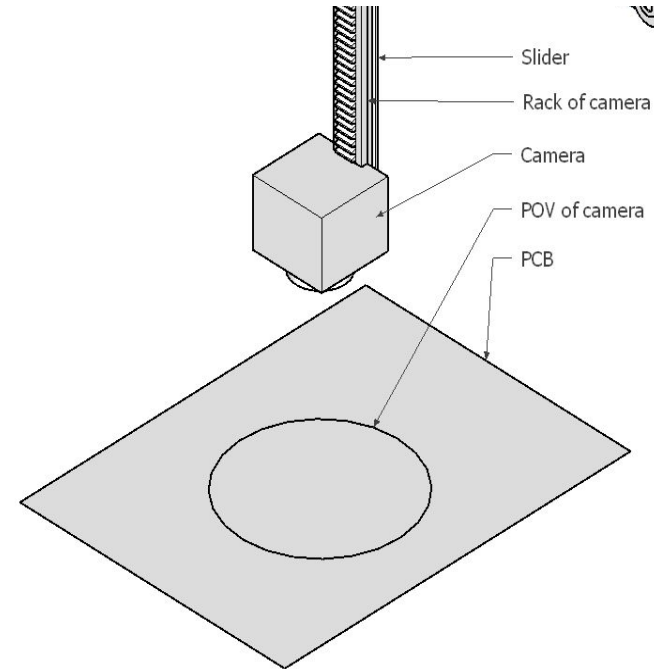
# Application: Automatic Optical Inspection (AOI)

- 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.

## AOI Machine



### Efficiency

Operate 24 hours a day.



### Consistency

High stability throughout the inspection process.



### Cost

A machine can replace almost five human inspectors.



### Documentation

Provide printed documents.

## Manual Human Inspection



### Efficiency

Inspect only one product at a time.



### Consistency

Human beings cannot keep consistency for long.



### Cost

Manual inspection incurs significant labor expenses.

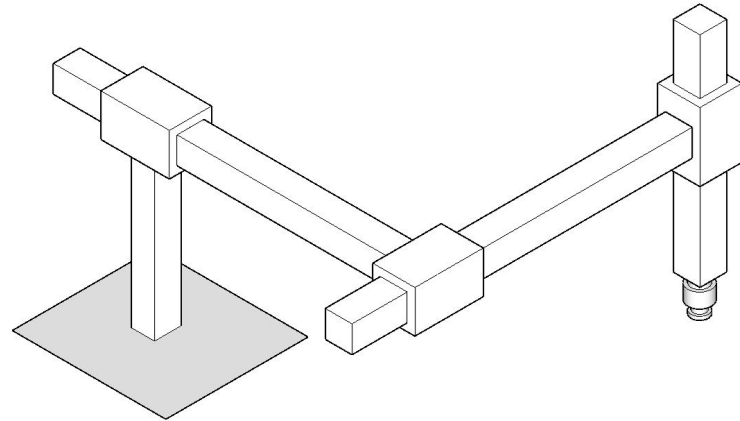


### Documentation

Provide printed documents.

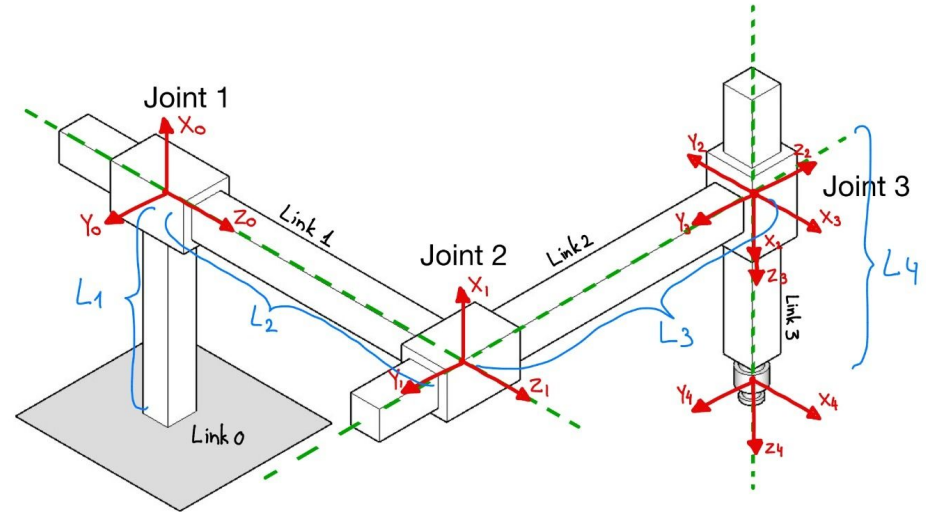
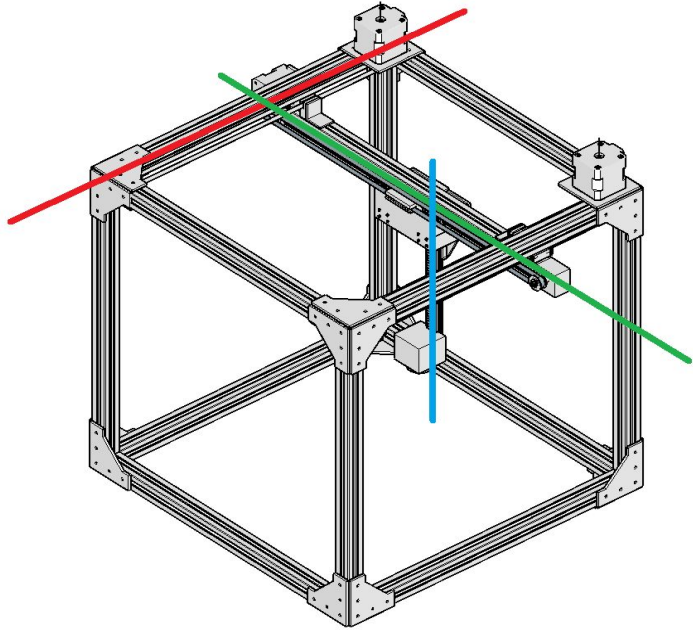
# Robot Type: Cartesian Robot (PPP)

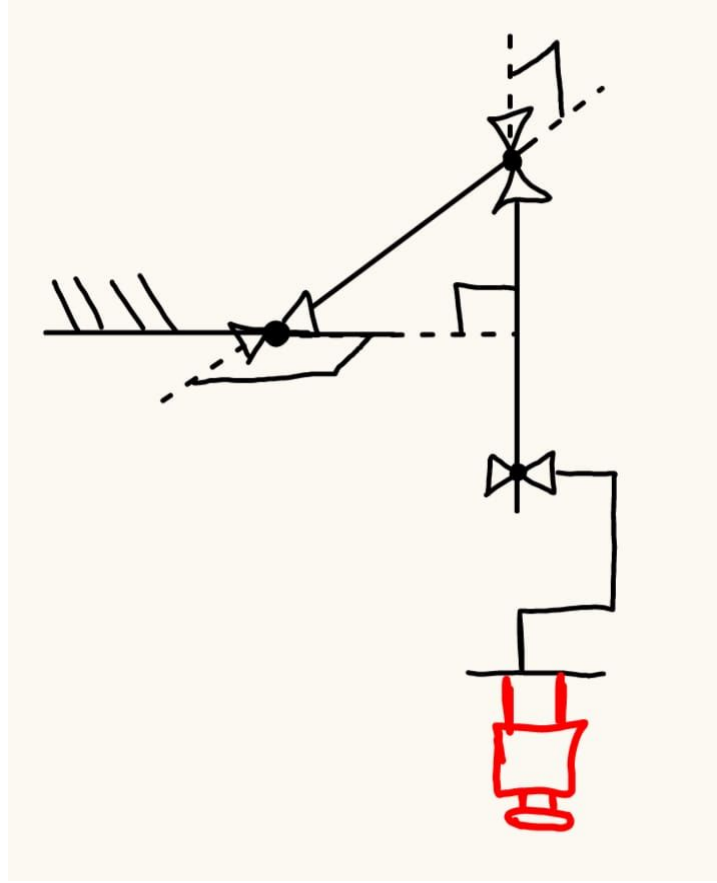
- Joint configuration:
  - Joint 1: Prismatic (X)
  - Joint 2: Prismatic (Y)
  - Joint 3: Prismatic (Z)
- DOF = 3
- Simple kinematics
- Decoupled motion
- Ideal for planar inspection



*This configuration simplifies control and inverse .*

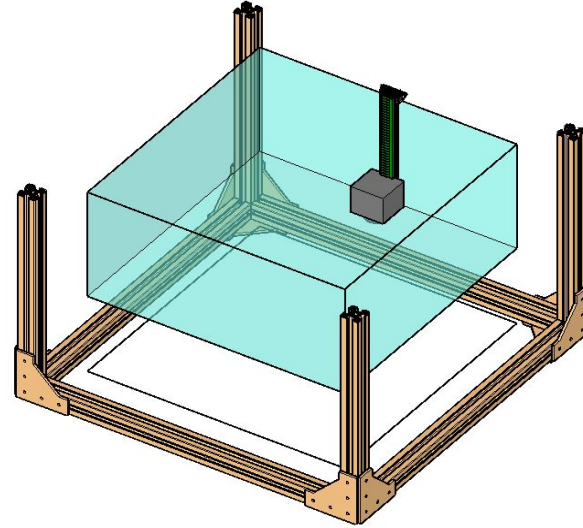
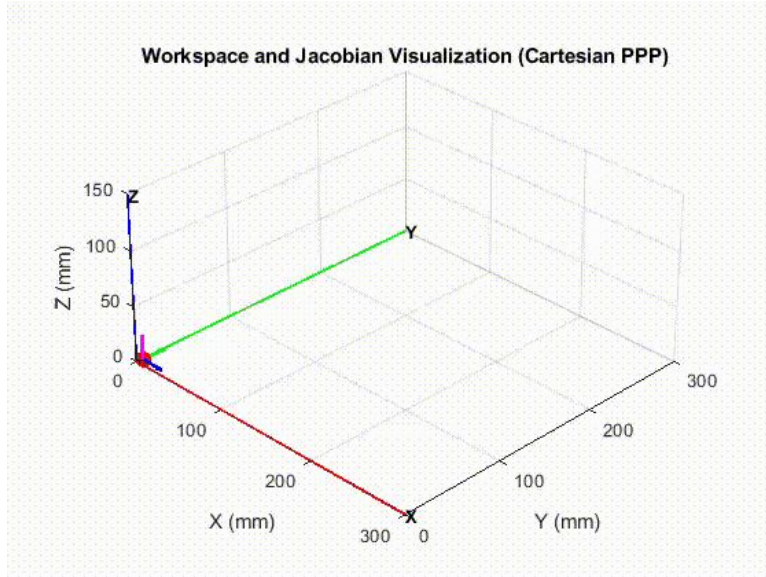
# Robot Diagram





# 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*

$i$	$\alpha_{i-1}$	$a_{i-1}$	$d_i$	$\theta_i$
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  $a_{i-1}$ ,  $\alpha_{i-1}$ ,  $d_i$  and  $\theta_i$  are the standard Denavit–Hartenberg parameters. The variables  $d_1$ ,  $d_2$  and  $d_3$  correspond to the prismatic joint displacements, while  $L_4$  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

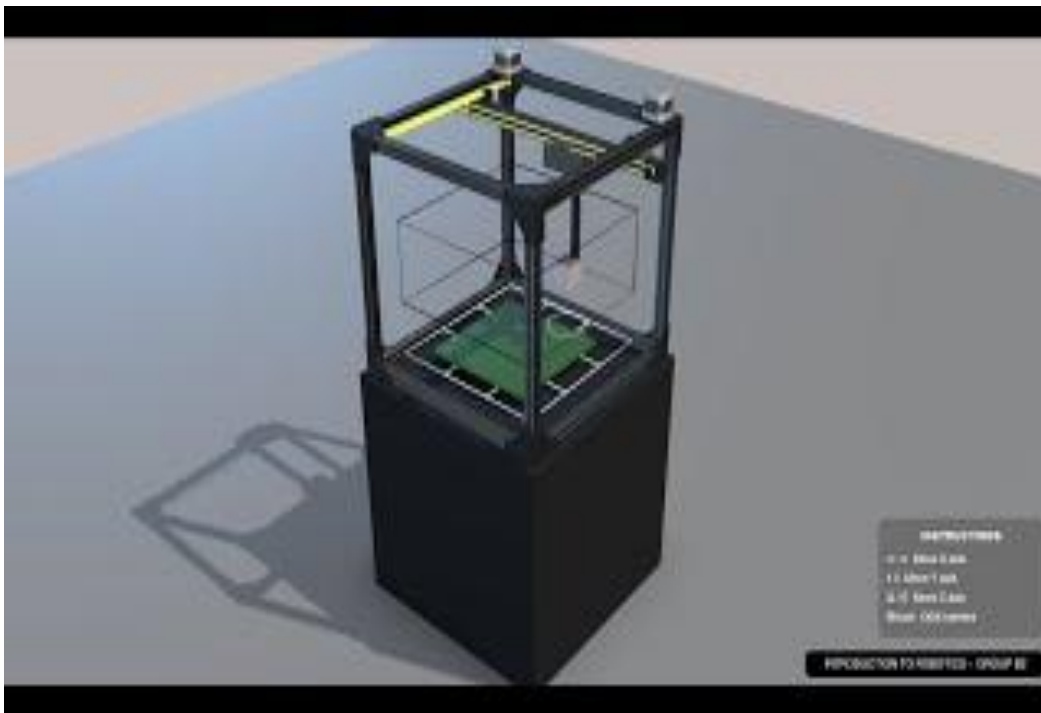
The camera field of view (FOV) defines a conical vision volume whose footprint on the PCB surface increases with the working distance  $z$ . The width of the imaged area is given by:

$$W(z) = 2z \tan(\text{FOV}/2)$$

The spatial resolution is given by:

$$\text{Resolution in mm/pixel} = W(z)/N_x$$

where  $N_x$  is 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  $\leq 0.03$  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:

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

Z axis:

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

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)

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

$$m_{\text{total}} = 0.65 \text{ kg}$$

Force in the z-axis:

$$F_z = m_{\text{total}} * g$$

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

Relationship force-torque in a belt system:

$$T = F_z * r \quad \text{where} \quad r = 8 \text{ mm} = 0.008 \text{ m}$$

$$T = 6.38 * 0.008$$

$$T = 0.051 \text{ N.m (Theoretical minimum torque)}$$

# 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  $SF = 2$ .

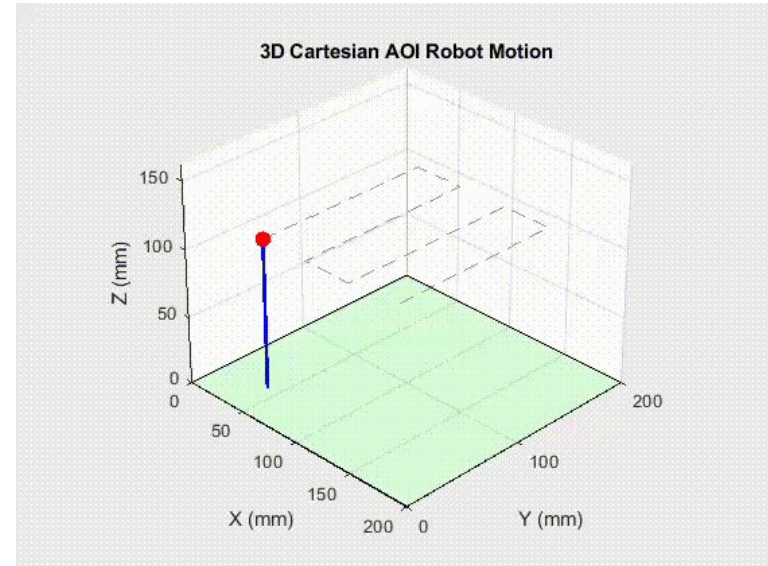
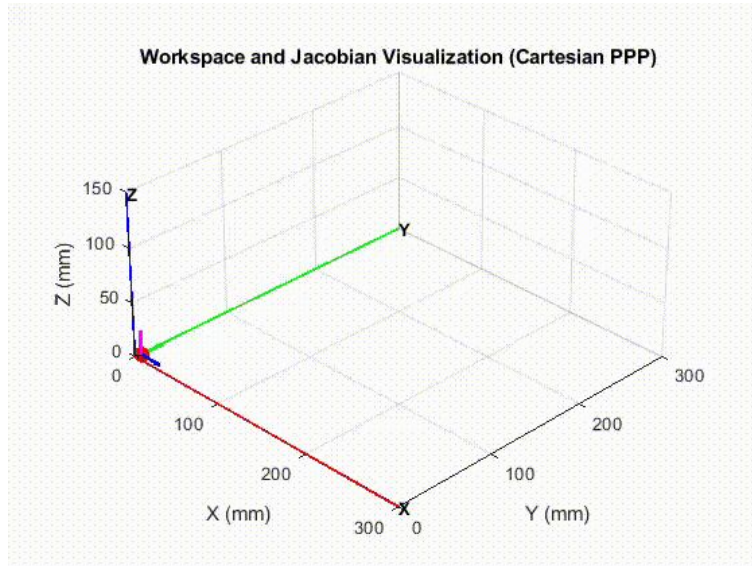
$$T_{\text{design}} = 20.051 = 0.10 \text{ N.m}$$

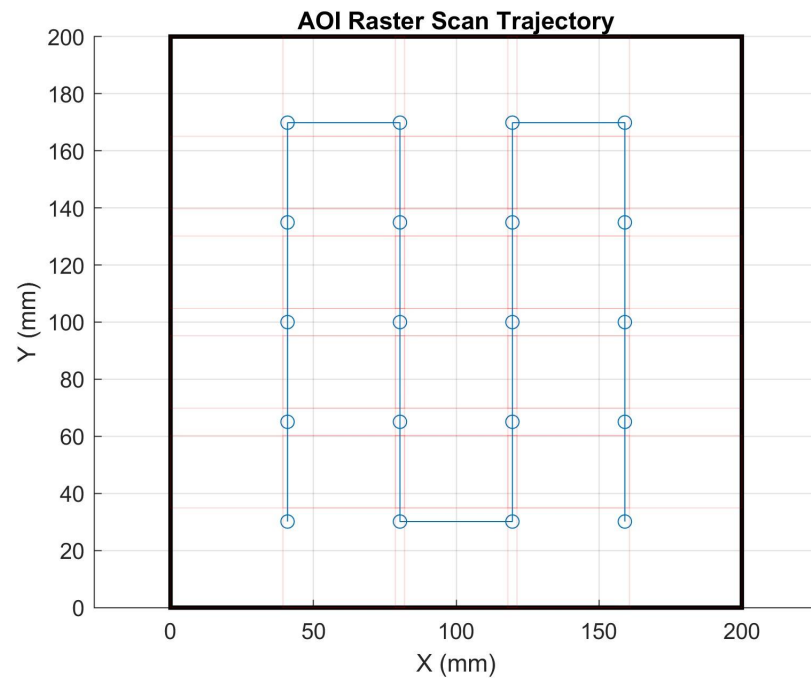
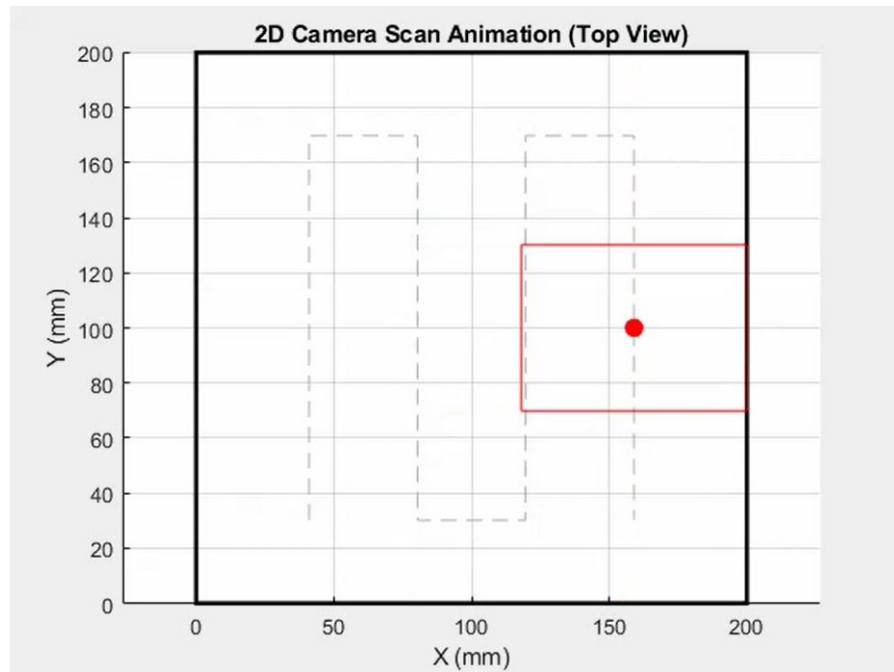
$T_{\text{motor}}$  is higher than the  $T_{\text{design}}$  and the nominal torque is between 0.4 N.m to 0.5 N.m

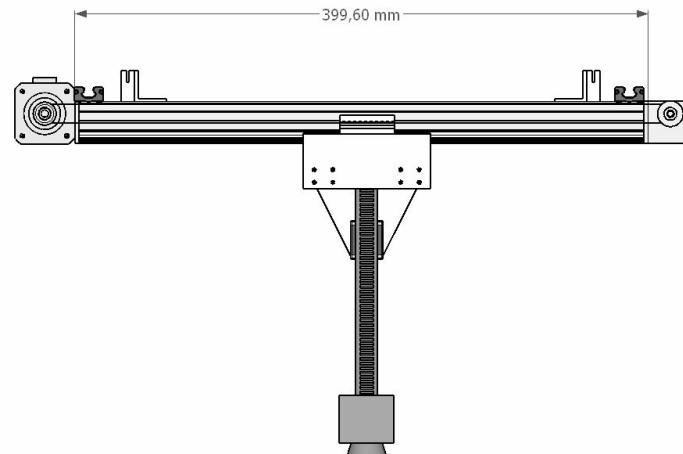
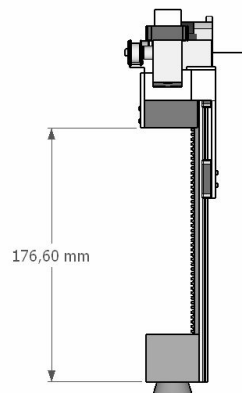
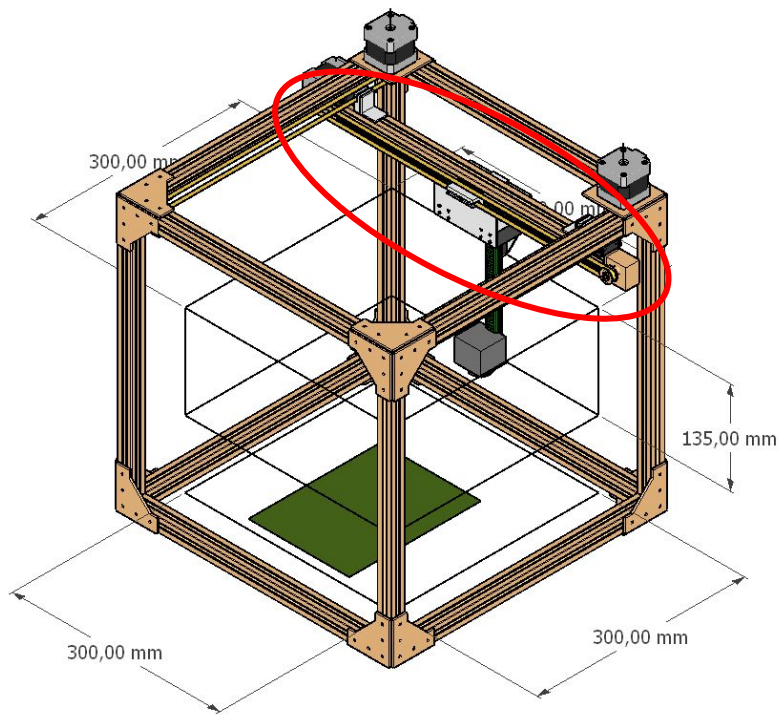
The resulting torque requirement is well below the nominal torque of a standard NEMA 17 stepper motor, confirming its suitability for the proposed AOI application.

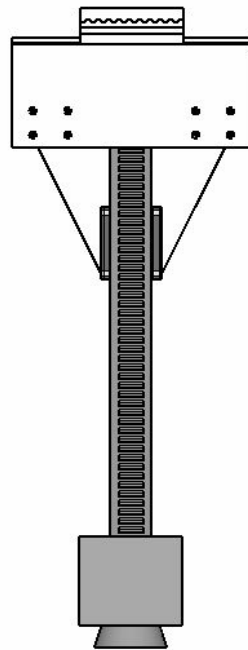
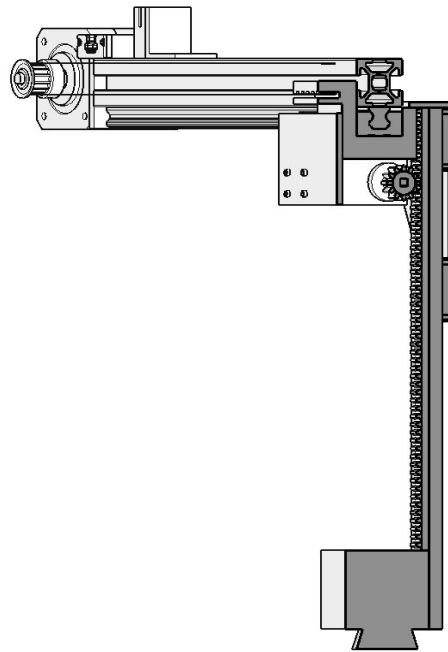
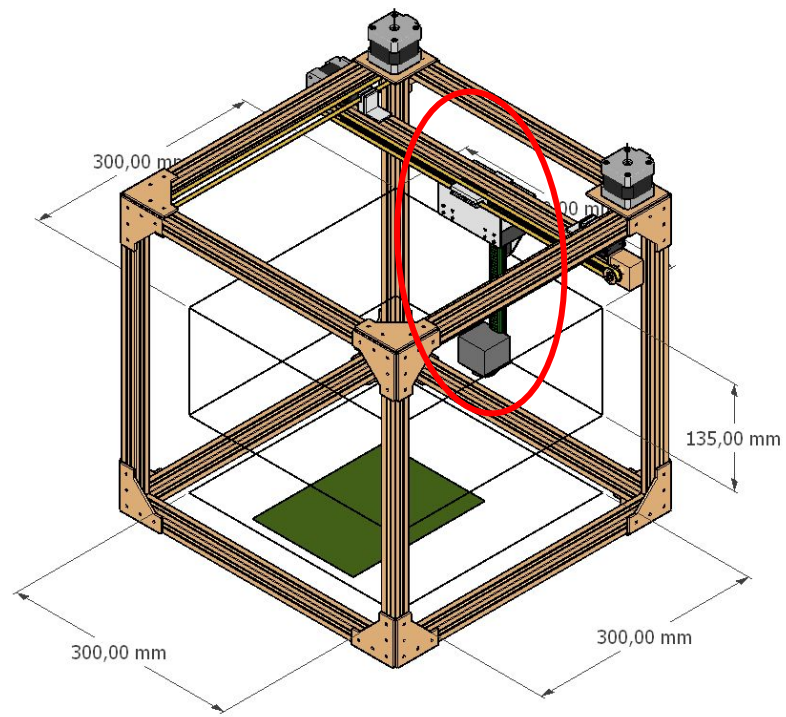


# Simulations

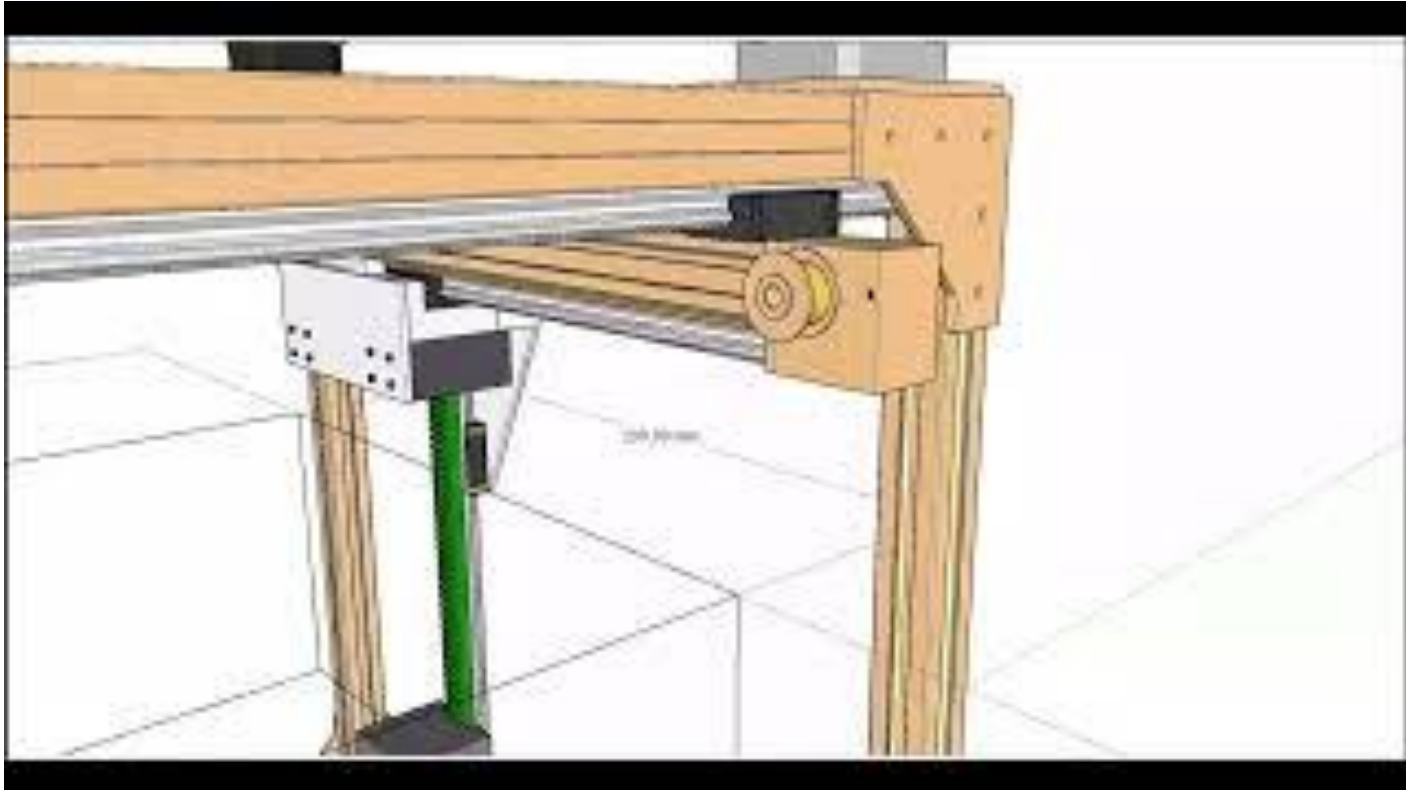


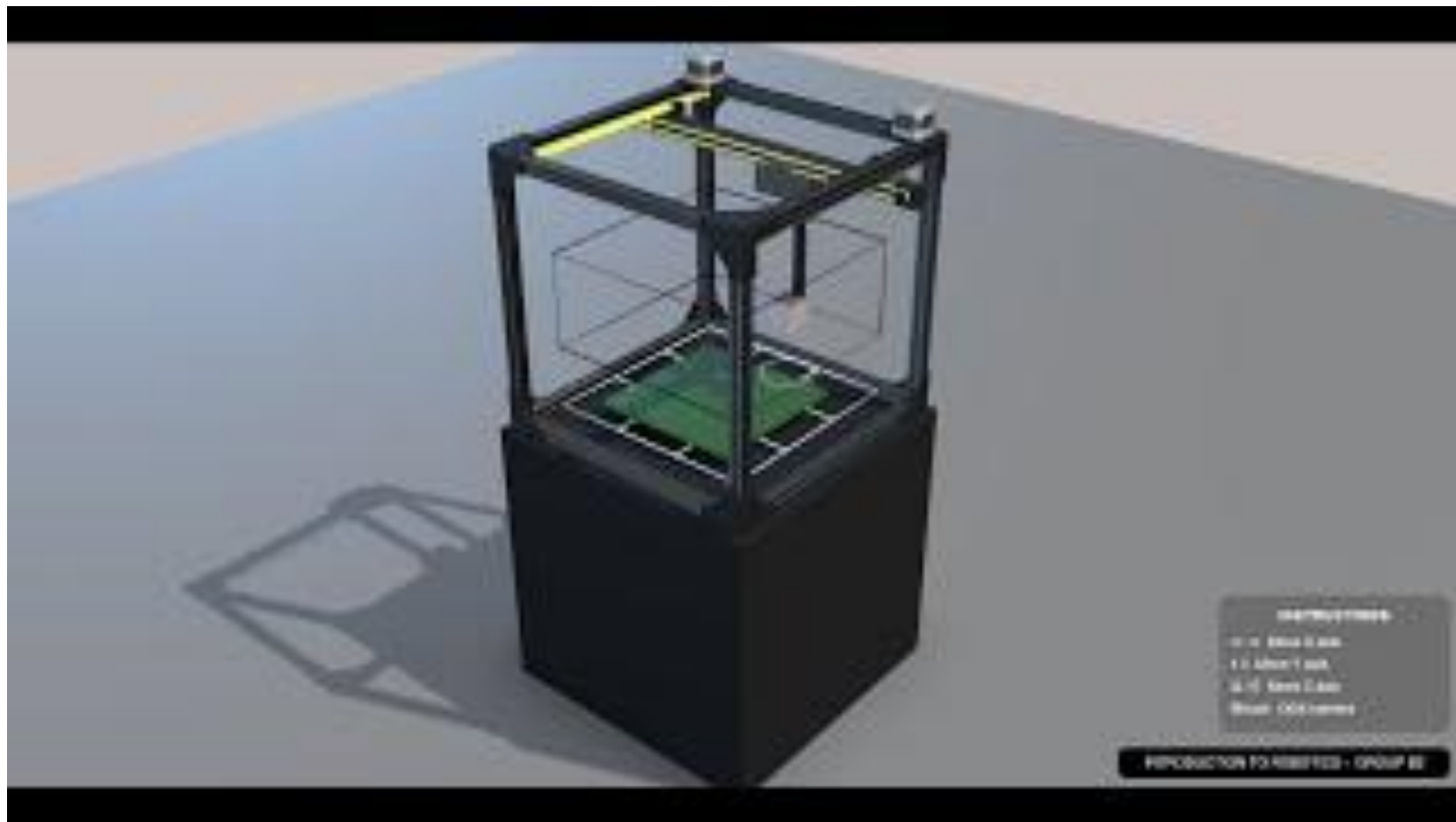




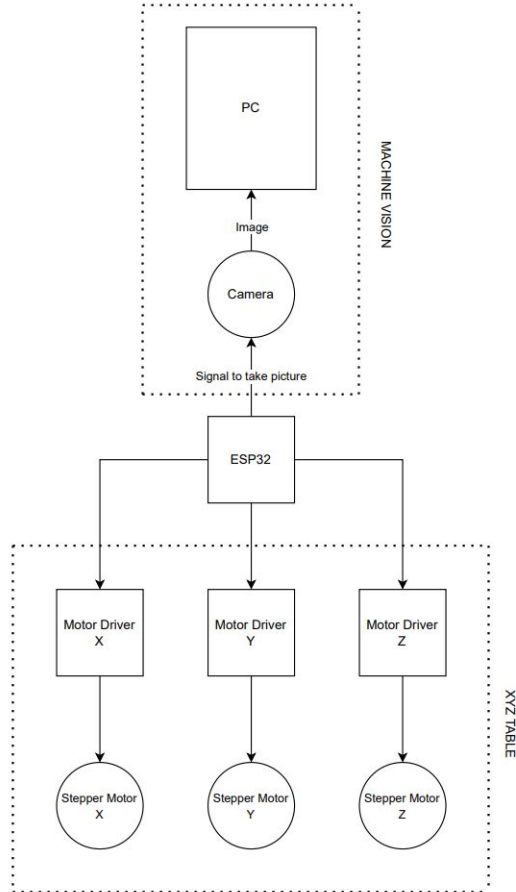


# Simulations

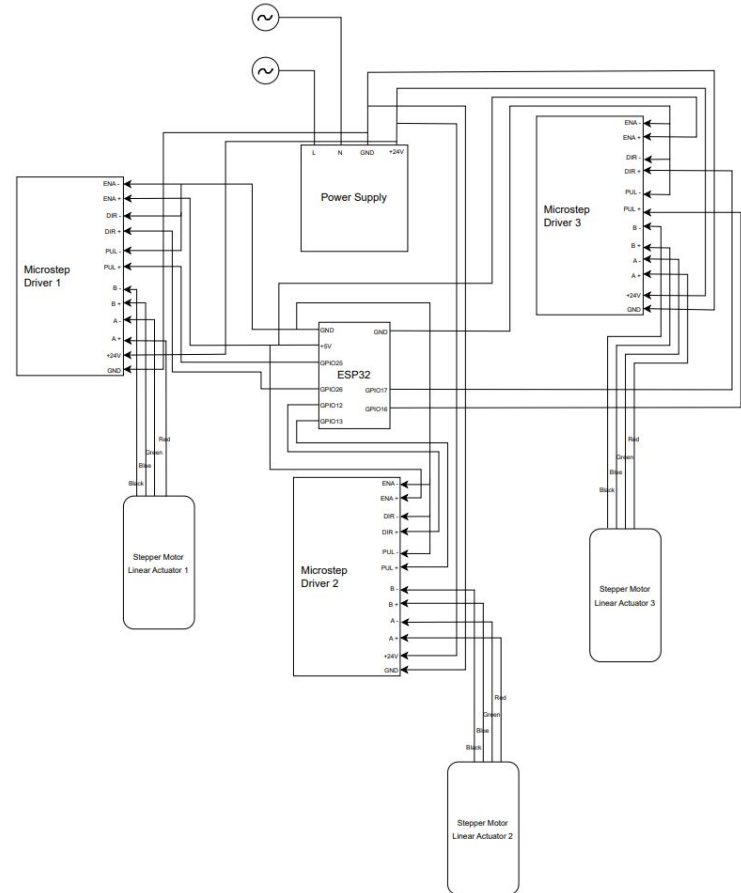




# Connection Diagram



# 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

 README 

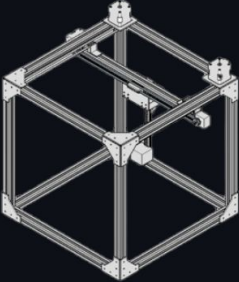
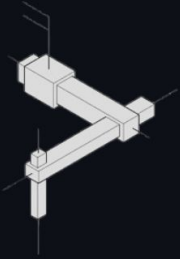
## Introduction to Robotics - Team B2 – Final Project



In this section, you can find an overview of the robotics project that the B2 group is working on. For more detailed information, please check the link to "Introduction to Robotics".

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### Group Members

- Leonardo Barrios F11303103
- Giulana Brizuela F11303106
- Demian Escurra F11303108
- Luis Prieto F11303116
- Eduardo Vazquez F11303117






UNIVERSIDAD POLITÉCNICA  
TAIWAN – PARAGUAY  
臺灣-巴拉圭科技大學


 <b>EduVazx</b>	Rename Diagram.drawio.pdf to Electrical Schematic.pdf	4aa7cb4 · 7 minutes ago	 81 Commits
	INTRODUCTION TO ROBOTICS	Rename Diagram.drawio.pdf to Electrical Schematic.pdf	7 minutes ago
	Report	Update README.md	54 minutes ago
	README.md	Update README.md	1 hour ago


This is our project's centralized GitHub repository,  
titled: **114UPTPB2\_RobotDesign**



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


# Report folder

**114UPTPB2\_RobotDesign** / **Report** / 

 **EduVazx** Update README.md

515f49f · 1 hour ago  **History**

Name	Last commit message	Last commit date
 ..		
 README.md	Update README.md	1 hour ago

README.md 

## Cartesian Robot for AOI (PPP) Report

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[https://docs.google.com/document/d/1YAqCGMi1mXo-7lv7sulJeExJz9hY5YWQ\\_nFHNoiqQM/edit?tab=t.0](https://docs.google.com/document/d/1YAqCGMi1mXo-7lv7sulJeExJz9hY5YWQ_nFHNoiqQM/edit?tab=t.0)

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

# INTRODUCTIONS TO ROBOTICS folder

The image shows a file explorer interface with a sidebar on the left and a main content area on the right. The sidebar displays a tree view of the repository structure, including folders like 'CAD Model', 'Electrical', 'Mathematical models', and 'Simulation'. The main content area shows the commit history for the 'INTRODUCTION TO ROBOTICS' folder, with a table listing commits by name, message, and date. Below the table, the 'README.md' file is open, displaying the project's documentation.

**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

114UPTB2\_RobotDesign / INTRODUCTION TO ROBOTICS /

Add file ...

EduVazzx Rename Diagram.drawio.pdf to Electrical Schematic.pdf 4aa7cb4 · 20 minutes ago History

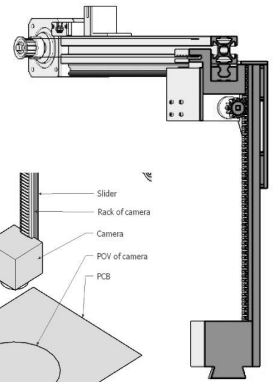
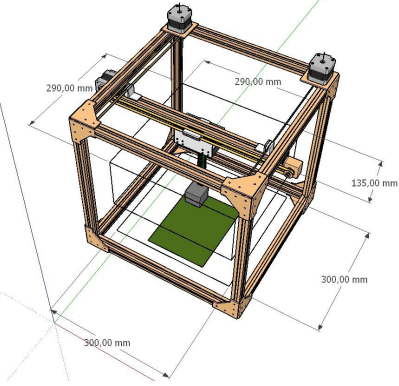
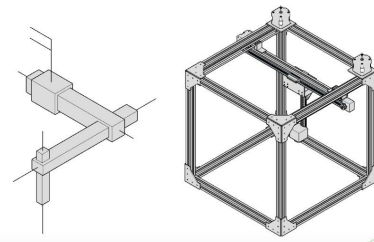
Name	Last commit message	Last commit date
..		
CAD Model	Update README.md	1 hour ago
Electrical	Rename Diagram.drawio.pdf to Electrical Schematic.pdf	20 minutes ago
Mathematical models	Update README.md	31 minutes ago
Simulation	Update README.md	23 minutes ago
README.md	Update README.md	last week

README.md

This repository contains the complete documentation for the robotics project.

- The structure is organized by component and includes the following main sections:
- CAD Model: Contains the computer-aided designs and models of the robot.
- Electrical: Includes diagrams, schematics, and documentation related to the electrical components and wiring.
- Mathematical Models: Contains the theoretical development and equations describing the robot's kinematics and dynamics.
- Simulation: Covers the files and results from the model testing and simulations.

# CAD Model



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

AOL\_scan\_2D.mp4

AOL\_scan\_3D.mp4

AOL\_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/B7aklYUKGKA?source=web&stoken=DIPzc3P\\_IHajUP8\\_VO-jXvMQ23hpMmH2cTKifSW8coMmlI9sq8aC43Q5rYKBZa2u](https://app.sketchup.com/share/tc/northAmerica/B7aklYUKGKA?source=web&stoken=DIPzc3P_IHajUP8_VO-jXvMQ23hpMmH2cTKifSW8coMmlI9sq8aC43Q5rYKBZa2u)

# 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

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AOL\_scan\_2D.mp4

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AOL\_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
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Control	ESP32	System controller

# Mathematical models

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

114UPTB2\_RobotDesign / INTRODUCTION TO ROBOTICS / Mathematical models /

Add file

...

EduVazx Update README.md ec8edd6 · 40 minutes ago History

Name	Last commit message	Last commit date
..		
MATHEMATICAL MODEL OF A 3-DOF CARTESIAN ROBOT.pdf	Add files via upload	9 hours ago
README.md	Update README.md	40 minutes ago
Required Force and Torque.png	Rename Required Force and Torque.pdf to Required Force and Torque.png	41 minutes ago

README.md

► This repository contains the documentation and the complete mathematical model of a 3-Degree-of-Freedom (3-DOF) Cartesian robot.

The robot is composed exclusively of prismatic joints (linear motion), which greatly simplifies its kinematic description. Therefore, the Denavit-Hartenberg (DH) parameterization is not particularly significant in this case.

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### 1. Kinematic Models

#### Direct Kinematic Model (DKM)

The model relates the position of the end-effector (X, Y, Z) to the joint displacements (q1, q2, q3).

Input Variables:

q1: Vertical displacement (Z-axis moving along Y).

q2: Horizontal displacement (Y-axis moving along X).

q3: Depth displacement (X-axis moving along Z).

Homogeneous Transformation Matrix: A 4x4 transformation matrix is provided, which represents the end-effector's position.

# 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.

The screenshot displays a file explorer on the left and a commit history table on the right, both within a dark-themed application window.

**File Explorer (Left Panel):**

- Root: main
- INTRODUCTION TO ROBOTICS
  - CAD Model
    - AOI 40x40cm.blend
    - AOI 40x40cm.skp
    - README.md
  - Electrical
    - Electrical Schematic.pdf
    - README.md
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  - Mathematical models
    - MATHEMATICAL MODEL OF A...
    - README.md
    - Required Force and Torque.png
  - Simulation** (selected)
    - AOI\_scan\_2D.mp4
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    - README.md
    - Trajectory\_Raster\_Animation.m
    - Workspace\_Jacobian\_3D.mp4
    - README.md
  - Report
    - README.md

**Commit History (Right Panel):**

Repository: 114UPTPB2\_RobotDesign / INTRODUCTION TO ROBOTICS / Simulation

User: EduVazx | Update README.md | dbb384b · 35 minutes ago | History

Name	Last commit message	Last commit date
..		
AOI_scan_2D.mp4	Add files via upload	7 hours ago
AOI_scan_3D.mp4	Add files via upload	7 hours ago
AOI_scan_grid.jpg	Add files via upload	7 hours ago
Kinematics_Workspace_Jacobian_Animation.m	Add files via upload	7 hours ago
README.md	Update README.md	35 minutes ago
Trajectory_Raster_Animation.m	Add files via upload	7 hours ago
Workspace_Jacobian_3D.mp4	Add files via upload	7 hours ago

**README.md (Right Panel):**

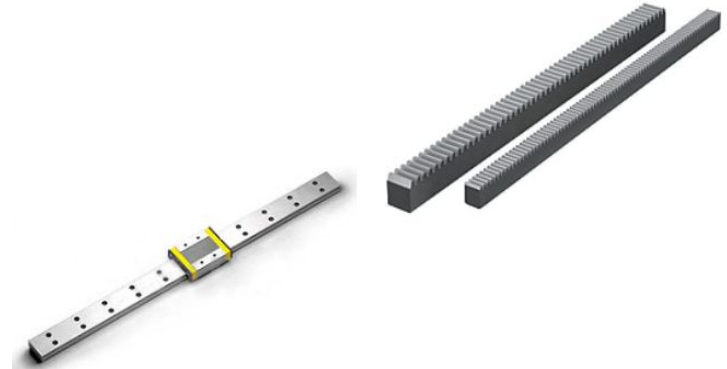
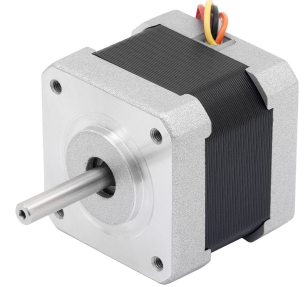
### Simulations & Modeling

- 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.



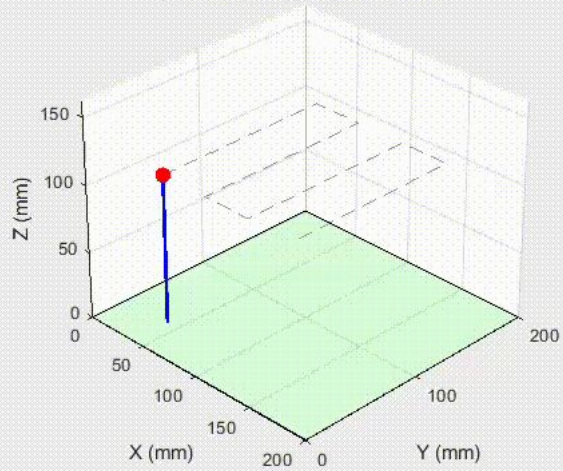
# Conclusion

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

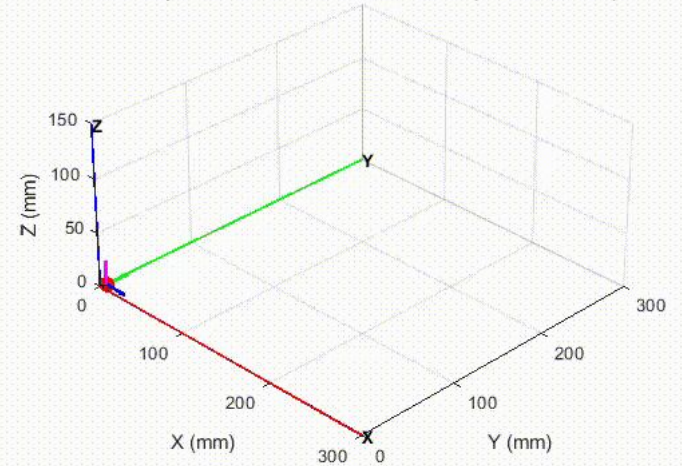


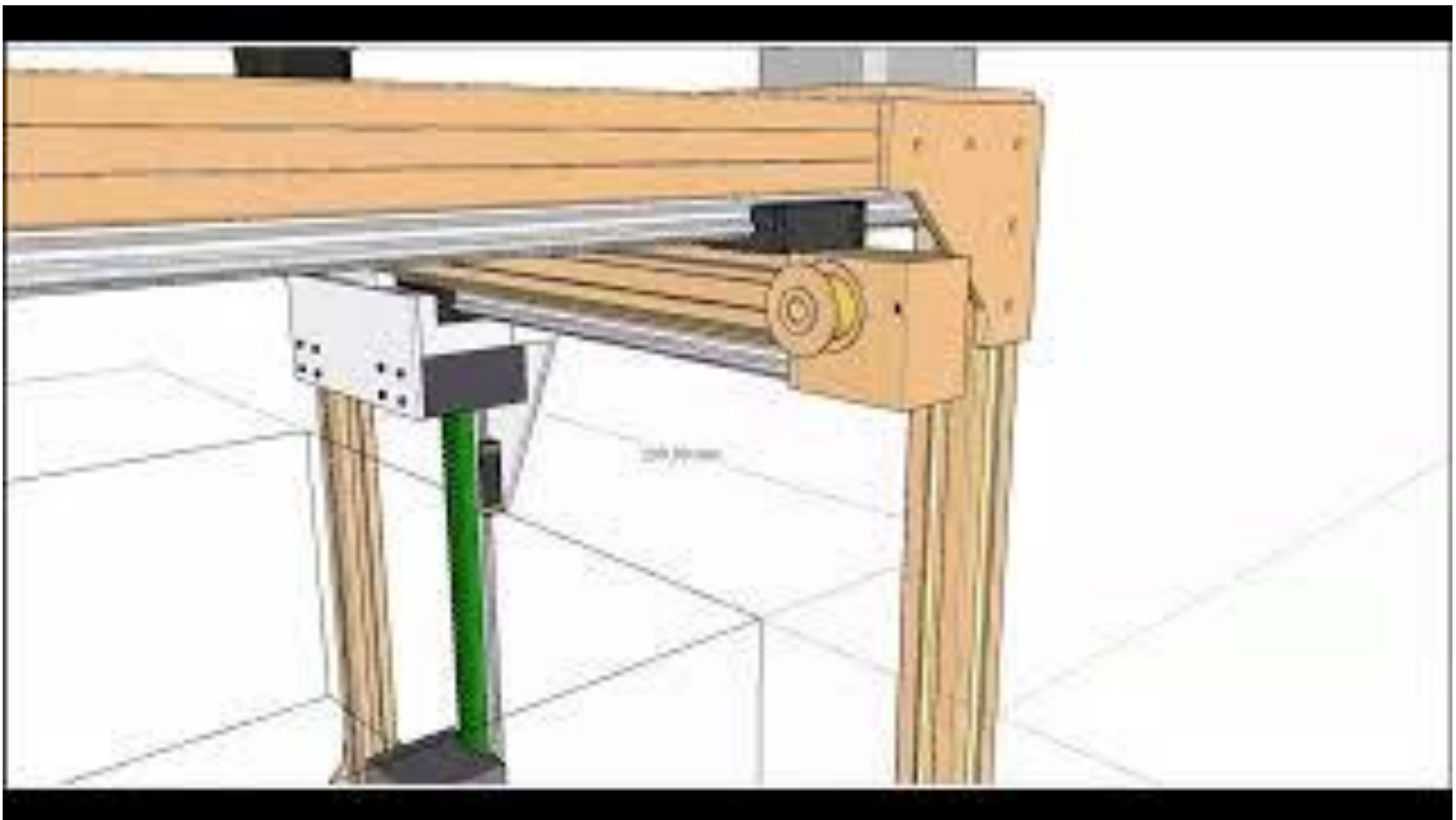
Feature	Description
Robot Type	Cartesian PPP
Application	AOI for PCB inspection
Degrees of Freedom	3 (X, Y, Z)
End-effector	Industrial Camera
Forward Kinematics	Linear, decoupled
Inverse Kinematics	Analytical, unique solution
Jacobian	Identity matrix, no singularities
Workspace	Rectangular prism
Trajectory	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



Workspace and Jacobian Visualization (Cartesian PPP)





[https://app.sketchup.com/share/tc/northAmerica/B7aklYUKGKA?source=web&stoken=DIPzc3P\\_IHAjUP8\\_VQ-jXvMQ23hpMmH2cTKifSW8coMmlI9sq8aC43QSrYKBZa2u](https://app.sketchup.com/share/tc/northAmerica/B7aklYUKGKA?source=web&stoken=DIPzc3P_IHAjUP8_VQ-jXvMQ23hpMmH2cTKifSW8coMmlI9sq8aC43QSrYKBZa2u)

# Thank you for your attention!

