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

Design and Analysis of a Cartesian PPP Robot for Automatic Optical Inspection

INTRODUCTION TO ROBOTICS

Final Project

Authors:

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

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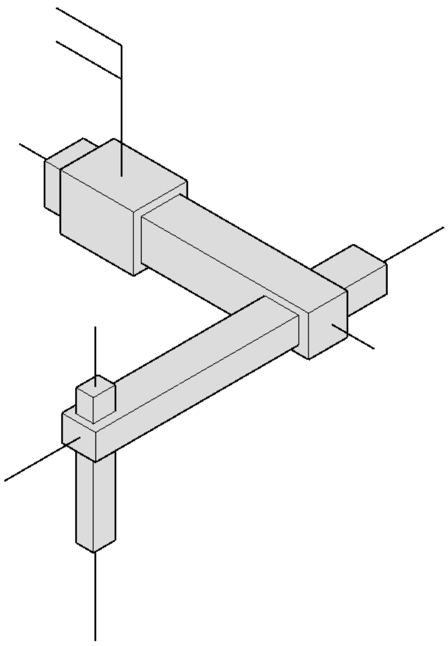
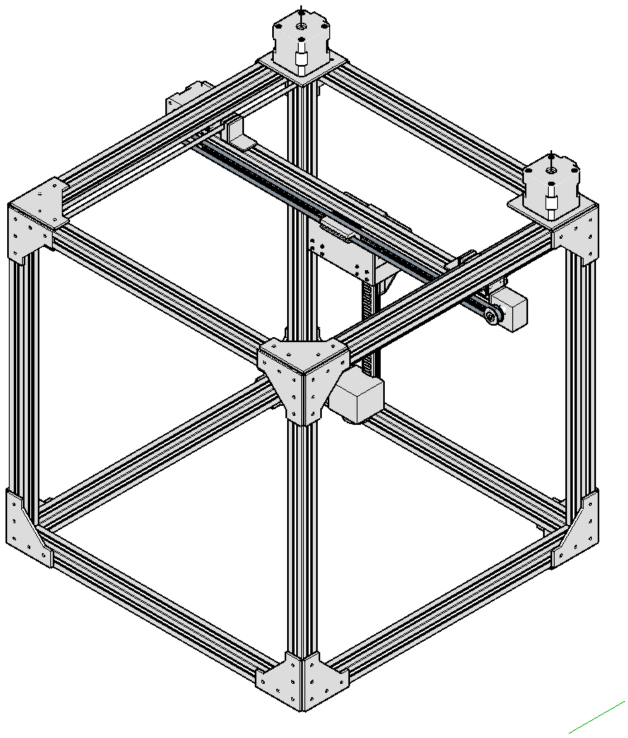
Introduction

Application and Robot Type

Automatic Optical Inspection (AOI) is a key process in modern electronics manufacturing, enabling the detection of defects in printed circuit boards (PCBs) with high accuracy and repeatability. AOI systems combine machine vision techniques with precise positioning mechanisms to ensure consistent inspection results across large production volumes.

This project presents the conceptual design and analysis of a Cartesian PPP robotic manipulator intended for AOI applications. The robot consists of three orthogonal prismatic joints providing independent linear motion along the X, Y, and Z axes. An industrial camera is mounted as the end-effector, allowing image acquisition of PCB surfaces placed on a fixed inspection platform.





Task Description

The primary task of the robot is to position the inspection camera at predefined locations above the PCB surface in order to capture high-resolution images for defect detection. Since the inspection task requires only translational motion, no end-effector orientation control is necessary. Image acquisition is performed following a raster scanning trajectory to ensure complete coverage of the inspection area.

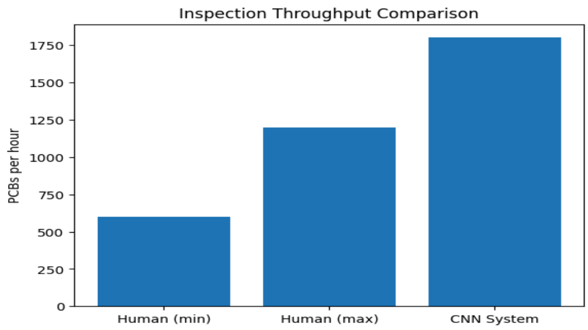
Functional and Performance Requirements

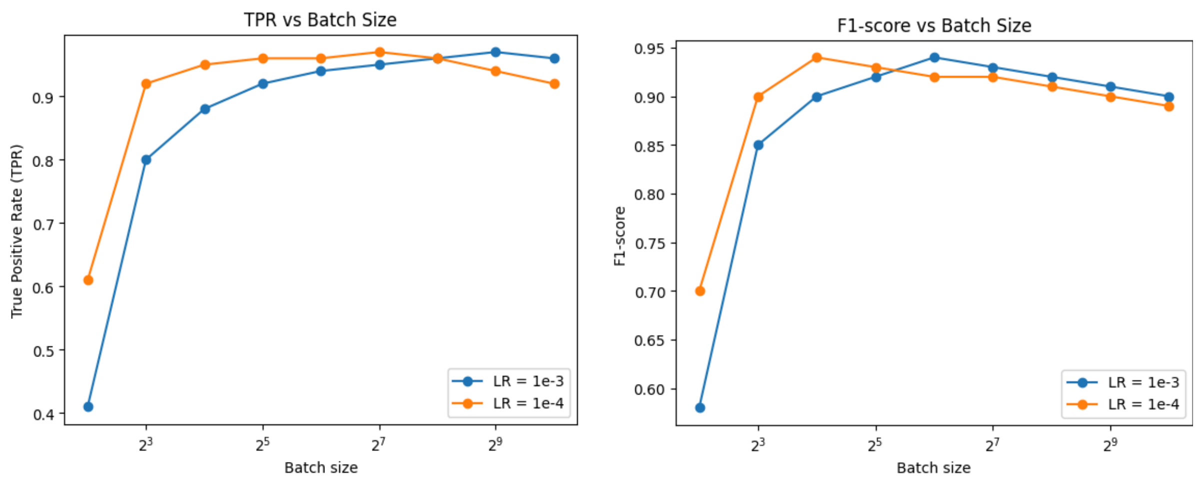
The main functional and performance requirements of the system are:

- Accurate positioning of the camera in three-dimensional space
- High repeatability to guarantee consistent image acquisition
- A workspace large enough to cover standard PCB dimensions
- Compatibility between robot positioning accuracy and camera resolution
- Smooth, low-speed motion suitable for visual inspection tasks

Motivation

Manual PCB inspection is time-consuming, subjective, and prone to human error. Automated Optical Inspection systems significantly improve inspection consistency, increase throughput, and reduce operational costs. Cartesian robots are widely used in AOI platforms due to their simple kinematic structure, high accuracy, and ease of integration. This project aims to demonstrate that a simplified PPP Cartesian robot is sufficient to meet AOI inspection requirements.





Human visual inspection achieves approximately 600–1,200 PCBs per hour, whereas the proposed CNN-based inspection system reaches about 1,800 PCBs per hour, clearly outperforming manual inspection in high-volume production. Hable et al., *Journal of Microelectronics and Electronic Packaging*, 2022

The true positive rate (TPR) increases with batch size up to a maximum, highlighting the trade-off between defect detection sensitivity and training configuration. Hable et al., *Journal of Microelectronics and Electronic Packaging*, 2022, Fig. 5

The highest F1-score (~93.9%) is achieved at low batch sizes and low learning rates, indicating better generalization performance under conservative training parameters. Hable et al., *Journal of Microelectronics and Electronic Packaging*, 2022, Fig. 8.

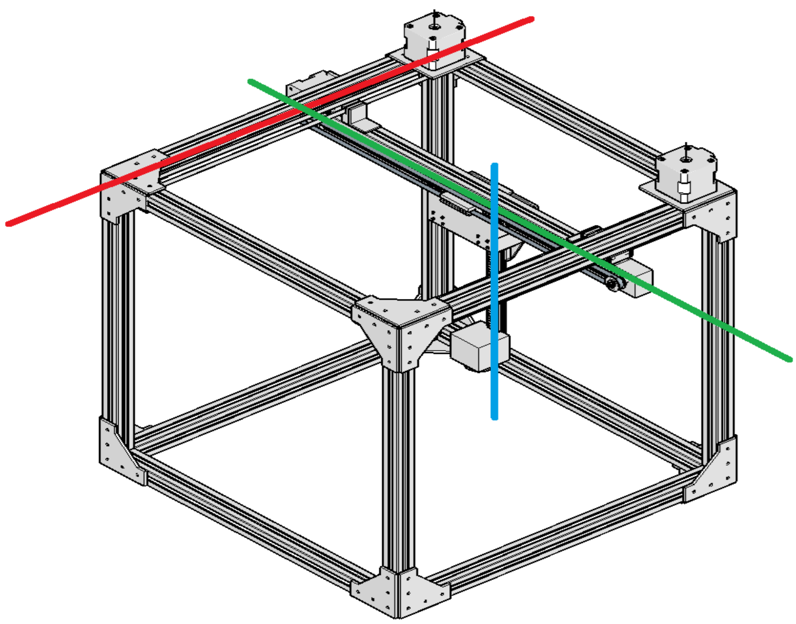
Overall Robot Design

Mechanical Structure

The robot adopts a Cartesian configuration consisting of three prismatic joints:

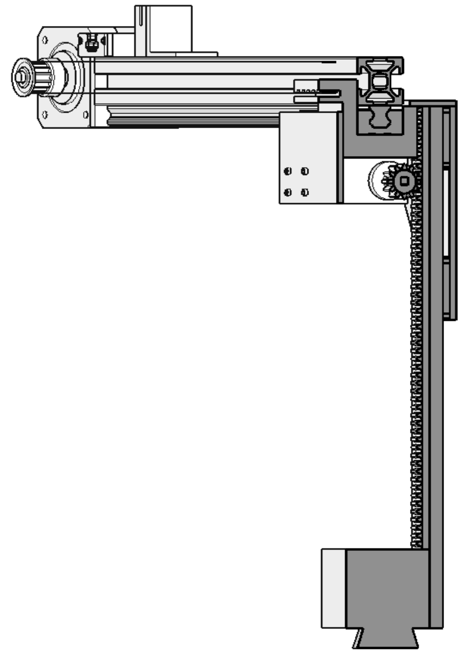
- Joint 1: Linear motion along the X-axis (Red)
- Joint 2: Linear motion along the Y-axis(Gren)
- Joint 3: Linear motion along the Z-axis(Blue)

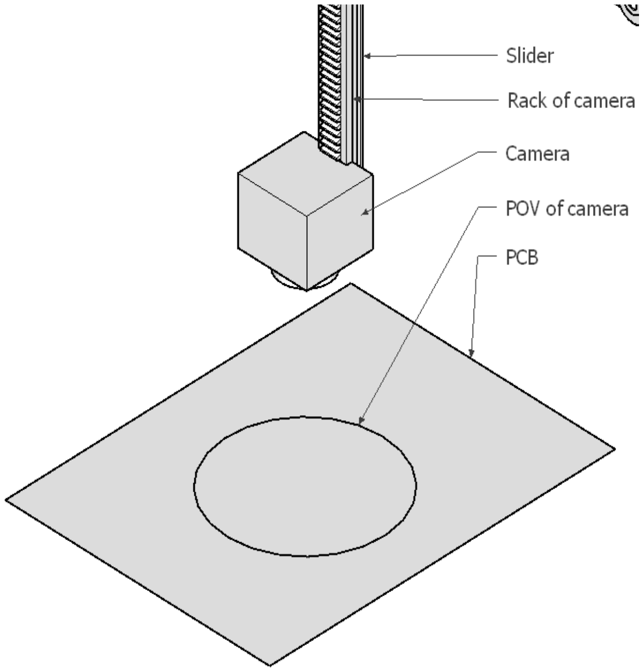
This configuration provides decoupled motion in each axis, simplifying kinematic modeling and control.



End-Effector

The end-effector is an industrial camera rigidly mounted to the Z-axis carriage. Since the inspection task requires only translational positioning, the camera orientation is fixed and does not require additional rotational degrees of freedom.

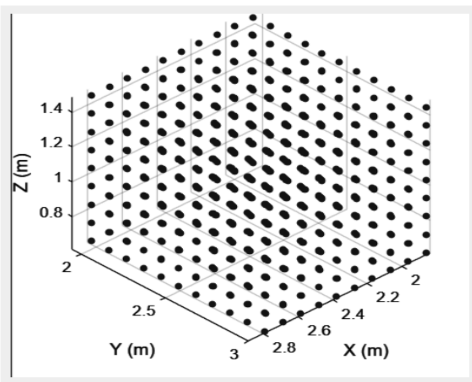




Workspace Definition

The robot workspace corresponds to a rectangular prism determined by the allowable displacements of the three prismatic joints. The workspace boundaries are defined as:

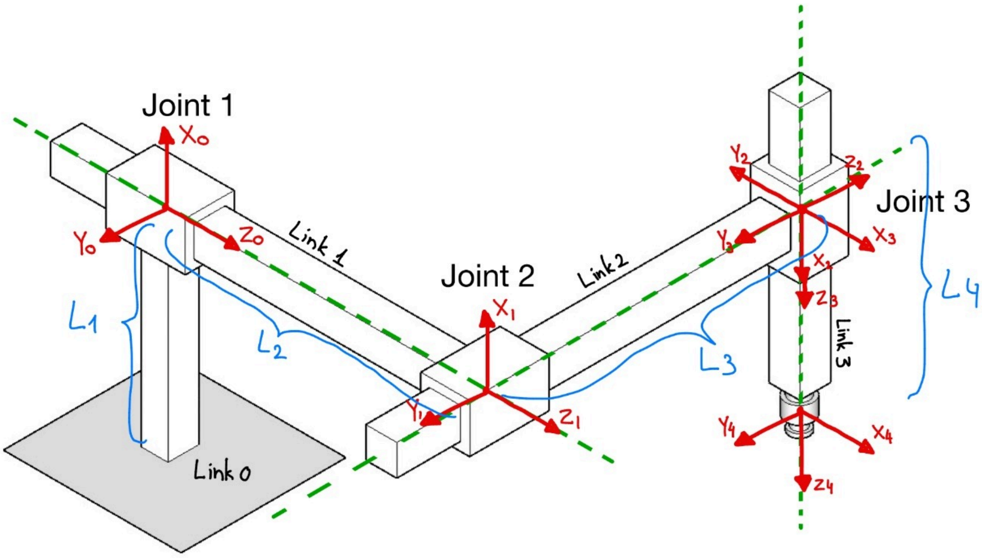
$X_{min} \leq x \leq X_{max}$ $Y_{min} \leq y \leq Y_{max}$ $Z_{min} \leq z \leq Z_{max}$



This workspace fully encloses the PCB inspection area and allows the camera to reach all required imaging positions. A three-dimensional visualization of the workspace is generated using MATLAB to verify kinematic feasibility and joint constraints.

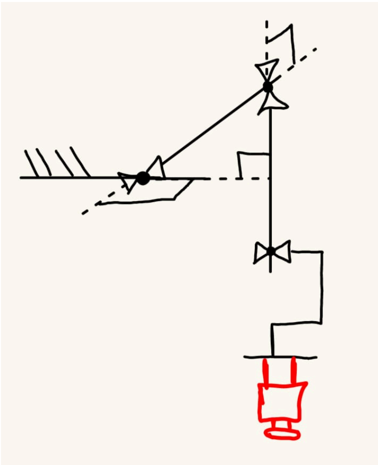
Denavit–Hartenberg Parameter

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 d_1, d_2 and d_3 correspond to the prismatic joint displacements, while L_4 represents the fixed end-effector offset.

Although the Denavit–Hartenberg (DH) convention is included for completeness, the Cartesian nature of the robot allows the kinematic model to be expressed directly in task space. As a result, the DH parameters are not strictly necessary for deriving the forward and inverse kinematics. The subsequent analysis therefore focuses on a Cartesian formulation, which simplifies the mathematical description and highlights the decoupled behavior of each axis.



Kinematic Analysis

Joint Definition

The robot has three degrees of freedom, all of which are prismatic. The joint variables are defined as:

$$q = [q1 \; q2 \; q3]^T$$

where $q1$, $q2$, $q3$ correspond to translations along the X, Y, and Z axes respectively.

Forward Kinematics

Due to the Cartesian configuration, the forward kinematics are straightforward:

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

$$[x \; y \; z]^T = [q1 \; q2 \; q3]^T$$

3. Homogeneous Transformation Matrix

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

Inverse Kinematics

The inverse kinematics problem has a unique analytical solution:

To reach a desired end–effector position (x_d, y_d, z_d), the Cartesian robot must generate the following prismatic joint displacements:

$$q_1 = x_d \quad ; \quad q_2 = y_d \quad ; \quad q_3 = z_d$$

Differential Kinematics

Since the robot is Cartesian, each joint produces a pure linear motion directly along one of the end-effector axes (X, Y, Z). Therefore, joint velocities map one-to-one to end-effector velocities without coupling. This results in a Jacobian equal to the 3×3 identity matrix.

$$J = \frac{\partial x}{\partial q} = I_3$$

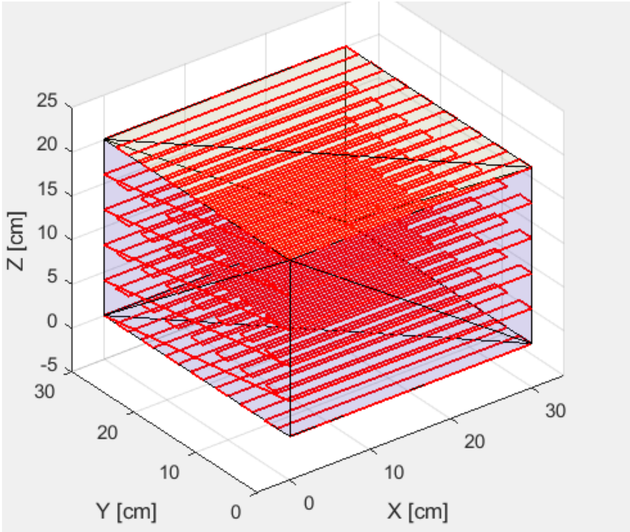
Workspace Analysis

Reachable and Dexterous Workspace

For a Cartesian robot with only translational degrees of freedom, the reachable and dexterous workspaces are identical. Any point within the defined workspace can be reached with full kinematic capability.

Numerical Workspace Visualization

The workspace and robot motion are numerically simulated in MATLAB. A raster scanning trajectory is generated to demonstrate full PCB coverage.



Singularities

Since the Jacobian matrix is full-rank everywhere within the workspace, no kinematic singularities exist for the proposed design.

Camera Model and AOI Constraints

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:

$$W(z) \; = \; 2z\,tan(\frac{FOV}{2})$$

The spatial resolution is given by:

$$\frac{mm}{pixel} \; = \; \frac{W(z)}{N_x}$$

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

PCB Coverage Considerations

Since the instantaneous camera footprint may not cover the entire PCB area, full inspection is achieved through raster scanning with overlapping image acquisition. This strategy ensures complete coverage while maintaining sufficient resolution for defect detection.

Dynamic Analysis and Actuator Considerations

Modeling Approach

The robot operates at low speeds and carries a lightweight camera payload. Consequently, dynamic effects such as Coriolis and centrifugal forces are negligible. A simplified quasi-static model is adopted, allowing independent axis-by-axis analysis.

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 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.

$camera\ mass$: $m_c = 0.30kg$

$motor\ mass$: $m_m = 0.35kg$ $(standard\ value)$

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

$$m_{total} = 0.65kg$$

Force in the z-axis:

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

$$F_z = 0.65 * 9.81 = 6.38N$$

Relationship force-torque in a belt system:

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

$$T = 6.38 * 0.008$$

$$T = 0.051\, N \cdot m \ (Theoretical\ minimum\ torque)$$

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 $SF = 2$.

$T_{design} = 2 \cdot 0.051 = 0.10\, N \cdot m$

$T_{motor} \gg T_{design}$ and the nominal torque is between $0.4N \cdot m$ to $0.5N \cdot m$

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.

Trajectory Planning and Simulation

Trajectory Type

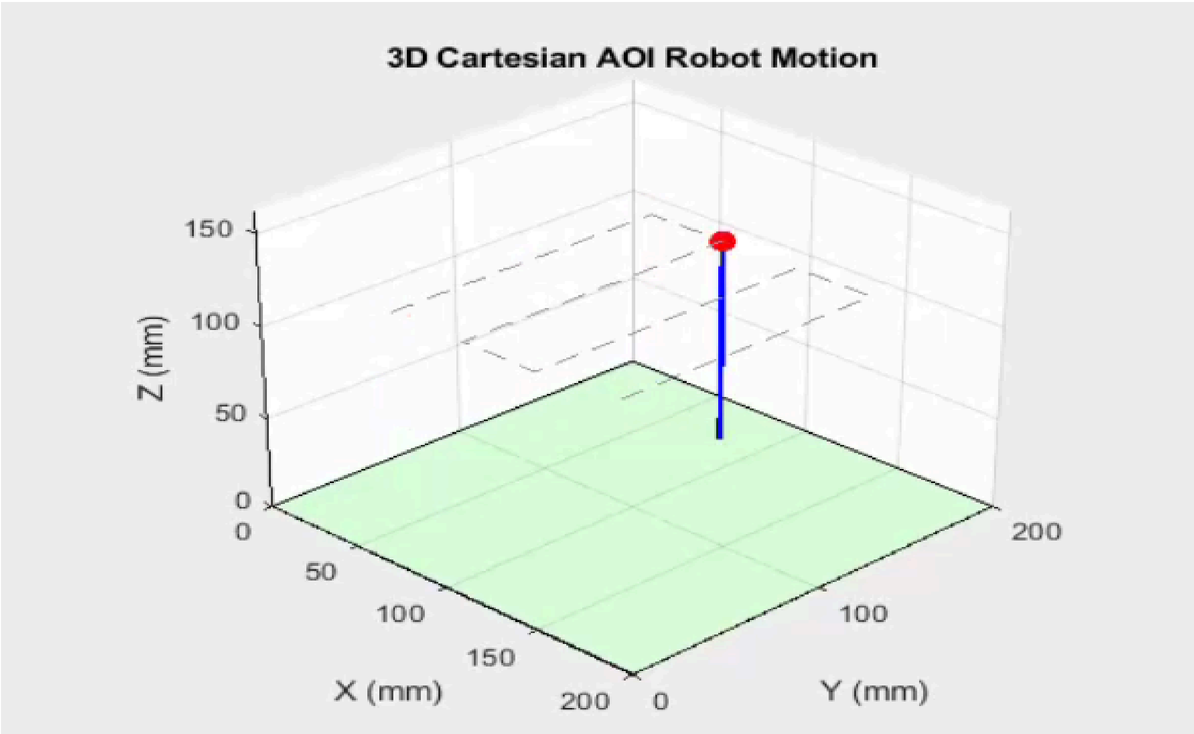
The selected trajectory type for the Cartesian PPP robot is a raster scanning trajectory implemented in task space. This trajectory consists of sequential linear motions along one horizontal axis, followed by incremental displacements along the orthogonal axis, forming a systematic back-and-forth scanning pattern.

Raster scanning is particularly well suited for Automatic Optical Inspection applications, as it guarantees complete coverage of the PCB surface while maintaining a predictable and repeatable motion sequence. The Cartesian structure of the robot allows each linear segment of the trajectory to be executed independently along a single axis, simplifying trajectory generation and control.

During the scanning process, the camera remains at a constant working distance along the Z-axis to ensure uniform image resolution and focus. Direction reversals occur only at the boundaries of the inspection area, minimizing unnecessary repositioning and improving inspection efficiency.

MATLAB Simulation

MATLAB simulations are used to visualize the robot workspace, scanning path, and motion animation.



Validation

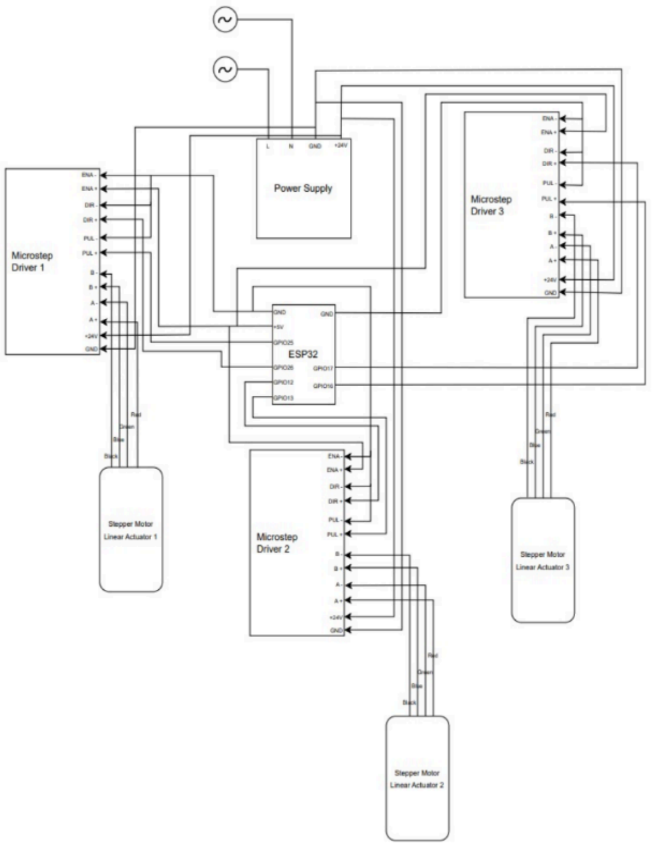
The trajectory planning approach ensures complete PCB coverage without kinematic singularities or loss of positioning accuracy. The simplicity of the Cartesian configuration allows predictable motion behavior and facilitates future implementation on real hardware. The results demonstrate that raster scanning in task space is an effective and robust trajectory planning method for AOI applications using Cartesian robots.

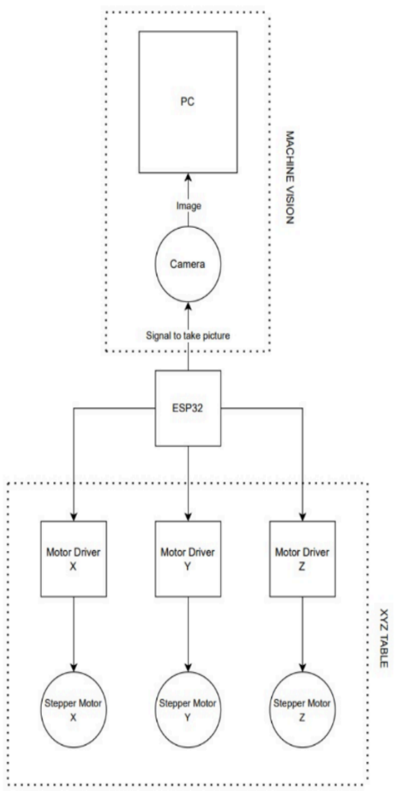
Electrical System Architecture and Components

The electrical system of the Cartesian PPP robot is designed to provide reliable motion control and seamless integration with the vision system required for Automatic Optical Inspection. An ESP32 microcontroller acts as the central control unit, generating step and direction signals for the motor drivers and synchronizing motion with image acquisition.

Each axis is driven by an independent TB6600 microstepping driver controlling a NEMA 17 stepper motor, providing precise and repeatable linear motion. A 24 V DC power supply delivers the required power to the actuation system, while mechanical motion is transmitted through GT2 belts and guided by MGN12 linear rails. The overall architecture ensures stable operation, accurate positioning, and compatibility with camera-based inspection tasks.

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





Conclusion

This project presented the conceptual design and analysis of a Cartesian PPP robotic manipulator intended for Automatic Optical Inspection (AOI) of printed circuit boards. The proposed system leverages the inherent simplicity of Cartesian architectures to achieve precise, repeatable, and decoupled motion along the X, Y, and Z axes, making it well suited for vision-based inspection tasks.

The kinematic analysis demonstrated that the robot exhibits a one-to-one mapping between joint variables and end-effector position, resulting in straightforward forward and inverse kinematics and the absence of kinematic singularities within the defined workspace. Workspace analysis confirmed that the robot is capable of fully covering the inspection area required for PCB analysis.

Trajectory planning based on raster scanning in task space was shown to be an effective strategy for ensuring complete PCB coverage while maintaining smooth and predictable motion. MATLAB simulations validated the feasibility of the proposed design, confirming that the robot can execute the planned trajectories within joint limits and inspection constraints.

Overall, the results indicate that a simplified Cartesian PPP robot is a robust and efficient solution for AOI applications. Future work may include actuator selection and control implementation, integration with image-processing algorithms, and experimental validation on a physical prototype to further assess system performance in real industrial environments.