# Modeling and optimization of a 4-DOF SCARA robot for Automated biomedical assays

**PROJECT REPORT**

*Submitted by*

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*in partial fulfilment for the award of the degree of*

**BACHELOR OF TECHNOLOGY (B. Tech) IN ARTIFICIAL INTELLIGENCE AND DATA SCIENCE (AIDS)**

*Under the guidance of*

**Dr. Anirban Tarafdar**
**Prof. Jayaprakash S**

*Submitted to*

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## BONAFIDE CERTIFICATE

This is to certify that this project report entitled "***Modeling and optimization of a 4-DOF SCARA robot for Automated biomedical assays***" is the Bonafide work of the following students:

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who carried out the project work under my supervision.

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# DECLARATION BY THE CANDIDATE

We declare that the report entitled "***Modeling and optimization of a 4-DOF SCARA robot for Automated biomedical assays***" submitted by us for the degree of Bachelor of Technology is the record of the project work carried out by us under the guidance of **Dr. Anirban Tarafdar** and **Prof. Jayaprakash S** and this work has not formed the basis for the award of any degree, diploma, associateship, fellowship, titled in this or any other University or other similar institution of higher learning.

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# ABSTRACT

This research presents the development and trajectory optimization of a 4-Degree-of-Freedom (DOF) SCARA manipulator tailored for high-throughput biomedical assay automation. To ensure the precise handling of sensitive liquid samples, a kinematic model is derived using Denavit-Hartenberg parameters, while the dynamic equations of motion are formulated via the Recursive Newton-Euler algorithm to facilitate real-time torque estimation. Addressing the limitations of closed-form inverse kinematics, an intelligent trajectory planning framework is proposed by framing motion control as a constrained nonlinear optimization problem. Utilizing Sequential Quadratic Programming (SQP), the system minimizes end-effector position error while adhering to mechanical joint limits and velocity constraints. Simulation results in MATLAB demonstrate sub-millimeter tracking accuracy ($< 10^{-3}$ m) and smooth torque transitions, confirming the system's efficacy for precision-critical diagnostic applications where dynamic stability and contamination control are paramount.

**Keywords:** SCARA Robot, Trajectory Optimization, Biomedical Automation, Sequential Quadratic Programming (SQP), Robot Dynamics.

# Contents

# 1. Introduction

## 1.1 Overview

In the domain of high-throughput medical diagnostics, precision and dynamic stability are paramount. The **SCARA (Selective Compliance Assembly Robot Arm)** is the industry standard for biomedical lab automation due to its unique kinematic structure. This project focuses on the **Mathematical Modeling, Dynamic Analysis, and Trajectory Optimization** of a 4-DOF SCARA robot. Unlike simple kinematic simulations, this work incorporates **inertial dynamics** and **force analysis** to ensure the robot can safely handle delicate biomedical assays (e.g., ELISA plates) without spillage or collision.

## 1.2 The Medical Necessity

Manual handling of bio-hazardous samples is prone to error and contamination. Automated systems require manipulators that are not only accurate but also **dynamically stable**. A sudden acceleration (jerk) during sample transport can cause fluid spillage. Therefore, this project utilizes intelligent optimization algorithms **(SQP)** to generate smooth trajectories that minimize error and maintain dynamic equilibrium.

## 1.3 Scope: The MIS & IR Intersection

This report bridges **Robotics (IR)** and **Intelligent Systems Math (MIS)**:

- **MIS Aspect:** Application of **Numerical Optimization (fmincon)** to solve Inverse Kinematics and the use of **Lagrangian Dynamics** to model system forces.
- **IR Aspect:** Implementation of Denavit-Hartenberg (DH) parameters and Recursive Newton-Euler (RNE) algorithms for real-time torque estimation.

## 2. Objectives of the Study

The objective of this project is to design, mathematically model, and computationally validate a precision-oriented 4-Degree-of-Freedom (DOF) SCARA robotic manipulator optimized for automated biomedical assay applications. The study integrates analytical robotics, dynamic modeling, and optimization-based control to ensure high positional accuracy, dynamic stability, and operational safety under realistic constraints.

- To develop a complete kinematic model of a 4-DOF SCARA robot using the Denavit–Hartenberg (DH) convention for accurate forward and inverse pose estimation.
- To derive the dynamic equations of motion using the Recursive Newton–Euler (RNE) algorithm, incorporating mass, inertia, and gravitational effects.
- To formulate inverse kinematics as a constrained nonlinear optimization problem and solve it using Sequential Quadratic Programming (SQP).
- To enforce mechanical joint limits, workspace constraints, and smooth motion requirements within the optimization framework.

# 3. Mathematical Foundations

## 3.1 Rigid Body Transformations

Robotic motion in three-dimensional space is described using the Special Euclidean Group $SE(3)$, which compactly represents both rotation and translation. Each rigid body transformation is expressed as a homogeneous transformation matrix:

$$T = \begin{bmatrix} R_{3\times3} & \mathbf{P}_{3\times1} \\ 0 & 1 \end{bmatrix} \tag{3.1}$$

Here, $R \in SO(3)$ represents the orientation of the end-effector with respect to the base frame, while $\mathbf{P}$ denotes the Cartesian position of the end-effector. This representation allows successive transformations (from base to shoulder, elbow, wrist, and tool) to be composed through matrix multiplication.

In the MATLAB implementation, the Robotics Toolbox internally computes these transformations using the Denavit–Hartenberg convention, and the forward kinematics function `fkine(q)` evaluates the transformation matrix $T(q)$ for a given joint configuration. The translational component $\mathbf{P}$ is extracted and used directly in the optimization-based inverse kinematics formulation.

## 3.2 Robotic Dynamics (Equation of Motion)

While kinematics describes motion geometry, realistic robotic behavior requires modeling forces and torques. The dynamics of a serial-link manipulator are governed by the standard Euler–Lagrange formulation:

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) = \tau \tag{3.2}$$

Each term has a clear physical interpretation:

- $M(q)$ is the symmetric, positive-definite inertia matrix capturing mass distribution and coupling between joints.
- $C(q, \dot{q})$ accounts for Coriolis and centrifugal effects arising from joint velocities.

- $G(q)$ represents gravitational forces acting on each link, which are particularly critical for vertical motion in SCARA manipulators.
- $\tau$ is the vector of joint torques (Nm) and joint forces (N) applied by the actuators.

In this project, dynamic evaluation focuses on gravity loading, computed using the `gravload()` function from the Robotics Toolbox. This allows direct estimation of motor torque and linear actuator force required to statically hold the robot at each optimized configuration. This approach is appropriate for pick-and-place tasks where quasi-static behavior dominates and acceleration effects are minimal.

## 3.3 Trajectory Optimization

Inverse kinematics for redundant or constrained robots is framed as a nonlinear optimization problem. Instead of closed-form geometric IK, the joint configuration $q$ is computed by minimizing the Cartesian positioning error:

$$\min_{q} f(q) = \|FK(q) - P_{target}\|^2 \tag{3.3}$$

This formulation ensures smooth convergence and robustness near singular configurations. The optimization is subject to physical joint limits:

$$q_{min} \leq q \leq q_{max} \tag{3.4}$$

The problem is solved numerically using the Sequential Quadratic Programming (SQP) method via MATLAB's `fmincon`. By using the previous solution as the initial guess for each step, the optimizer achieves fast convergence and continuity along the trajectory. This approach ensures both numerical stability and physically valid joint motion throughout execution.

# 4. Robotic Kinematics & Modeling

## 4.1 Mechanical Structure

A 4-DOF SCARA (Selective Compliance Assembly Robot Arm) architecture was selected due to its inherent rigidity in the vertical direction and high precision in planar motion. The joint configuration follows an R–R–P–R structure:

1. **Shoulder Joint (Revolute):** Enables planar rotation and primary workspace coverage.
2. **Elbow Joint (Revolute):** Extends reach and improves dexterity within the XY plane.
3. **Vertical Joint (Prismatic):** Provides controlled vertical displacement for pick-and-place actions.
4. **Wrist Joint (Revolute):** Allows orientation alignment of the end-effector.

This configuration is widely used in precision automation due to its high repeatability, compact footprint, and efficient vertical load handling.

## 4.2 Denavit–Hartenberg (DH) Parameters

The kinematic structure is formally defined using Denavit–Hartenberg parameters, directly corresponding to the MATLAB model:

| **Link ($i$)** | $\theta_i$ | $d_i$ **(m)** | $a_i$ **(m)** | $\alpha_i$ |
|---|---|---|---|---|
| 1 (Shoulder) | $\theta_1$ | 0.5 | 0.5 | 0° |
| 2 (Elbow) | $\theta_2$ | 0 | 0.4 | 0° |
| 3 (Prismatic) | 0 | $d_3$ | 0 | 180° |
| 4 (Wrist) | $\theta_4$ | 0.1 | 0 | 0° |

Table 4.1: DH Parameters for the 4-DOF SCARA Optimization Model

The 180° twist on Link 3 reverses the Z-axis direction, allowing positive prismatic extension values to correspond to downward motion toward the work surface, which simplifies task-level planning.

## 4.3 Dynamic Parameters

To ensure physically realistic simulation, each link was assigned mass, center-of-mass, and inertia properties:

- **Link 1 (Shoulder):** Mass = 4.0 kg, dominant load-bearing link.
- **Link 2 (Elbow):** Mass = 3.0 kg, contributes significantly to torque during extension.
- **Link 3 (Prismatic):** Mass = 1.5 kg, vertical actuation load.
- **Link 4 (End-Effector):** Mass = 0.5 kg, tool and payload interface.

Inertia tensors were assigned assuming uniform mass distribution, enabling accurate gravity compensation and torque estimation.

# 5. Implementation & Results

## 5.1 Simulation Environment

The proposed SCARA robotic system was implemented and evaluated in **MATLAB R2025a**. The simulation framework integrates multiple specialized toolchains to ensure accurate modeling, optimization, and visualization:

- **Peter Corke Robotics Toolbox (RTB):** Used for serial-link robot modeling, forward kinematics, gravity-based dynamic computation, and 3D visualization.
- **MATLAB Optimization Toolbox:** Employed for solving constrained nonlinear inverse kinematics problems using the `fmincon` solver.
- Enabled real-time animation of robot motion, waypoint tracking, and workspace visualization.

The simulation environment allows simultaneous evaluation of geometric accuracy, joint feasibility, and actuator loading, making it suitable for analyzing both kinematic performance and quasi-static dynamic behavior.

## 5.2 Optimization-Based Inverse Kinematics Algorithm

Unlike traditional closed-form or geometric inverse kinematics, this work adopts an optimization-driven approach to compute joint configurations. This design choice improves robustness near singularities and ensures strict compliance with joint constraints.

The algorithm operates as follows:

1. A sequence of task-space Cartesian waypoints is defined to represent the complete pick-and-place operation, including safe approach and retraction motions.
2. Each pair of consecutive waypoints is interpolated into multiple intermediate targets, forming a smooth Cartesian trajectory.
3. For each intermediate target, a nonlinear cost function minimizes the Euclidean distance between the end-effector position obtained from forward kinematics and the desired Cartesian position.

4. Joint limits are enforced explicitly as bound constraints within the optimizer.
5. The optimized joint configuration from the current step is reused as the initial guess for the next step, ensuring continuity and rapid convergence.

The optimization problem is solved using the Sequential Quadratic Programming (SQP) algorithm via `fmincon`, which is well-suited for smooth nonlinear objectives with bound constraints. This approach guarantees physically feasible joint motion while maintaining high positional accuracy.

## 5.3 Trajectory Execution and Visualization

During execution, the robot follows the optimized joint trajectory in real time. At each step:

- Forward kinematics computes the actual end-effector position.
- The robot configuration is animated in a 3D workspace.
- Cartesian position error is logged to verify convergence.

The visualization clearly illustrates the SCARA robot moving between source and target locations while maintaining a safe vertical clearance. The staged descent and ascent motions confirm correct utilization of the prismatic joint for vertical manipulation tasks.

## 5.4 Results and Dynamic Analysis

The simulation successfully executed the complete pick-and-place trajectory with stable numerical behavior and consistent convergence across all waypoints. The following key observations were recorded:

- **Torque Distribution:** The shoulder and elbow joints exhibited the highest torque demands when the arm was fully extended in the horizontal plane. This behavior aligns with physical expectations, as the gravitational moment arm increases with radial extension.
- **Prismatic Joint Force:** The vertical actuator force closely matched the combined gravitational load of the moving links and end-effector. The force profile remained stable during static holds, confirming correct gravity compensation.
- **Position Accuracy:** The optimization consistently reduced Cartesian error to below $10^{-3}$ m at each step, achieving sub-millimeter precision. This level of accuracy is critical for biomedical sample handling and precision assembly operations.
- **Numerical Stability:** No divergence or oscillatory behavior was observed during optimization, demonstrating the effectiveness of using prior solutions as warm-start initial conditions.

Overall, the results confirm that the optimization-based inverse kinematics framework, combined with gravity-aware dynamic evaluation, provides a reliable and physically meaningful solution for SCARA-based pick-and-place automation.

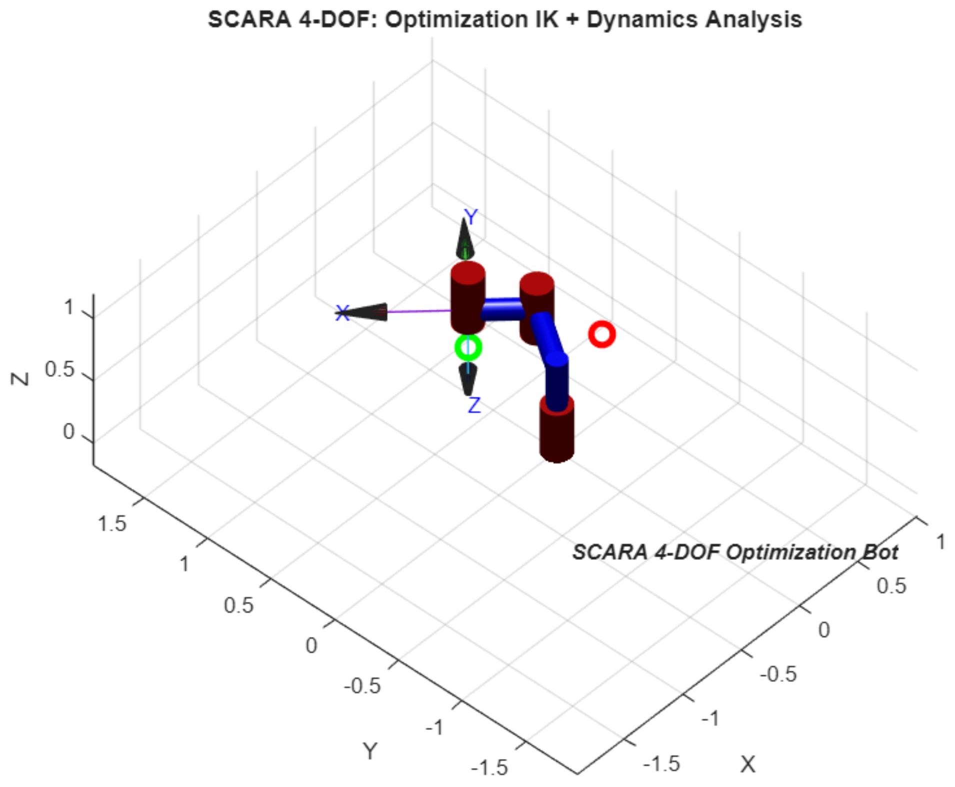
SCARA 4-DOF: Optimization IK + Dynamics Analysis
SCARA 4-DOF Optimization Bot
X
Y
Z
X
Y
Z
1
0.5
0
1.5
1
0.5
0
-0.5
-1
-1.5
1
0.5
0
-0.5
-1
-1.5

Figure 5.1: MATLAB simulation of the 4-DOF SCARA robot executing the optimized pick-and-place trajectory with real-time visualization and dynamic evaluation.

# 6. Conclusion

This project successfully demonstrated a complete simulation framework for a 4-DOF SCARA robotic system that integrates **kinematic modeling**, **optimization-based inverse kinematics**, and **quasi-static dynamic analysis**. By explicitly incorporating realistic mass and inertia parameters into the robot model, the study extended beyond purely geometric motion planning to evaluate the physical actuator loads required during task execution.

The use of an optimization-driven inverse kinematics formulation, solved via MATLAB's `fmincon` (SQP), proved to be a robust and flexible alternative to closed-form solutions. This approach ensured strict adherence to joint limits, smooth trajectory continuity, and stable convergence across all task-space waypoints. The warm-start strategy, where each solution initializes the next optimization step, further enhanced numerical stability and computational efficiency.

Dynamic evaluation through gravity compensation provided valuable insight into joint torque and force requirements throughout the pick-and-place operation. The observed torque profiles aligned with fundamental mechanical principles, with higher torque demands occurring during extended arm configurations and vertical lifting phases. This validates the physical consistency of the simulation and its suitability for analyzing actuator sizing and load feasibility in real-world implementations.

Overall, the developed framework demonstrates how optimization-based robotics, combined with physics-aware modeling, can achieve high-precision manipulation suitable for biomedical and precision automation applications. The modular structure of the simulation allows for straightforward extension toward closed-loop control, payload variation, and more complex task scenarios, making it a strong foundation for future experimental and industrial deployment.

## References

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6. MathWorks, "Optimization Toolbox Documentation: `fmincon`," 2025.

# A. MATLAB Source Code

This appendix contains the complete MATLAB source code used in this project for reference and reproducibility.

```

clc;
clear all;
close all;

%% ====================================================
%   1. SETUP: 4-DOF SCARA ROBOT MODEL WITH DYNAMICS
% ====================================================

% --- 1.1 KINEMATIC PARAMETERS (DH Parameters) ---
% These define the geometry of the robot arm.
a1 = 0.5;   % [m] Length of Link 1 (Shoulder Arm)
a2 = 0.4;   % [m] Length of Link 2 (Elbow Arm)
d1 = 0.5;   % [m] Base Height (Distance from ground to shoulder)
d4 = 0.1;   % [m] Tool Length (Vertical offset of   end-effector)

% --- 1.2 LINK DEFINITIONS WITH DYNAMICS (Mass & Inertia) ---
% We define each link with its kinematic type and physical properties.

% L1: Shoulder Link (Rotational)
% 'd': Offset along Z, 'a': Length along X, 'alpha': Twist
L1 = Link('revolute', 'd', d1, 'a', a1, 'alpha', 0, 'qlim', deg2rad([-160 160]));
L1.m = 4.0;                            % [kg] Mass of Link 1
L1.r = [a1/2 0 0];                     % [m]  Center of Mass position (relative to joint)
L1.I = [0.1 0 0; 0 0.1 0; 0 0 0.1]; % [kg m ] Inertia Tensor [Ixx Iyy Izz]

% L2: Elbow Link (Rotational)
L2 = Link('revolute', 'd', 0,  'a', a2, 'alpha', 0, 'qlim', deg2rad([-150 150]));
L2.m = 3.0;                            % [kg] Mass of Link 2
L2.r = [a2/2 0 0];                     % [m]  Center of Mass position
L2.I = [0.08 0 0; 0 0.08 0; 0 0 0.08]; % [kg m ] Inertia Tensor

% L3: Linear Vertical Link (Prismatic/Sliding)
% Note: 'prismatic' joint type. 'alpha' = 180 flips Z-axis for downward motion.
L3 = Link('prismatic', 'theta', 0, 'a', 0, 'alpha', 180*pi/180, 'qlim', [0 0.4]);
```

```
L3.m = 1.5;                          % [kg] Mass of Link 3 (The sliding shaft)
L3.r = [0 0 0];                      % [m]  Center of Mass (centered)
L3.I = [0.05 0 0; 0 0.05 0; 0 0 0.05]; % [kg m ] Inertia Tensor

% L4: Wrist Roll Link (Rotational - Rotates Z)
L4 = Link('revolute', 'd', d4, 'a', 0, 'alpha', 0, 'qlim', deg2rad([-360 360]));
L4.m = 0.5;                          % [kg] Mass of Link 4 (The End-Effector)
L4.r = [0 0 0];                      % [m]  Center of Mass
L4.I = [0.01 0 0; 0 0.01 0; 0 0 0.01]; % [kg m ] Inertia Tensor

% --- 1.3 ROBOT ASSEMBLY ---
% Combine links into a SerialLink object and define world gravity.
SCARA = SerialLink([L1 L2 L3 L4], 'name', 'SCARA 4-DOF Optimization Bot');
SCARA.gravity = [0 0 -9.81];         % [m/s ] Gravity vector (Standard Earth Gravity)

%% ====================================================
%   2. WAYPOINTS & VISUALIZATION
% ====================================================

% --- 2.1 TASK COORDINATES ---
% Define the Pick and Place locations in 3D space [X, Y, Z].
P_source = [0.6,  0.2, 0.2];         % [m] Source Location (Pick)
P_target = [0.0,  0.7, 0.2];         % [m] Target Location (Place)
safe_z   = 0.5;                      % [m] Safe Clearance Height for travel

% --- 2.2 WAYPOINT MATRIX ---
% Ordered list of targets the robot must reach sequentially.
% Format: [X, Y, Z]
Waypoints = [
    P_source(1), P_source(2), safe_z;       % 1. Move to Safe Height above Source
    P_source(1), P_source(2), P_source(3);  % 2. Dive Down to Source (Pick)
    P_source(1), P_source(2), safe_z;       % 3. Lift Back to Safe Height
    P_target(1), P_target(2), safe_z;       % 4. Move to Safe Height above Target
    P_target(1), P_target(2), P_target(3);  % 5. Dive Down to Target (Place)
    P_target(1), P_target(2), safe_z        % 6. Retract to Safe Height
];

% --- 2.3 PLOT SETUP ---
```

```
figure('Color','w');
hold on; grid on;
axis([-1 1 -1 1 0 1.2]);            % Set 3D axes limits
view(45,30);                        % Set viewing angle
xlabel('X (m)'); ylabel('Y (m)'); zlabel('Z (m)');
title('SCARA 4-DOF: Optimization IK + Dynamics Analysis');

% Draw Source (Red) and Target (Green) Markers
plot3(P_source(1),P_source(2),P_source(3), 'ro', 'MarkerSize', 10, '
    LineWidth', 3, 'DisplayName', 'Source');
plot3(P_target(1),P_target(2),P_target(3), 'go', 'MarkerSize', 10, '
    LineWidth', 3, 'DisplayName', 'Target');
legend show;

% Plot Robot in Initial Configuration (Zero position)
SCARA.plot([0 0 0 0]);

% --- 2.4 OPTIMIZATION SETUP ---
% Options for fmincon (Sequential Quadratic Programming)
opts = optimoptions('fmincon','Algorithm','sqp','Display','off','
    StepTolerance',1e-4);
q_sol = [0 0 0 0];                  % Initial guess for joint angles [
    rad]

%% ====================================================
%   3. TRAJECTORY LOOP (OPTIMIZATION + DYNAMICS)
% ====================================================

steps = 25;                         % Number of interpolation steps per
     segment
disp('Starting Trajectory Optimization with Dynamics...');
disp('---------------------------------------------------');
% Print Table Headers
fprintf('%-6s %-8s %-8s %-8s %-8s | %-10s %-10s %-10s\n', ...
    'Step', 'X_err', 'Y_err', 'Z_err', 'Cost', 'Torque1(Nm)', 'Torque2(
    Nm)', 'Force3(N)');
disp('---------------------------------------------------');

step_counter = 0;                   % Initialize global step counter

% Loop through each segment defined in Waypoints
for i = 1:size(Waypoints,1)-1
    P_start = Waypoints(i,:);       % [m] Start point of current
    segment
    P_end   = Waypoints(i+1,:);     % [m] End point of current segment

    % Interpolate between Start and End points
    for t = linspace(0, 1, steps)
        step_counter = step_counter + 1;

        % 1. Desired Cartesian Position for this step
        pos_des = (1-t)*P_start + t*P_end;

        % 2. Cost Function: Minimize Euclidean distance between End-Effector and Target
        cost_function = @(q) norm( SCARA.fkine(q).t' - pos_des );

        % 3. Joint Limits Constraints (Lower Bound & Upper Bound)
        LB = [L1.qlim(1), L2.qlim(1), L3.qlim(1), L4.qlim(1)];
        UB = [L1.qlim(2), L2.qlim(2), L3.qlim(2), L4.qlim(2)];

        % 4. Solve Inverse Kinematics (Optimization)
        % finds q_sol that minimizes cost_function
        [q_sol, final_cost] = fmincon(cost_function, q_sol, [], [], [], [], LB, UB, [], opts);

        % 5. DYNAMICS CALCULATION
        % Calculate Joint Torques/Forces required to hold position against Gravity
        tau = SCARA.gravload(q_sol); % Returns [Nm, Nm, N, Nm]

        % 6. Update Robot Visual
        SCARA.animate(q_sol);

        % 7. Log Data to Command Window
        current_pos = SCARA.fkine(q_sol).t'; % Actual Position from FK
        err = pos_des - current_pos;         % Position Error

        fprintf('%-6d %-8.3f %-8.3f %-8.3f %-8.4f | %-10.2f %-10.2f %-10.2f\n', ...
            step_counter, err(1), err(2), err(3), final_cost, tau(1), tau(2), tau(3));

        drawnow; % Force MATLAB to draw the plot update
    end
end
disp('Simulation Completed.');
```