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

B.Tech (AIDS)
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Subject Coordinator
Dr. Anirban Tarafdar
Prof. Jayaprakash

Presented By:

Gowripriya R(DL.AI.U4AID24113)
Yaalini R (DL.AI.U4AID24043)
Vepuri Satya Krishna (DL.AI.U4AID24140)

MATA AMRITANANDAMAYI MATH
श्रद्धावान् लभते ज्ञानम्

AMRITA VISHWA VIDYAPEETHAM, DELHI NCR, FARIDABAD
Department of Artificial Intelligence & Data Science (AIDS)

INTRODUCTION

Automation plays a critical role in modern biomedical laboratories where accuracy, speed, and safety are essential. Manual handling of biological samples increases the risk of contamination and human error, especially during repetitive tasks such as pipetting and sample transfer.

To address this challenge, this project focuses on the kinematic modeling and simulation of a 4-DOF SCARA robot designed for automated biomedical assays such as ELISA testing and PCR sample preparation.

The SCARA robot is chosen due to its high planar accuracy, vertical rigidity, and fast pick-and-place capability, making it well-suited for laboratory automation.

OBJECTIVE OF THE PROJECT

- To mathematically model a 3-DOF SCARA robot suitable for biomedical applications
- To derive Forward and Inverse Kinematics equations
- To simulate pick-and-place operations using MATLAB

MEDICAL MOTIVATION

Medical Necessity

- Biomedical assays require precise microliter-level sample handling
- Manual pipetting is:
  - Error-prone
  - Time-consuming
  - Unsafe for bio-hazardous samples
- Robotic automation ensures:
  - High repeatability
  - Reduced contamination
  - Increased throughput
- Why SCARA Robot?
  - Excellent planar motion control
  - Vertical rigidity for pipette insertion

SYSTEM OVERVIEW

System Description

- Robot Type: 4-DOF SCARA (R-R-P-R)
- Task: Pick sample from source vial and place into target well
- Environment:
  - Laboratory table
  - Source vial
  - Target well plate

MECHANICAL STRUCTURE (R-R-P-R)

Robot Configuration

1. Joint 1 (Revolute): Shoulder rotation (θ_1)
2. Joint 2 (Revolute): Elbow rotation (θ_2)
3. Joint 3 (Prismatic): Vertical motion (d_3)
4. Joint 4 (Revolute): Tool rotation (θ_4)

Advantages

- Planar flexibility
- Vertical precision
- Compact workspace

FORWARD KINEMATICS

- Role of Forward Kinematics in the Project
- Forward kinematics is used to:
- Compute actual end-effector position at each time step
- Compare it with the desired position
- Calculate position error during optimization

Visualize the robot motion during trajectory tracking

$$T_i = \begin{bmatrix} \cos\theta & -\sin\theta & 0 & a\cos\theta \\ \sin\theta & \cos\theta & 0 & a\sin\theta \\ 0 & 0 & 1 & d \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

INVERSE KINEMATICS

Formulating the Optimization Problem

Instead of solving equations analytically, we convert IK into a numerical optimization problem.

Objective Function:

$$J(q) = \|f(q) - x_{\text{desired}}\|$$

This represents the distance between actual and desired end-effector position.

DYNAMICS

- Dynamics deals with the forces and torques required to produce motion in the robot.
- In this project, dynamics is used to compute the joint torques needed to support the robot under gravity.
- Each link of the SCARA robot is assigned:
  - Mass
  - Center of mass
  - Inertia
- The robot is modeled as a rigid-body system, and gravitational effects are considered for realistic behavior.
- Dynamics is evaluated after obtaining joint positions from inverse kinematics.

In implementation, this is computed using:

```
tau = SCARA.gravload(q);
```

- This calculates the torque required at each joint to balance gravity.
- The result ensures physically accurate and stable robot motion.

gravload(q) calculates:

$\tau_g(q)=\partial V(q)/\partial q$

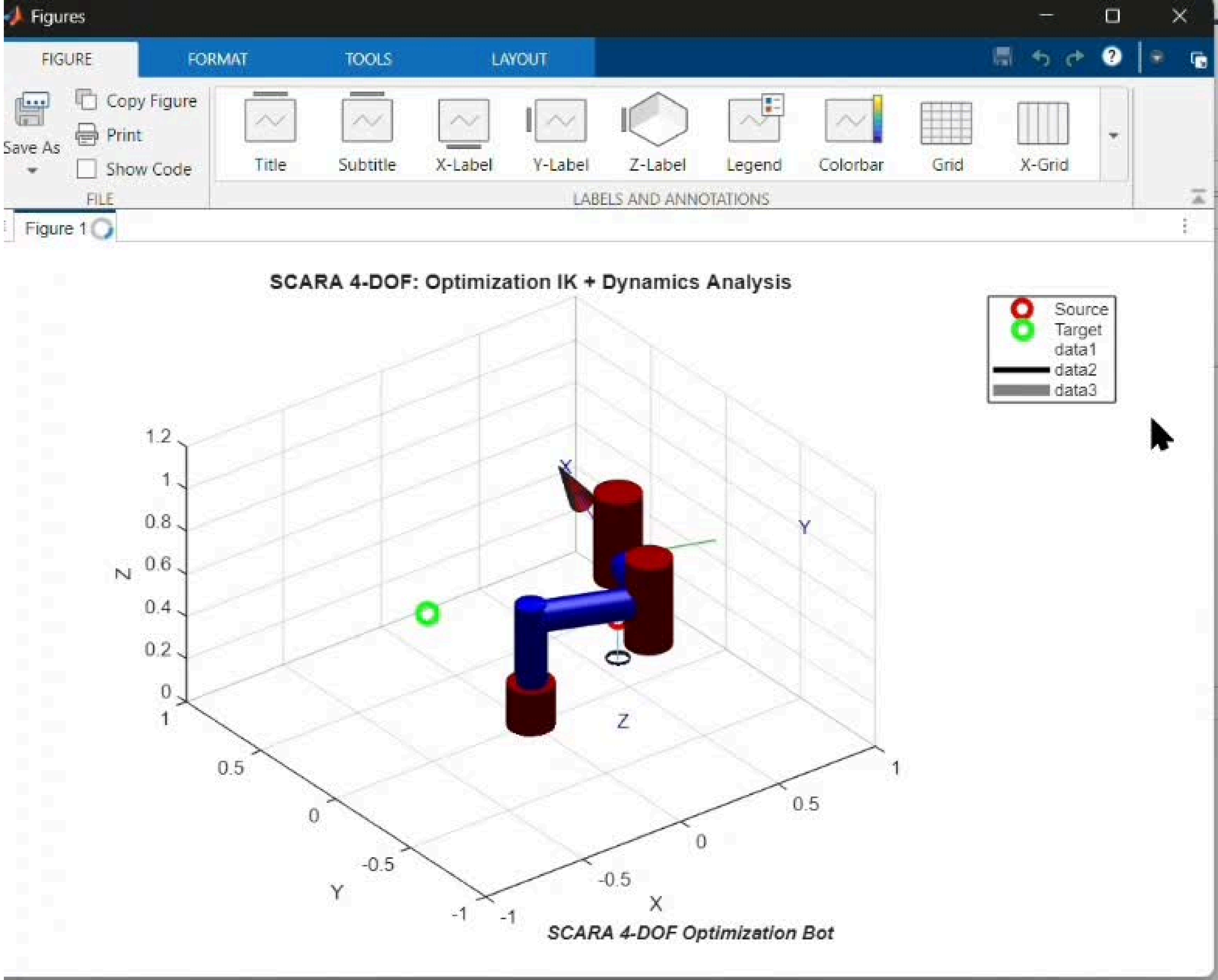
Where:

$V(q)$ is the gravitational potential energy

and τ_g are the gravity compensation torque

FUTURE SCOPE AND DIRECTIONS

- Extend the model to include full dynamic control (inertia and Coriolis effects)
- Implement closed-loop control using PID or model-based controllers
- Add trajectory optimization for smoother and energy-efficient motion
- Integrate real-time sensor feedback for improved accuracy
- Interface the model with actual hardware for real-world validation
- Explore advanced optimization techniques such as GA or PSO
- Expand to multi-robot coordination and collaborative tasks


Figures
FIGURE
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FILE
Title
Subtitle
X-Label
Y-Label
Z-Label
Legend
Colorbar
Grid
X-Grid
LABELS AND ANNOTATIONS
Figure 1
SCARA 4-DOF: Optimization IK + Dynamics Analysis
Source
Target
data1
data2
data3
Z
Y
X
SCARA 4-DOF Optimization Bot

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THANK YOU