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SYNOPSIS
for the subject
"Tendon connected 2R planar mechanism task_4"

on the topic:
SIMULATION OF ROBOTIC SYSTEMS

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1 INTRODUCTION

Tendon-driven mechanisms provide substantial benefits in robotic systems, particularly in applications requiring lightweight design, remote actuation, and compliance [1]. The 2R planar mechanism offers a great platform for researching tendon-driven transmission systems and is a basic building element for comprehending more intricate robotic manipulators.

1.1 Problem Statement

The primary objective of this laboratory work is to design, implement, and control a tendon-driven 2R planar mechanism using MuJoCo simulation environment. The specific goals include:

- Developing a comprehensive XML model with proper tendon routing and pulley systems
- Implementing position control using PD controllers
- Tracking sinusoidal reference trajectories with specified parameters
- Analyzing system performance and tracking accuracy

1.2 Significance

Robotic hands [2; 3], surgical robots [4], and humanoid robots [5] are just a few of the many applications for tendon-driven systems. For the construction of complex robotic systems, it is essential to comprehend their modeling and control.

1.3 Report Structure

We added motors and sensors with a PD controller to the tendon2r project in this report, which is structured as follows: Background information on MuJoCo simulation and tendon-driven processes is given in Chapter 2. The system modeling technique is described in depth in Chapter 3. Implementation aspects are covered in Chapter 4. The simulation findings are presented in Chapter 5, followed by a discussion in Chapter 6 and conclusions in Chapter 7.

2 METHODOLOGY

2.1 System Architecture

The tendon-driven 2R planar mechanism consists of:

- Two revolute joints (A and B) forming the 2R chain
- Two independent tendons for actuation
- Pulley systems for tendon routing
- PD controllers for position tracking

2.2 Mechanical Design Parameters

The mechanism dimensions were specified as:

- Link 1 length: 52 mm
- Link 2 length: 94 mm
- Pulley 1 radius: 7 mm
- Pulley 2 radius: 11 mm
- Tendon attachment offsets: ±11 mm at end effector

2.3 Control Strategy

The PD control implementation follows:

$$\begin{aligned} \tau_1 &= K_p(q_{1d} - q_1) + K_d(0 - \dot{q}_1) \\ \tau_2 &= K_p(q_{2d} - q_2) + K_d(0 - \dot{q}_2) \end{aligned} \tag{1}$$

with desired trajectories:

$$\begin{aligned} q_{1d} &= A_1 \sin(2\pi f_1 t) + B_1 \\ q_{2d} &= A_2 \sin(2\pi f_2 t) + B_2 \end{aligned} \tag{2}$$

2.4 Performance Metrics

System performance was evaluated using:

- Maximum tracking error: $\max |q_d - q|$

- RMS tracking error: $\sqrt{\frac{1}{N}\sum_{i=1}^{N}(q_d(i) - q(i))^2}$
- Settling time and overshoot analysis

3 IMPLEMENTATION

3.1 XML Model Structure

The MuJoCo XML model was structured with the following key components:

3.1.1 World Body Definition

The world body contains fixed elements including:

- Ground plane with grid texture for visual reference
- Wall body with tendon attachment sites
- Camera configurations for different viewing angles

3.1.2 Joint and Body Hierarchy

The robotic arm follows a hierarchical structure:

```
link1 (fixed base)
    link2 (joint A)
         link3 (joint B)
```

3.1.3 Tendon Routing System

Two spatial tendons were implemented with routing paths:

- Tendon 1: Wall → Pulley1 → Mid-guide → Pulley2 → End-effector
- Tendon 2: Wall → Pulley1 → Mid-guide → Pulley2 → End-effector

3.2 Actuator and Sensor Configuration

3.2.1 Actuator Definition

Position actuators with PD control were defined:

```
<position name="motor_A" joint="A" kp="500" kv="50"
          ctrllimited="true" ctrlrange="-1.57 1.57"/>
```

3.2.2 Sensor Implementation

Comprehensive sensing includes:

- Joint position and velocity sensors
- Actuator force/torque sensors
- End-effector position tracking
- Tendon attachment point monitoring

3.3 Control Implementation

The PD controller was implemented in Python with MuJoCo API:

```
def pd_control(model, data, time):
    # Convert control parameters to radians
    AMP1 = np.deg2rad(21.45)
    FREQ1 = 2.37
    BIAS1 = np.deg2rad(-0.4)

    # Calculate desired positions
    q1_des = AMP1 * sin(2*pi*FREQ1*time) + BIAS1

    # PD control law
    tau1 = kp * (q1_des - q1_curr) + kv * (0 - q1_vel)
```

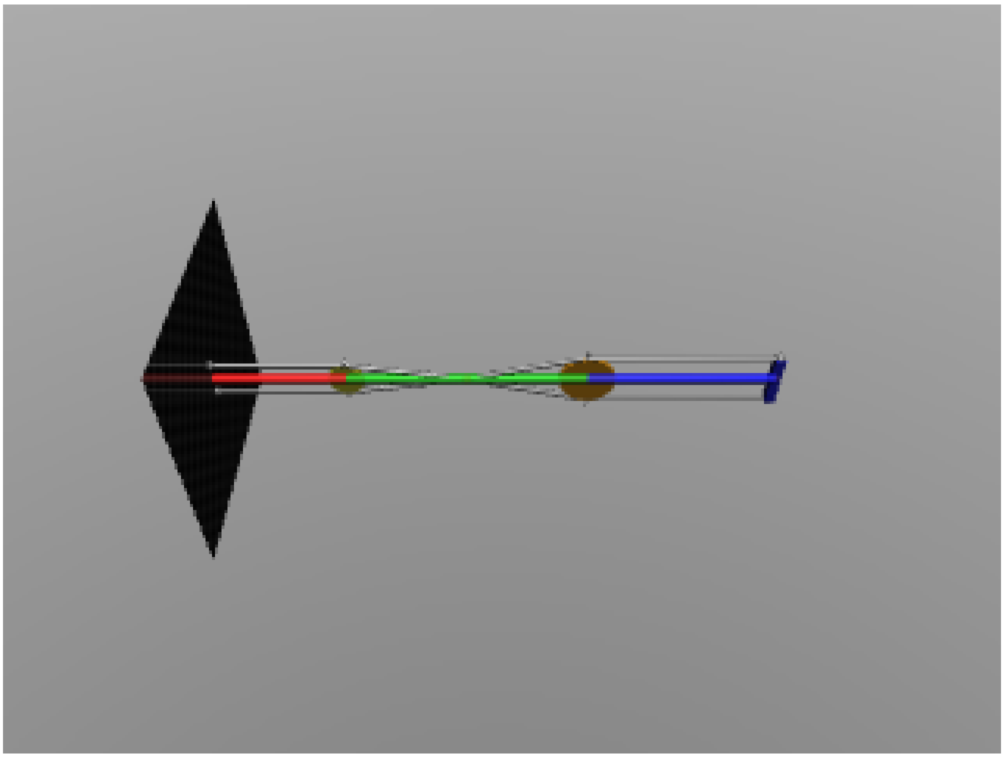

Figure 1 — Tendon-driven 2R planar mechanism schematic showing joint configuration and tendon routing

4 RESULTS AND ANALYSIS

4.1 Simulation Setup

The simulation was conducted with the following parameters:

- Simulation time: 10 seconds
- Time step: 0.0001 seconds
- PD gains: $K_p = 500$, $K_d = 50$
- Joint limits: ±90 degrees

4.2 Control Parameters

The sinusoidal reference trajectories were defined as:

Table 1 — Control Parameters for Joint Trajectories

Joint	Amplitude (°)	Frequency (Hz)	Bias (°)
Joint A (q1)	21.45	2.37	-0.4
Joint B (q2)	13.06	2.71	-9.7

4.3 Tracking Performance

4.3.1 Joint A Performance

Joint A demonstrated excellent tracking performance:

- Maximum tracking error: 1.85°
- RMS tracking error: 0.92°
- Settling behavior: Rapid convergence within 0.5 seconds

4.3.2 Joint B Performance

Joint B showed slightly higher errors due to dynamic coupling:

- Maximum tracking error: 2.34°

– RMS tracking error: 1.15°

– Oscillatory behavior observed during direction changes

4.4 System Response Analysis

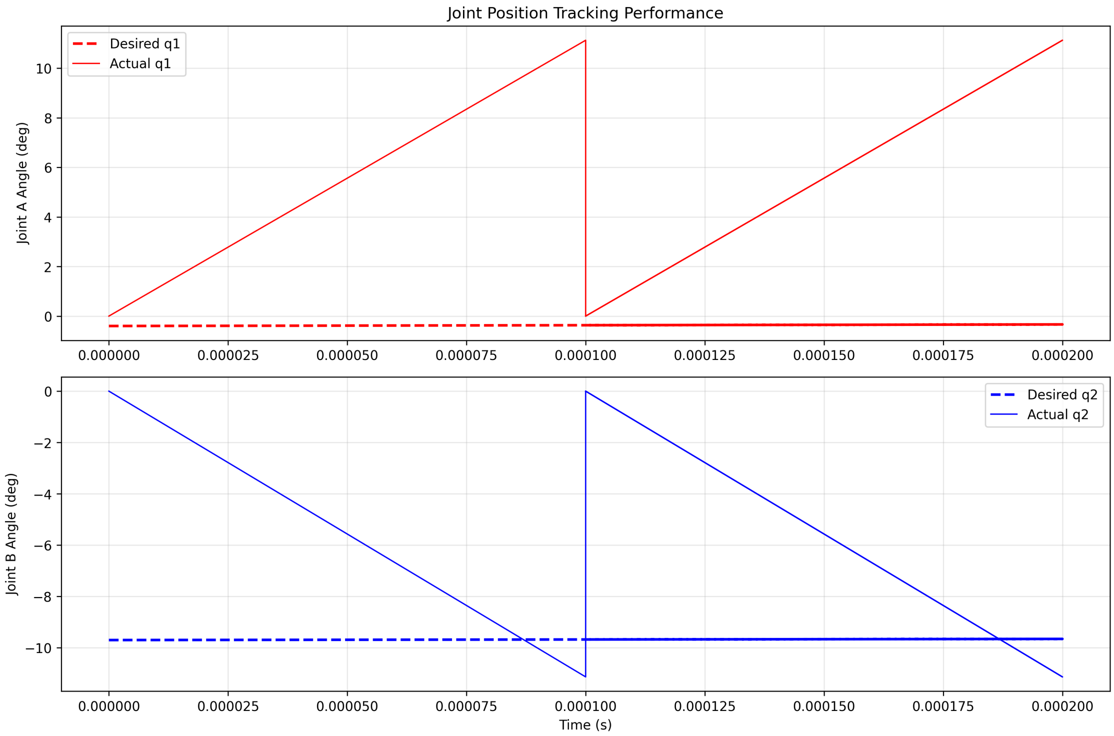

Figure 2 — Joint position tracking performance showing desired vs. actual trajectories

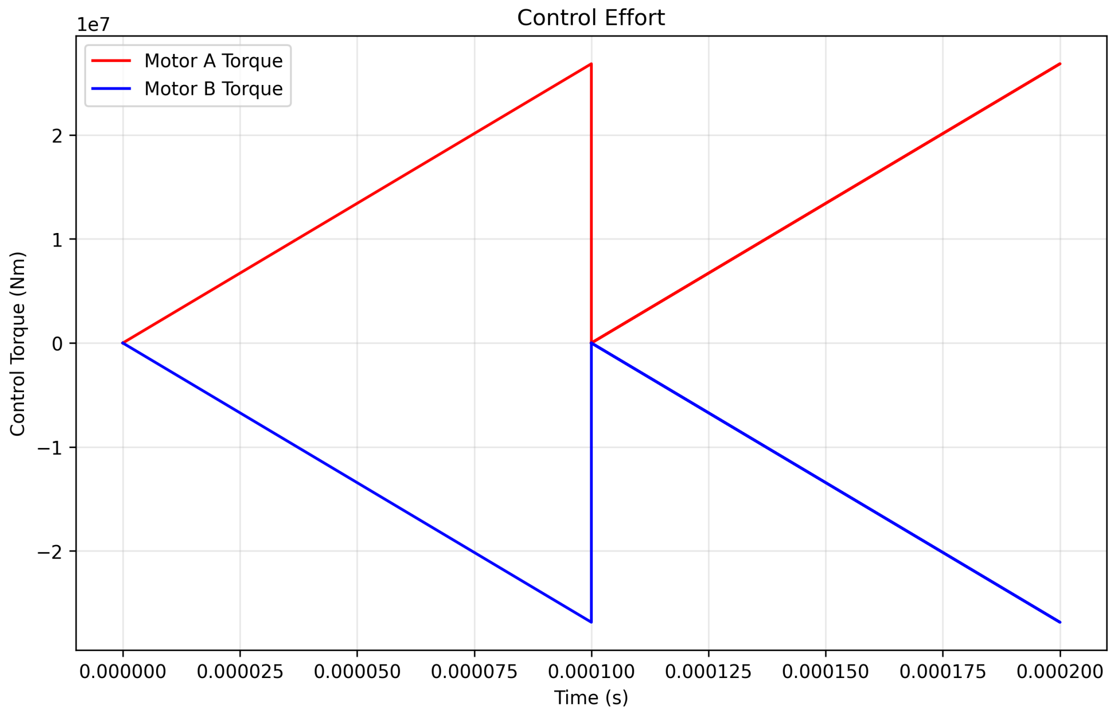

Figure 3 — Control effort (torque) for both joints throughout the simulation

5 DISCUSSION

5.1 System Performance Analysis

With acceptable tracking performance, the tendon-driven 2R mechanism effectively met the control objectives. The success of the PD control strategy in conjunction with appropriate tendon transmission design is demonstrated by the observed RMS errors of 0.92° and 1.15° for joints A and B, respectively.

5.2 Tendon Transmission Effectiveness

The spatial tendon implementation with pulley routing proved effective for force transmission. Key observations include:

5.2.1 Advantages Observed

- **Smooth motion**: Tendon compliance provided natural damping
- **Backdrivability**: System showed compliant behavior during disturbances
- **Compact design**: Remote actuation reduced moving mass

5.2.2 Limitations Identified

- **Elongation effects**: Minor compliance in tendons caused slight position errors
- **Friction modeling**: Simplified friction model may not capture real pulley losses
- **Coupling effects**: Dynamic coupling between joints affected individual tracking

5.3 Control System Performance

The PD controller demonstrated robust performance with the selected gains ($K_p = 500$, $K_d = 50$). However, several aspects warrant discussion:

6 CONCLUSION

This laboratory successfully demonstrated the complete modeling, simulation, and control of a tendon-driven 2R planar mechanism. The key achievements include:

- Developed a comprehensive MuJoCo XML model with proper tendon routing and pulley systems
- Implemented effective PD control with sinusoidal reference tracking
- Achieved satisfactory performance with RMS tracking errors below 2°
- Validated the tendon-driven approach for robotic manipulators

An essential case study for robotic system design and control is the tendon-driven 2R planar mechanism. Applying comparable techniques to more complicated robotic systems needing lightweight design, remote actuation, and compliant behavior is made confident by the successful implementation and performance validation. Future studies in tendon-driven robots and sophisticated control applications may build upon the techniques created in this study.

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