```
%% PID Tuning for Robot Joints Using Control System Toolbox
% This script demonstrates PID tuning for the 7-DOF robot using
% the standard pidtune function from the Control System Toolbox.

clear; clc; close all;

% Add paths and load parameters
addpath(genpath('../functions'));
addpath(genpath('./data/generated_functions')); % Path to dynamic model functions

%% Robot Model Parameters
% These should match the parameters used in generate_dynamics.m
model_params = struct();
model_params.L_45 = 0.121851;  % Link 4-5 length (m)
model_params.L_6 = 0.1;        % Link 6 length (m)
model_params.m1 = 0.5;         % Base mass (kg)
model_params.m2 = 1.0;         % Vertical prismatic joint mass (kg)
model_params.m3 = 1.0;         % Horizontal prismatic joint mass (kg)
model_params.m4 = 0.5;         % Link 4 mass (kg)
model_params.m5 = 0.5;         % Link 5 mass (kg)
model_params.m6 = 0.3;         % Link 6 mass (kg)
model_params.m7 = 0.1;         % End effector mass (kg)
model_params.g = 9.81;         % Gravity (m/s^2)

link_lengths = [model_params.L_45; model_params.L_6];

% Simulation parameters
sample_time = 0.005;  % 100 Hz sampling rate

%% Initial PID Parameters
% Create initial PID parameters for each joint
pid_params = cell(7, 1);

% Base rotation (revolute)
pid_params{1} = struct(...
    'Kp', 100, ...
    'Ki', 5, ...
    'Kd', 10, ...
    'max_integral', 10.0, ...
    'joint_type', 'revolute');

% Vertical prismatic joint
pid_params{2} = struct(...
    'Kp', 400, ...
    'Ki', 20, ...
    'Kd', 40, ...
    'max_integral', 10.0, ...
    'joint_type', 'prismatic');

% Horizontal prismatic joint
```

```
pid_params{3} = struct(...
    'Kp', 400, ...
    'Ki', 20, ...
    'Kd', 40, ...
    'max_integral', 10.0, ...
    'joint_type', 'prismatic');

% Joint 4 (revolute)
pid_params{4} = struct(...
    'Kp', 100, ...
    'Ki', 5, ...
    'Kd', 10, ...
    'max_integral', 10.0, ...
    'joint_type', 'revolute');

% Joint 5 (revolute)
pid_params{5} = struct(...
    'Kp', 100, ...
    'Ki', 5, ...
    'Kd', 10, ...
    'max_integral', 10.0, ...
    'joint_type', 'revolute');

% Joint 6 (revolute)
pid_params{6} = struct(...
    'Kp', 100, ...
    'Ki', 5, ...
    'Kd', 10, ...
    'max_integral', 10.0, ...
    'joint_type', 'revolute');

% Joint 7 (revolute)
pid_params{7} = struct(...
    'Kp', 50, ...
    'Ki', 2, ...
    'Kd', 5, ...
    'max_integral', 10.0, ...
    'joint_type', 'revolute');

%% Step 1: Generate a test trajectory for tuning
fprintf('Generating test trajectory for controller tuning...\n');
```

```
Generating test trajectory for controller tuning...
```

```
% Generate a characteristic chess move trajectory for tuning
start_square = 'e2';
end_square = 'e4';
move_duration = 2.0;  % seconds
```

```
[q_traj, qd_traj, qdd_traj, time_vec] = generateChessTraj(start_square, end_square,
link_lengths, move_duration, sample_time);

%% Step 2: Evaluate the performance of the initial controller
fprintf('\nEvaluating initial controller performance...\n');
```

```
Evaluating initial controller performance...
```

```

% Simulate with initial PID parameters
[q_init, qd_init, qdd_init, tau_init] = simulateRobotDynamicsWithJointPID(...
    q_traj, qd_traj, qdd_traj, time_vec, pid_params, model_params,
struct('enabled', false));

% Calculate initial tracking error
init_error = q_traj - q_init;
init_rms_error = sqrt(mean(init_error.^2, 2));

fprintf('Initial controller RMS errors:\n');
```

```
Initial controller RMS errors:
```

```
for i = 1:7
    fprintf('  Joint %d: %.6f\n', i, init_rms_error(i));
end
```

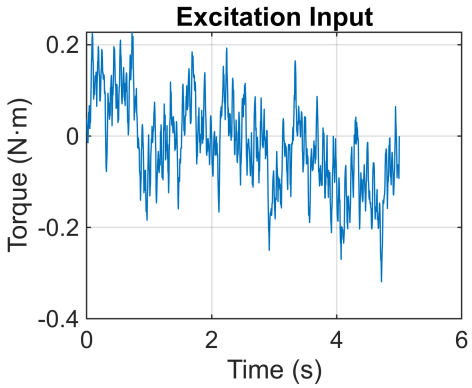
```
  Joint 1: 0.079186
  Joint 2: 0.084680
  Joint 3: 0.009875
  Joint 4: 0.715562
  Joint 5: 1.404417
  Joint 6: 0.657022
  Joint 7: 0.669042
```

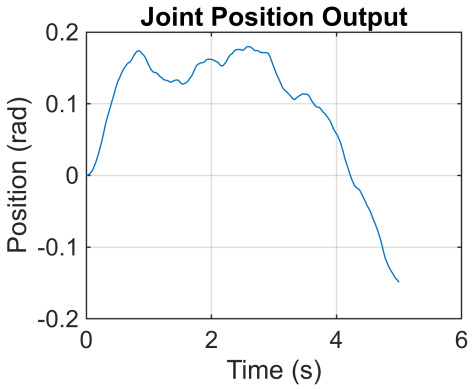
```

%% Step 3: System Identification for PID Tuning
fprintf('\nPerforming system identification for PID tuning...\n');
```

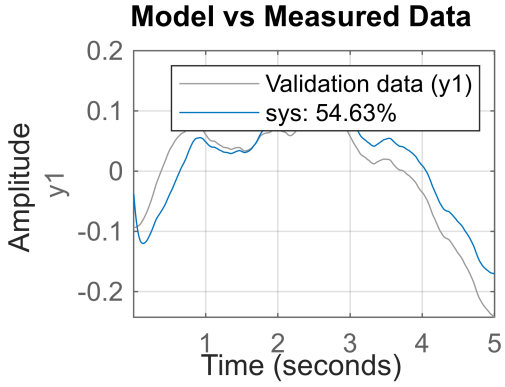
```
Performing system identification for PID tuning...
```

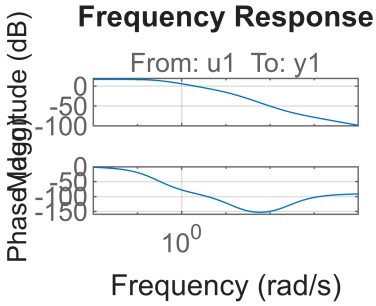
```

% System identification options
id_options = struct(...
    'model_order', 2, ...
    'simulation_time', 5, ...  % 5 seconds for demo
    'sample_time', sample_time);

% Identify linear models for each joint
joint_models = identifyJointModels(model_params, id_options);
```

```
System Identification for Robot Joints
--------------------------------------
Identifying model for joint 1 (revolute)...
  Model order: 2, Fit: 54.63%
```

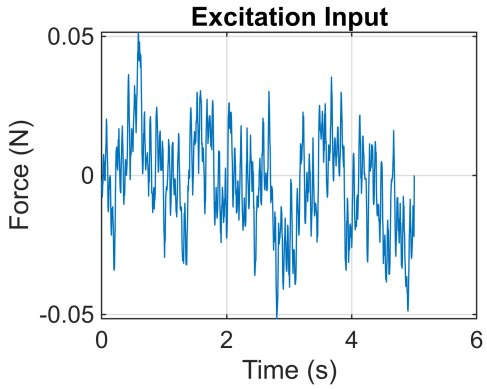


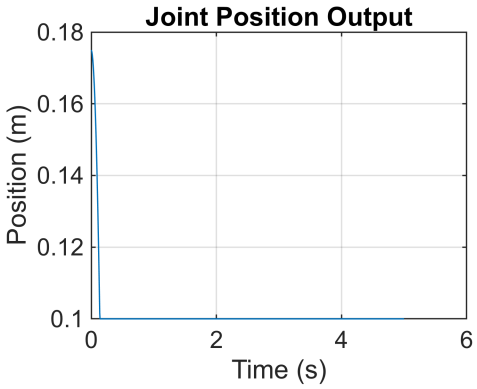


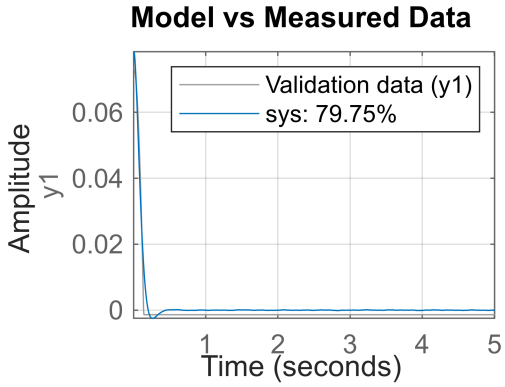


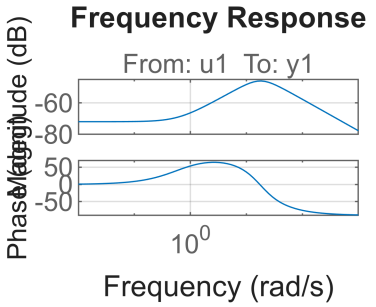



```
Identifying model for joint 2 (prismatic)...
  Model order: 2, Fit: 79.75%
```

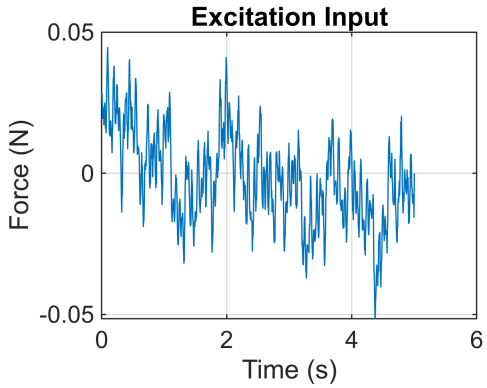


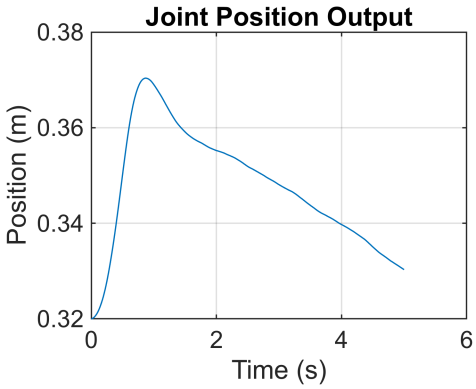


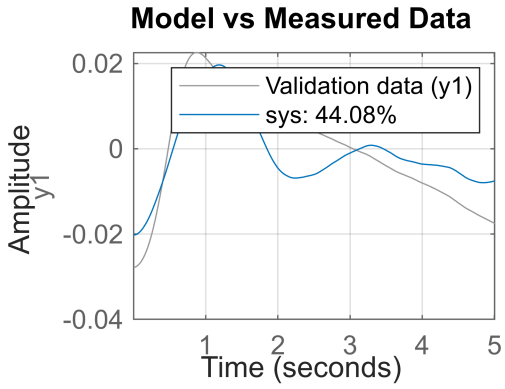


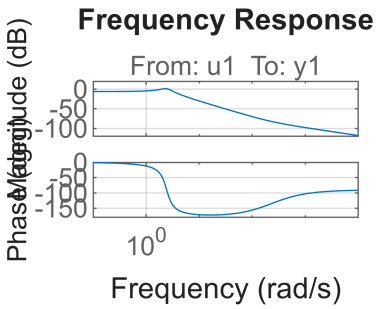



```
Identifying model for joint 3 (prismatic)...
  Model order: 2, Fit: 44.08%
```

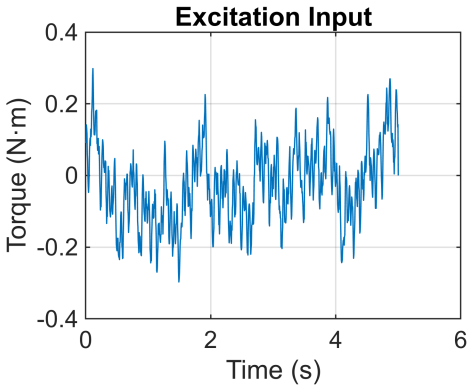


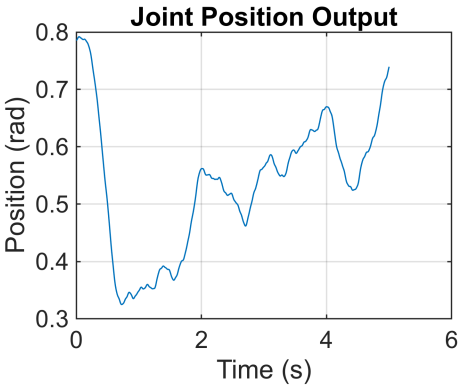


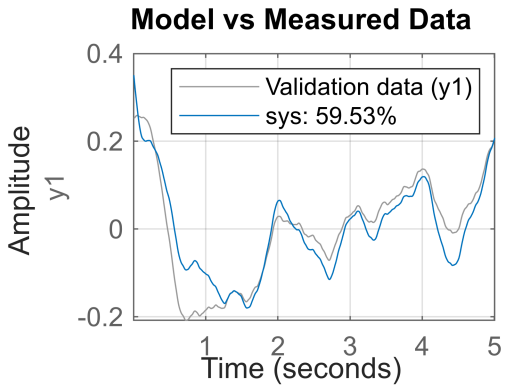


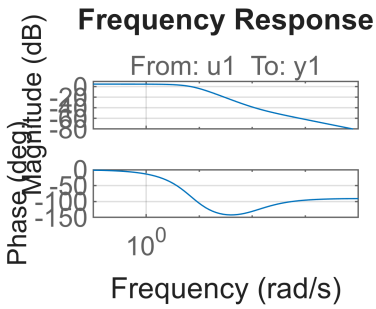



```
Identifying model for joint 4 (revolute)...
  Model order: 2, Fit: 59.53%
```

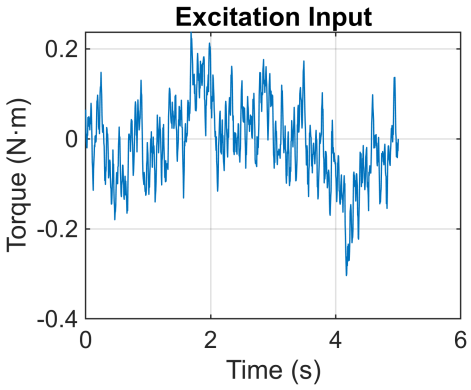


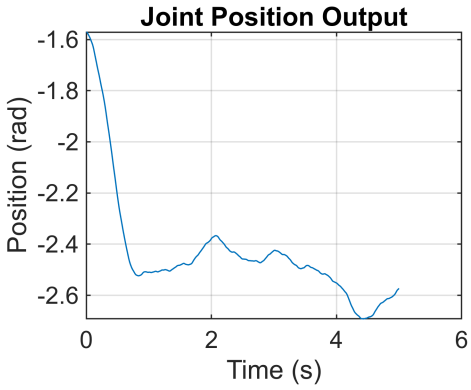


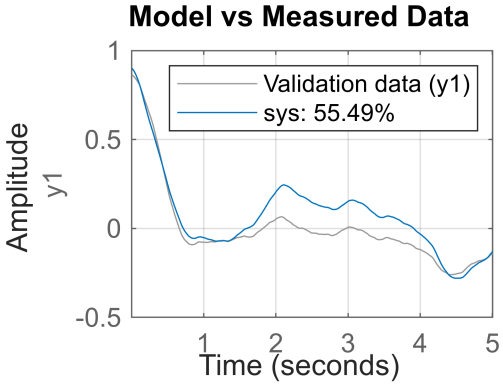


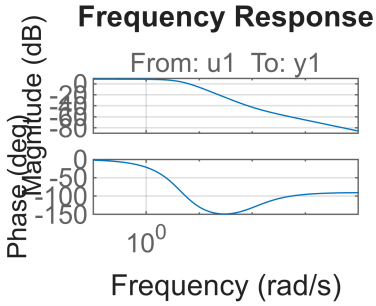



```
Identifying model for joint 5 (revolute)...
  Model order: 2, Fit: 55.49%
```

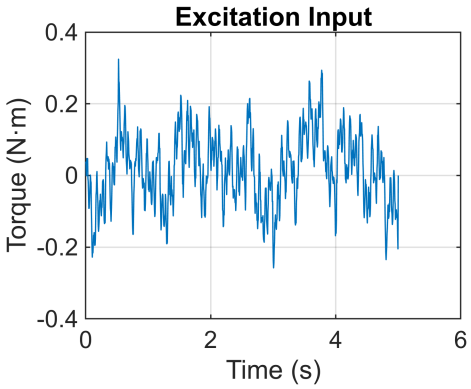


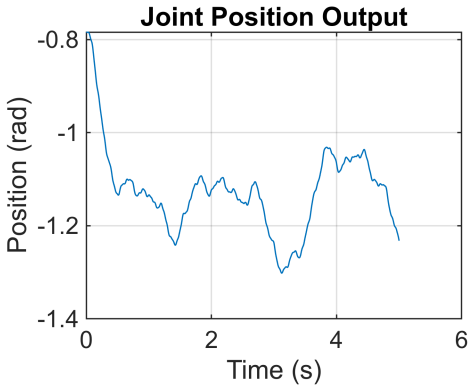


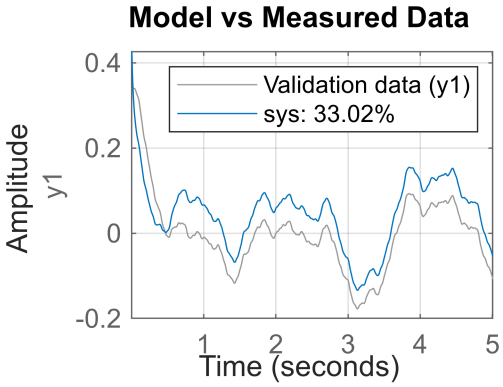


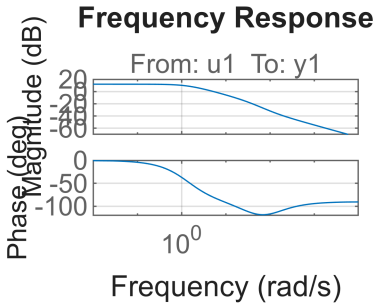



```
Identifying model for joint 6 (revolute)...
  Model order: 2, Fit: 33.02%
```

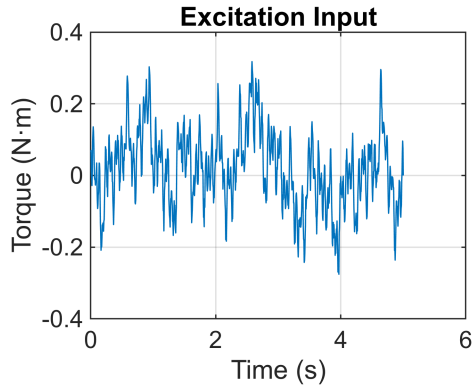


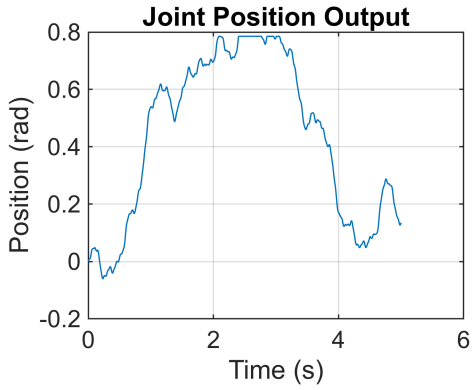


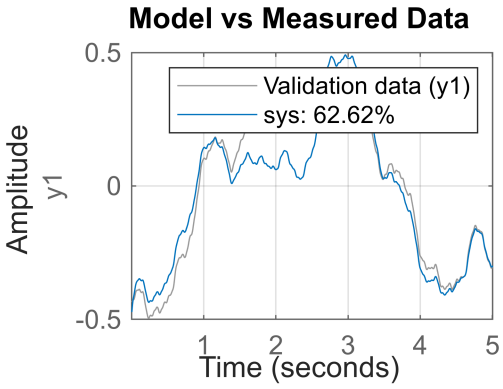


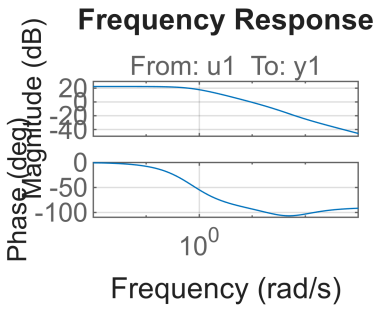



```
Identifying model for joint 7 (revolute)...
  Model order: 2, Fit: 62.62%
```










```
System identification completed.
```

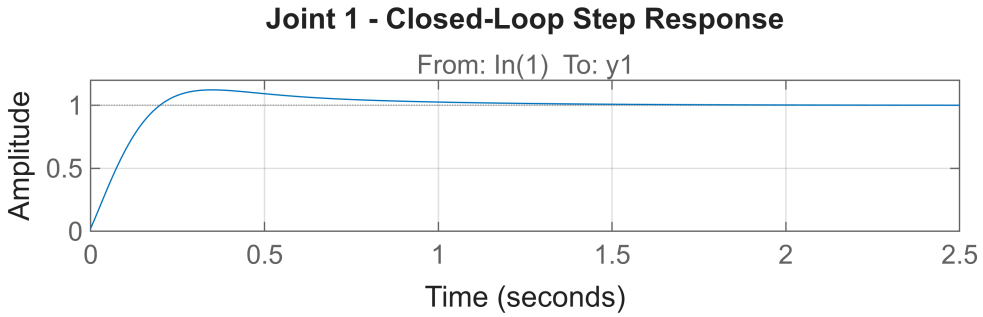
```
%% Step 4: PID Tuning using Control System Toolbox
fprintf('\nPerforming PID tuning using Control System Toolbox...\n');
```

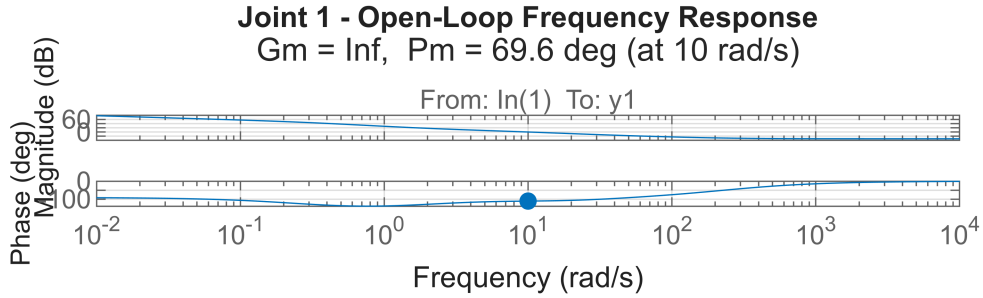
```
Performing PID tuning using Control System Toolbox...
```

```
% Define joints to tune
joints_to_tune = [1, 2, 3, 4, 5, 6, 7];  % Focus on key revolute joints

% PID tuning options - different bandwidths for different joint types
bandwidths = zeros(7, 1);
bandwidths(1) = 10;   % Base rotation (medium bandwidth)
bandwidths(2) = 5;    % Vertical prismatic (lower bandwidth)
bandwidths(3) = 5;    % Horizontal prismatic (lower bandwidth)
bandwidths(4) = 15;   % Joint 4 (higher bandwidth)
bandwidths(5) = 15;   % Joint 5 (higher bandwidth)
bandwidths(6) = 15;   % Joint 6 (higher bandwidth)
bandwidths(7) = 10;   % Joint 7 (medium bandwidth)

% Setup tuning options
tuning_options = struct(...
    'joints_to_tune', joints_to_tune, ...
    'bandwidth', bandwidths, ...
    'phase_margin', 60);  % 60 degrees phase margin for robustness
```

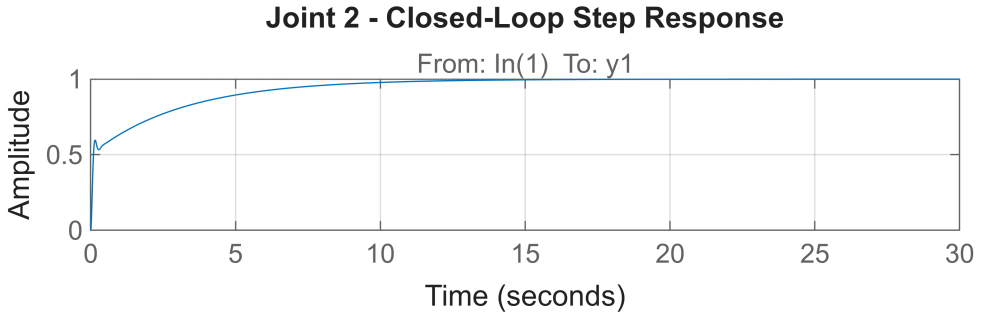
```
% Perform PID tuning
try
    tuned_pid_params = tuneJointPIDWithPIDTune(joint_models, pid_params,
tuning_options);

    % Simulate with tuned parameters
    [q_tuned, qd_tuned, qdd_tuned, tau_tuned] =
simulateRobotDynamicsWithJointPID(...
        q_traj, qd_traj, qdd_traj, time_vec, tuned_pid_params, model_params,
struct('enabled', false));

    % Calculate tracking error after tuning
    tuned_error = q_traj - q_tuned;
    tuned_rms_error = sqrt(mean(tuned_error.^2, 2));

    fprintf('\nTuned controller RMS errors:\n');
    for i = 1:7
        if ismember(i, joints_to_tune)
            fprintf('  Joint %d: %.6f (tuned)\n', i, tuned_rms_error(i));
        else
            fprintf('  Joint %d: %.6f\n', i, tuned_rms_error(i));
        end
    end
catch ME
    warning('PID tuning failed: %s', ME.message);
    tuned_pid_params = pid_params;
    q_tuned = q_init;
    tuned_error = init_error;
    tuned_rms_error = init_rms_error;
end
```

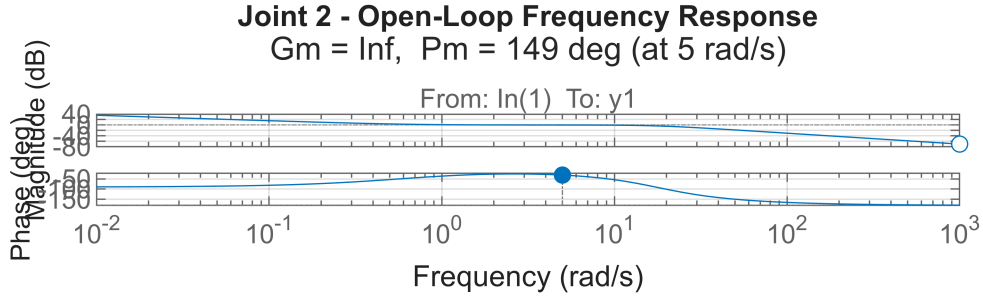
```
Tuning joint 1 (revolute) with pidtune...
Joint 1 tuned successfully: Kp=5.64, Ki=9.86, Kd=0.21
  Rise time: 0.149 s, Settling time: 1.116 s, Overshoot: 12.25%
```



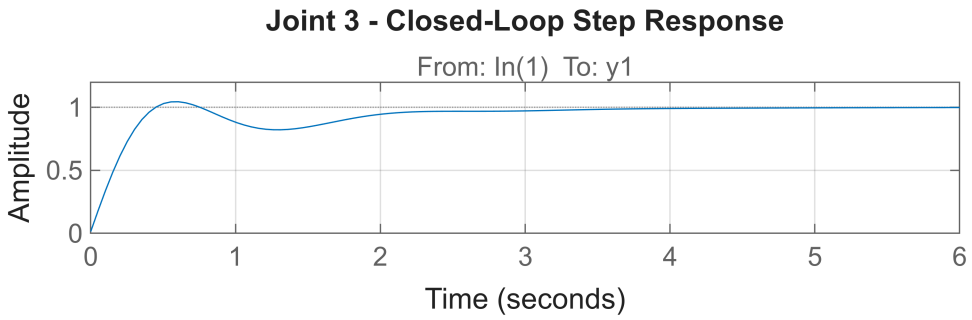


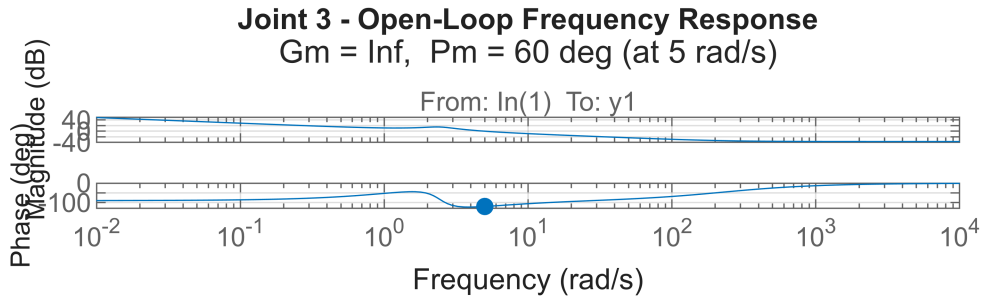

```
Tuning joint 2 (prismatic) with pidtune...
Joint 2 tuned successfully: Kp=0.00, Ki=2434.63, Kd=0.00
  Rise time: 5.130 s, Settling time: 10.321 s, Overshoot: 0.00%
```



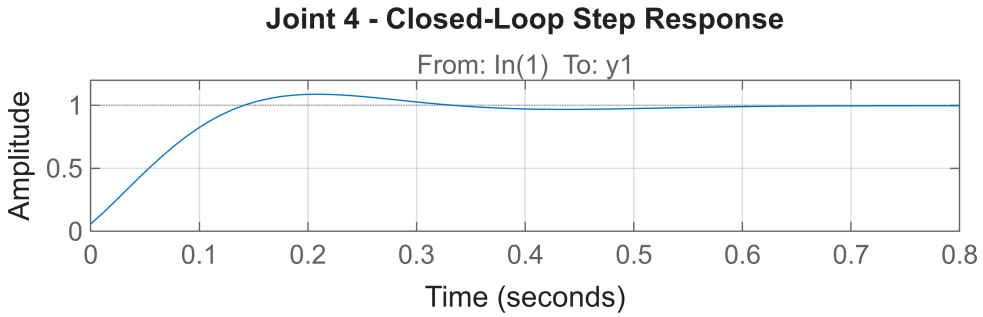


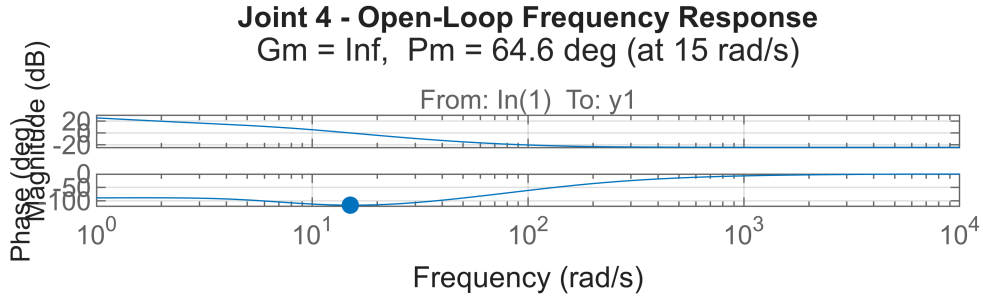
```
Tuning joint 3 (prismatic) with pidtune...
Joint 3 tuned successfully: Kp=4.88, Ki=5.30, Kd=1.12
  Rise time: 0.325 s, Settling time: 3.350 s, Overshoot: 4.43%
```



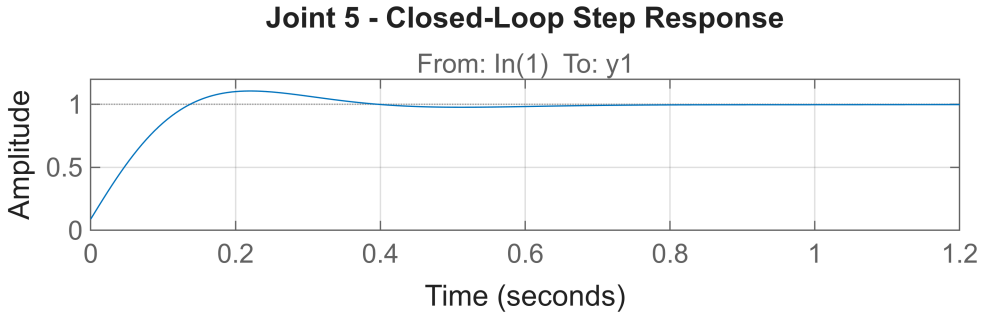


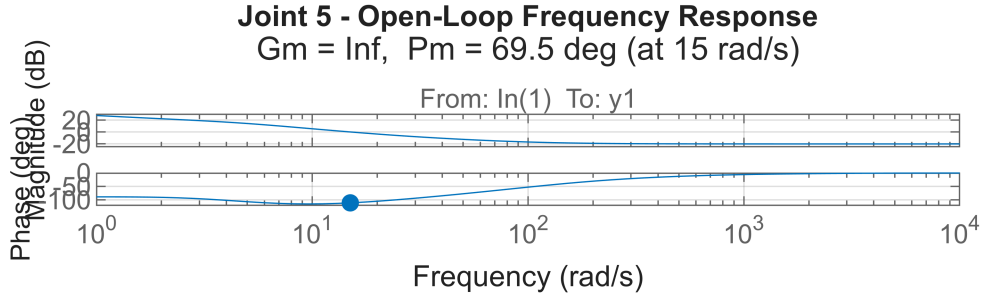

```
Tuning joint 4 (revolute) with pidtune...
Joint 4 tuned successfully: Kp=2.84, Ki=10.68, Kd=0.08
  Rise time: 0.110 s, Settling time: 0.534 s, Overshoot: 8.82%
```



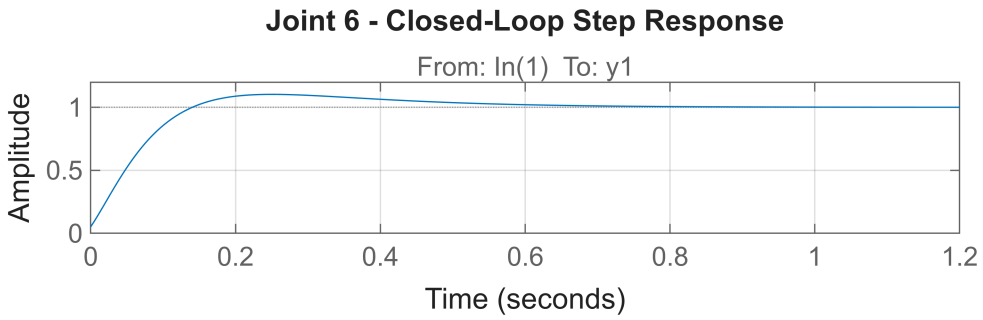


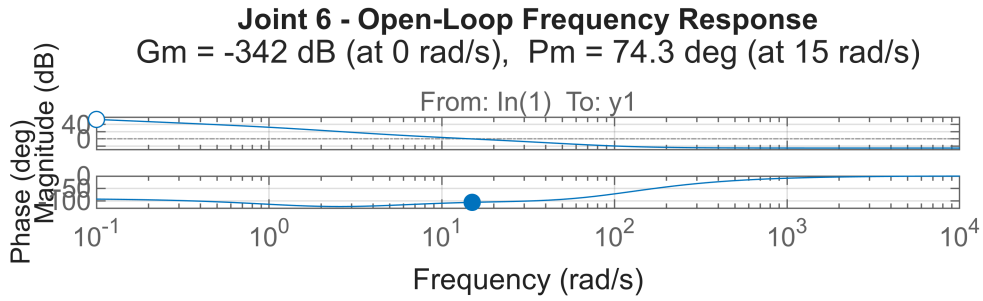

```
Tuning joint 5 (revolute) with pidtune...
Joint 5 tuned successfully: Kp=3.71, Ki=8.85, Kd=0.19
  Rise time: 0.109 s, Settling time: 0.573 s, Overshoot: 10.58%
```



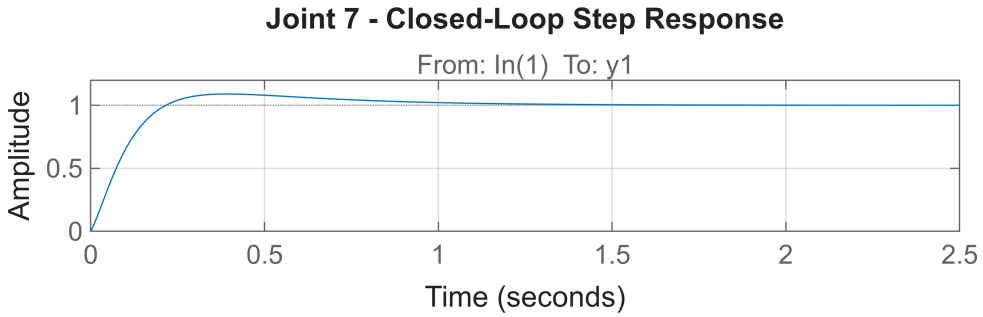


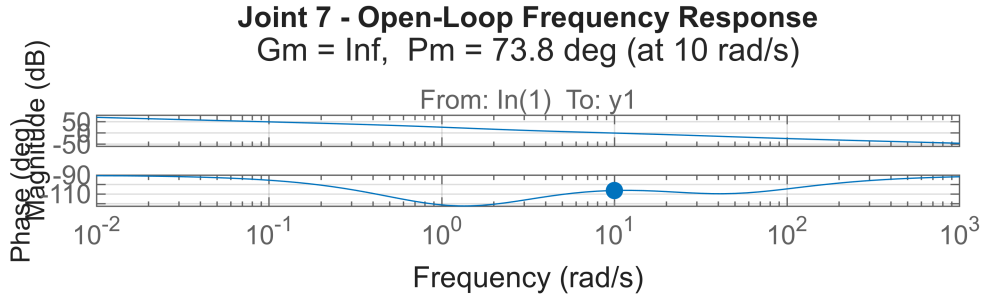
```
Tuning joint 6 (revolute) with pidtune...
Joint 6 tuned successfully: Kp=2.90, Ki=12.20, Kd=0.03
  Rise time: 0.105 s, Settling time: 0.606 s, Overshoot: 10.28%
```






```
Tuning joint 7 (revolute) with pidtune...
Joint 7 tuned successfully: Kp=1.05, Ki=2.42, Kd=0.00
  Rise time: 0.150 s, Settling time: 1.026 s, Overshoot: 8.99%
```



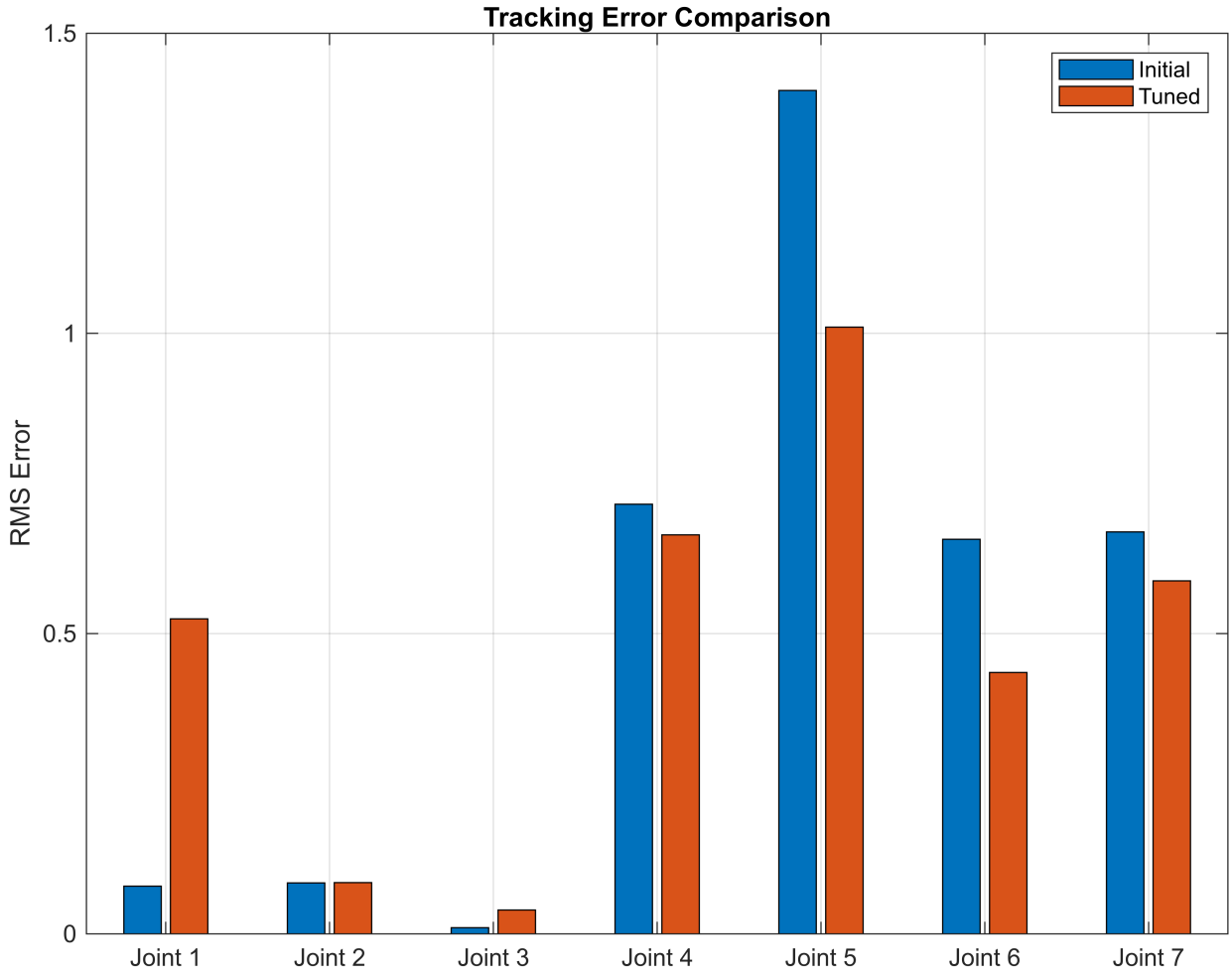



```
PID tuning completed for 7 joints.
Tuned controller RMS errors:
  Joint 1: 0.524493 (tuned)
  Joint 2: 0.085315 (tuned)
  Joint 3: 0.039748 (tuned)
  Joint 4: 0.664110 (tuned)
  Joint 5: 1.010343 (tuned)
  Joint 6: 0.434981 (tuned)
  Joint 7: 0.587559 (tuned)
```

```
%% Step 5: Compare Controller Performance
fprintf('\nComparing controller performance...\n');
```

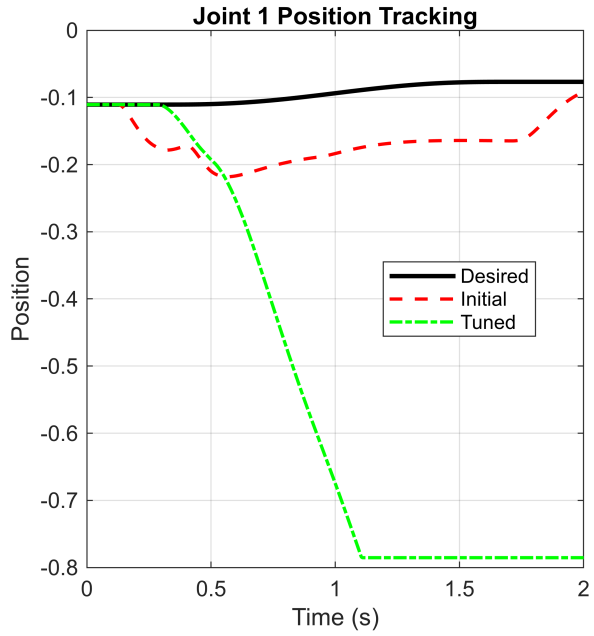
```
Comparing controller performance...
```

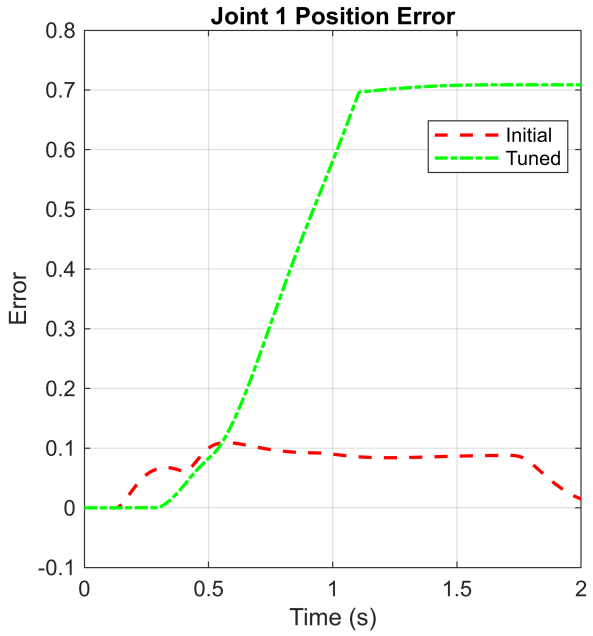
```
% RMS tracking error comparison
figure('Name', 'RMS Tracking Error Comparison', 'Position', [100, 100, 800, 600]);
bar([init_rms_error, tuned_rms_error]);
set(gca, 'XTickLabel', {'Joint 1', 'Joint 2', 'Joint 3', 'Joint 4', 'Joint 5',
'Joint 6', 'Joint 7'});
legend('Initial', 'Tuned');
ylabel('RMS Error');
title('Tracking Error Comparison');
grid on;
```

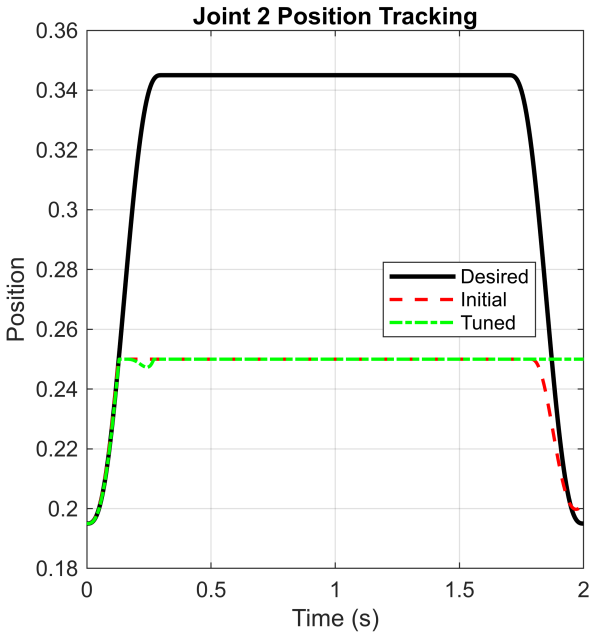


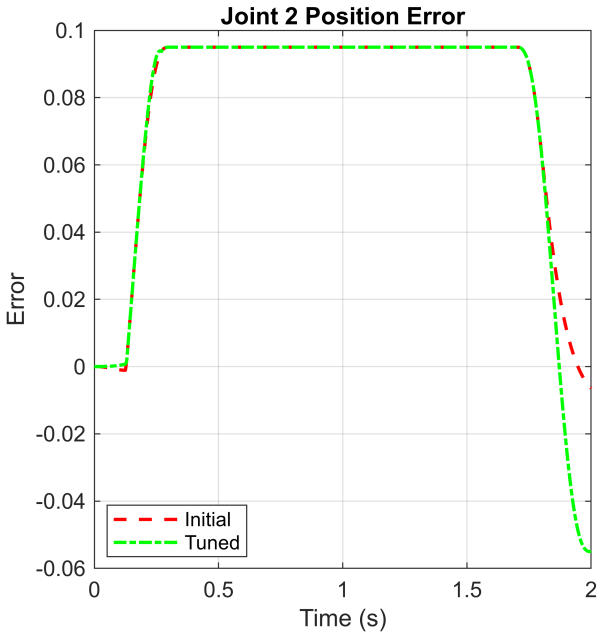

```
% Joint position tracking comparison for tuned joints
for j = joints_to_tune
    figure('Name', sprintf('Joint %d Position Tracking Comparison', j), 'Position',
[150, 150, 900, 400]);

    % Position tracking
    subplot(1, 2, 1);
    plot(time_vec, q_traj(j,:), 'k-', 'LineWidth', 2, 'DisplayName', 'Desired');
    hold on;
    plot(time_vec, q_init(j,:), 'r--', 'LineWidth', 1.5, 'DisplayName', 'Initial');
    plot(time_vec, q_tuned(j,:), 'g-.', 'LineWidth', 1.5, 'DisplayName', 'Tuned');
    title(sprintf('Joint %d Position Tracking', j));
    xlabel('Time (s)');
    ylabel('Position');
    legend('Location', 'best');
    grid on;

    % Position error
```

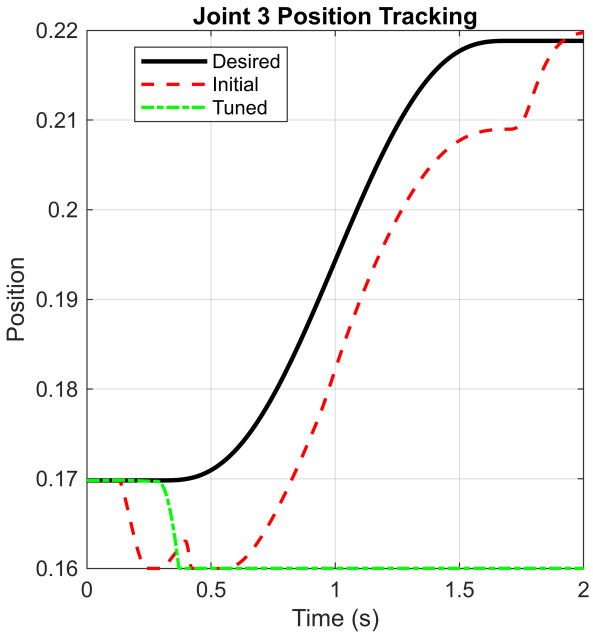
```
    subplot(1, 2, 2);
    plot(time_vec, init_error(j,:), 'r--', 'LineWidth', 1.5, 'DisplayName',
'Initial');
    hold on;
    plot(time_vec, tuned_error(j,:), 'g-.', 'LineWidth', 1.5, 'DisplayName',
'Tuned');
    title(sprintf('Joint %d Position Error', j));
    xlabel('Time (s)');
    ylabel('Error');
    legend('Location', 'best');
    grid on;
end
```

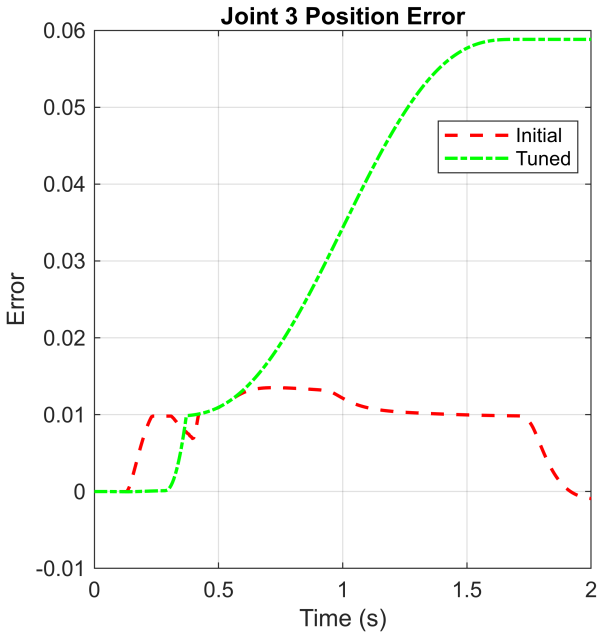


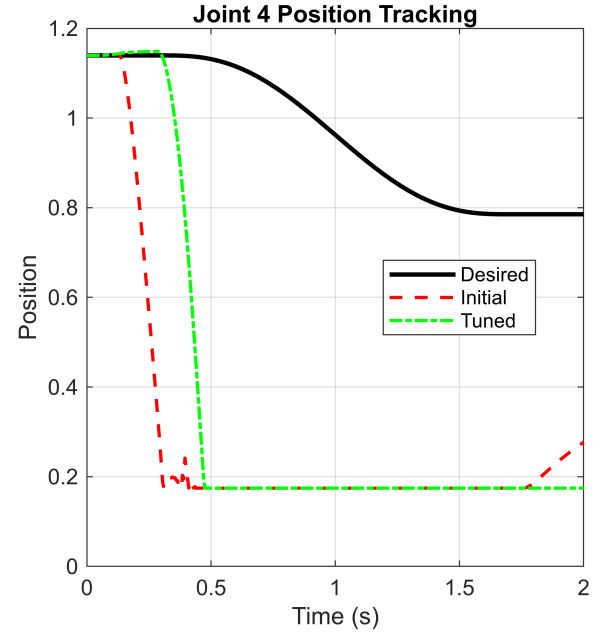


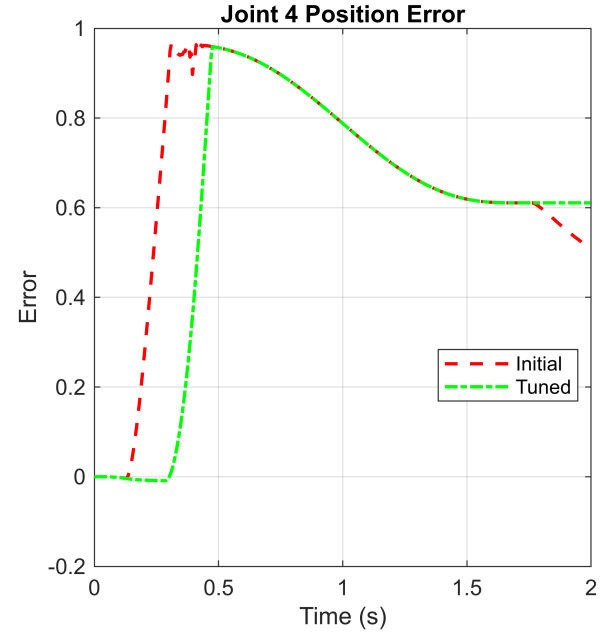


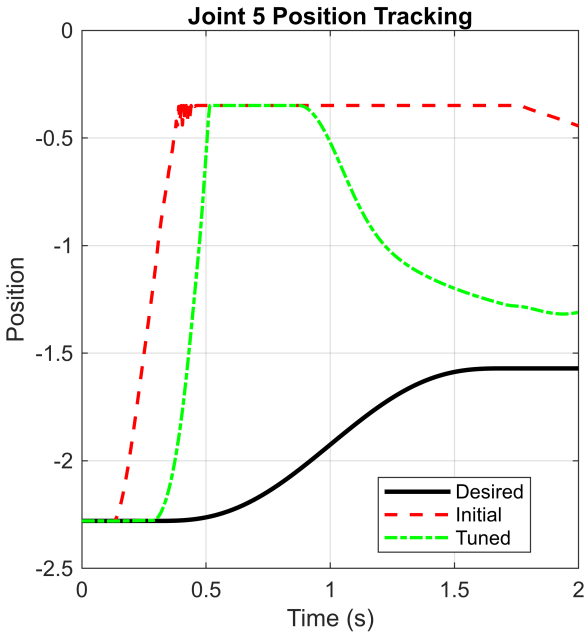


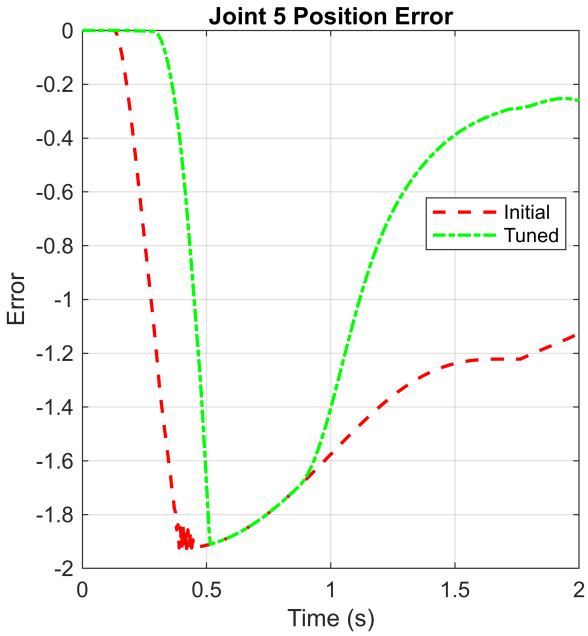

Joint 3 Position Tracking
Desired
Initial
Tuned
Position
Time (s)
0.22
0.21
0.2
0.19
0.18
0.17
0.16
0
0.5
1
1.5
2

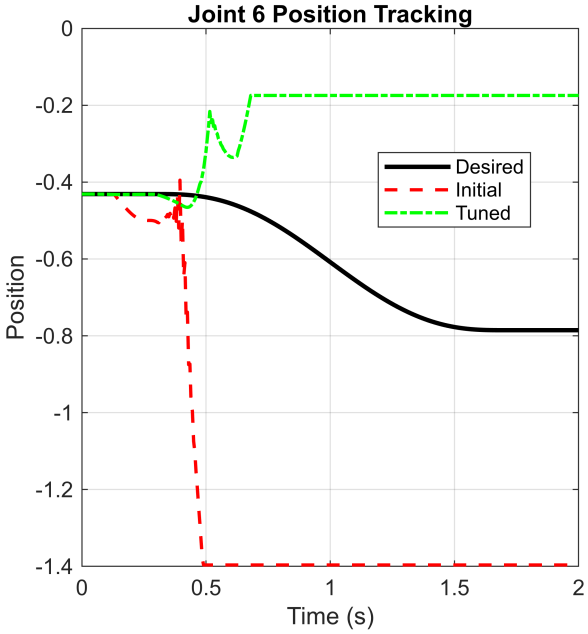

Joint 3 Position Error
Initial
Tuned
Error
Time (s)
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0
0.5
1
1.5
2

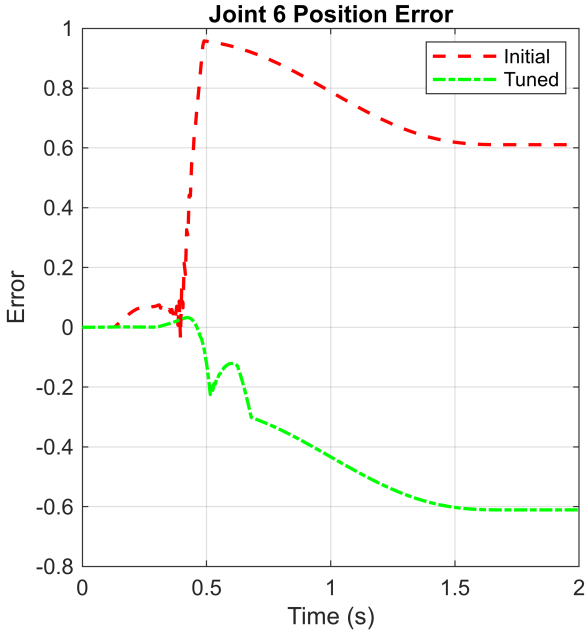

Joint 4 Position Tracking
Desired
Initial
Tuned
Position
Time (s)
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2

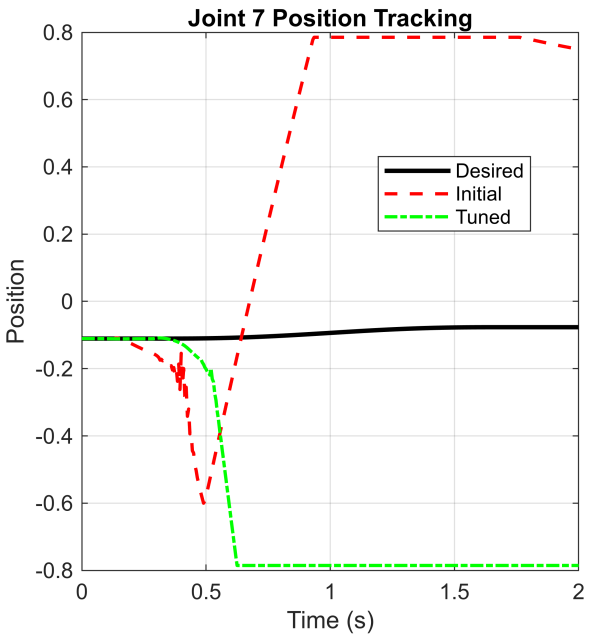

Joint 4 Position Error
Initial
Tuned
Error
Time (s)
1
0.8
0.6
0.4
0.2
0
-0.2
0
0.5
1
1.5
2

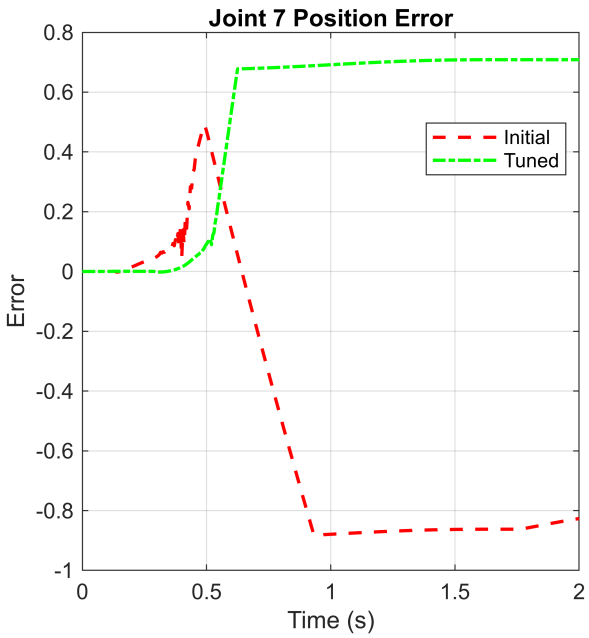

Joint 5 Position Tracking
Position
Time (s)
Desired
Initial
Tuned


Joint 5 Position Error
Error
Time (s)
Initial
Tuned

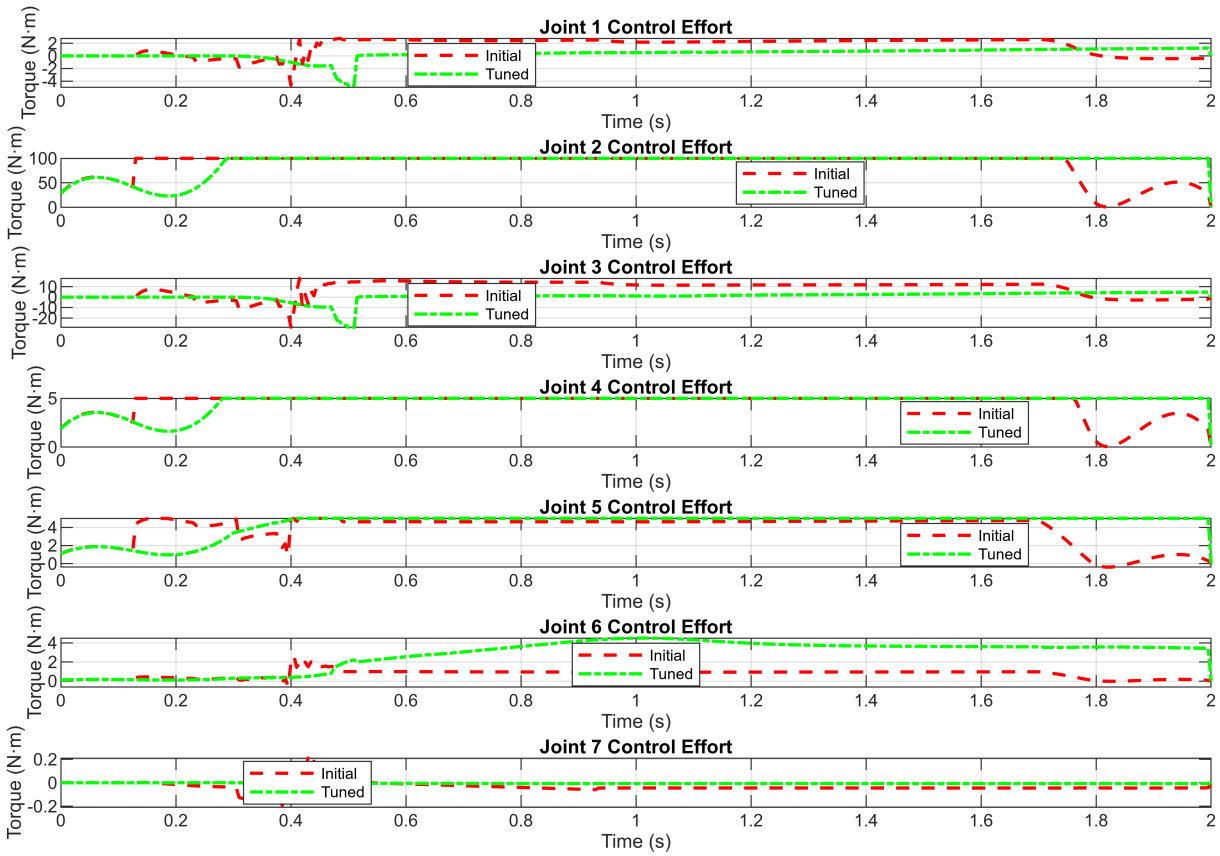

Joint 6 Position Tracking
Position
Time (s)
Desired
Initial
Tuned


Joint 6 Position Error
Error
Time (s)
Initial
Tuned






```
% Control effort comparison for tuned joints
figure('Name', 'Control Effort Comparison', 'Position', [200, 200, 900, 600]);
for i = 1:length(joints_to_tune)
    j = joints_to_tune(i);

    subplot(length(joints_to_tune), 1, i);
    plot(time_vec, tau_init(j,:), 'r--', 'LineWidth', 1.5, 'DisplayName',
'Initial');
    hold on;
    plot(time_vec, tau_tuned(j,:), 'g-.', 'LineWidth', 1.5, 'DisplayName', 'Tuned');
    title(sprintf('Joint %d Control Effort', j));
    xlabel('Time (s)');
    ylabel('Torque (N·m)');
    legend('Location', 'best');
    grid on;
end
```

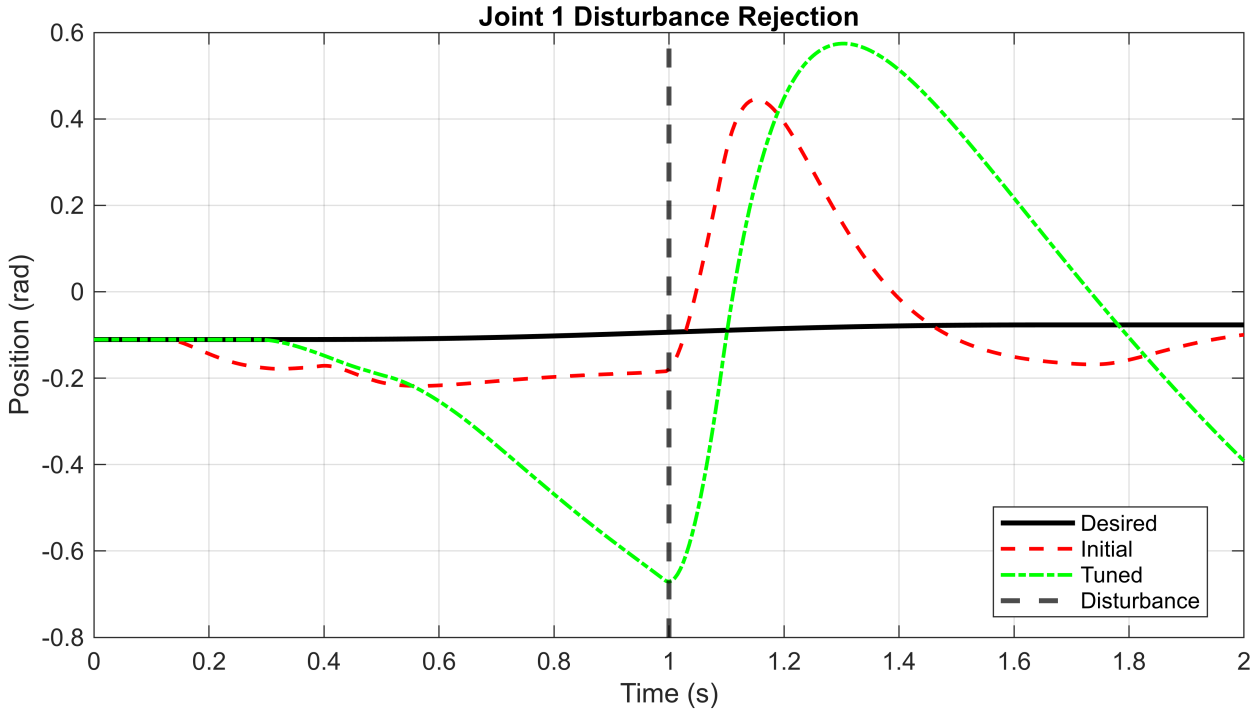



```
%% Step 6: Disturbance Rejection Test
fprintf('\nTesting disturbance rejection...\n');
```

```
Testing disturbance rejection...
```

```
% Define disturbance
disturbance = struct(...
    'enabled', true, ...
    'time', 1.0, ...      % Apply at 1 second
    'joint', 1, ...       % Apply to base joint
    'magnitude', 10);     % Large torque disturbance

% Test disturbance rejection with each controller
[q_init_dist, ~, ~, ~] = simulateRobotDynamicsWithJointPID(...
    q_traj, qd_traj, qdd_traj, time_vec, pid_params, model_params, disturbance);

[q_tuned_dist, ~, ~, ~] = simulateRobotDynamicsWithJointPID(...
    q_traj, qd_traj, qdd_traj, time_vec, tuned_pid_params, model_params,
disturbance);

% Plot disturbance rejection performance
```

```
figure('Name', 'Disturbance Rejection Comparison', 'Position', [250, 250, 800,
400]);
plot(time_vec, q_traj(1,:), 'k-', 'LineWidth', 2, 'DisplayName', 'Desired');
hold on;
plot(time_vec, q_init_dist(1,:), 'r--', 'LineWidth', 1.5, 'DisplayName', 'Initial');
plot(time_vec, q_tuned_dist(1,:), 'g-.', 'LineWidth', 1.5, 'DisplayName', 'Tuned');
xline(disturbance.time, 'k--', 'LineWidth', 2, 'DisplayName', 'Disturbance');
title('Joint 1 Disturbance Rejection');
xlabel('Time (s)');
ylabel('Position (rad)');
legend('Location', 'best');
grid on;
```

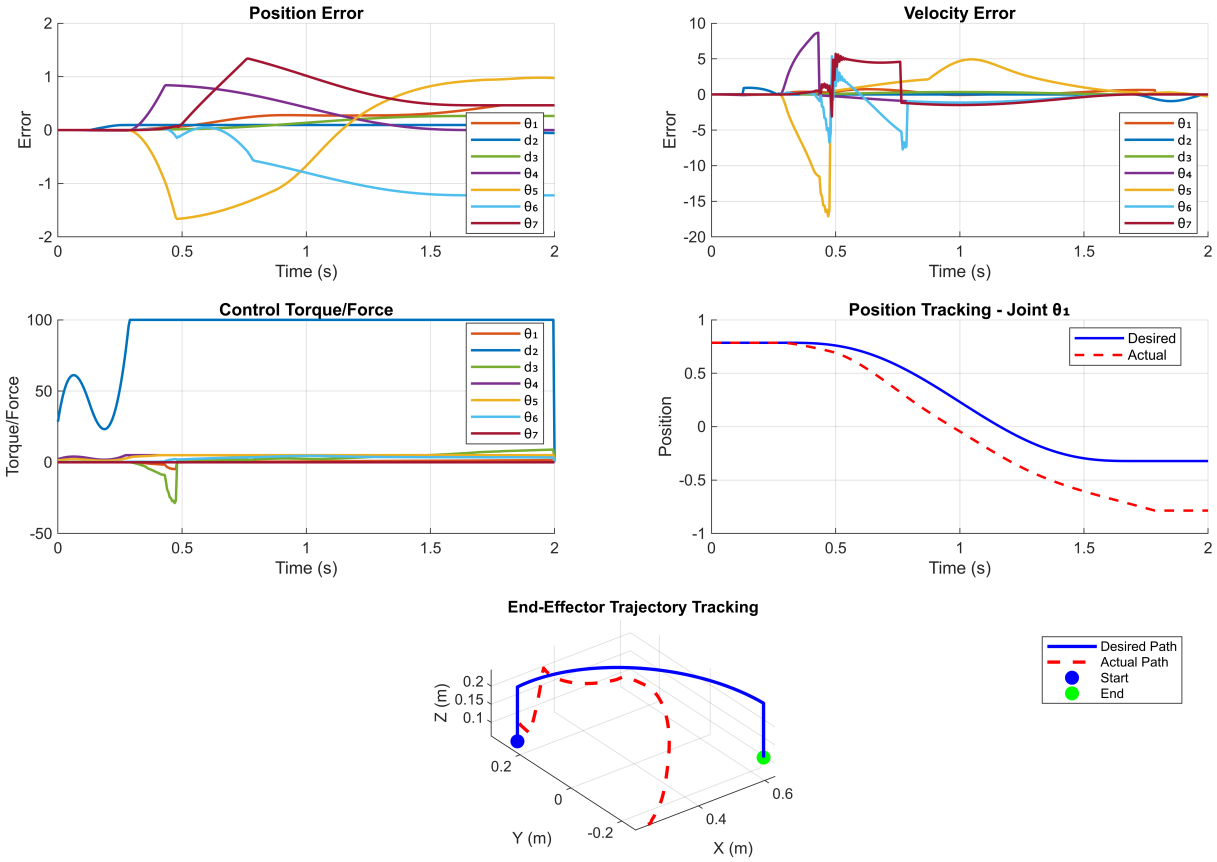



```
%% Step 7: Visualize Chess Move with Tuned Controller
fprintf('\nVisualizing chess move with tuned controller...\n');
```

```
Visualizing chess move with tuned controller...
```

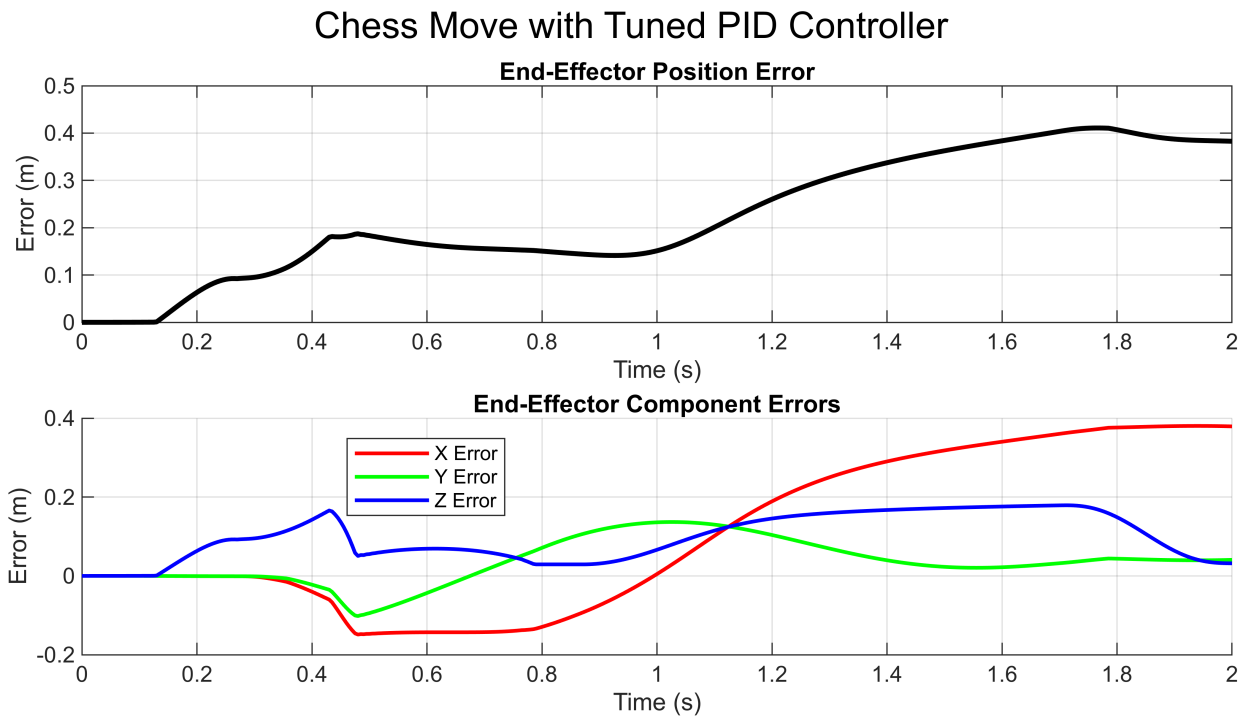
```
% Generate a full chess move trajectory
start_square = 'a1';
end_square = 'h8';
move_duration = 2.0;  % seconds
clear q_chess qd_chess qdd_chess t_chess
[q_chess, qd_chess, qdd_chess, t_chess] = generateChessTraj(...
    start_square, end_square, link_lengths, move_duration, sample_time);

% Simulate with the tuned controller
```

```
[q_chess_actual, qd_chess_actual, qdd_chess_actual, tau_chess] =
simulateRobotDynamicsWithJointPID(...
    q_chess, qd_chess, qdd_chess, t_chess, tuned_pid_params, model_params,
struct('enabled', false));

% Visualize the performance
visualizeControlPerformance(t_chess, q_chess, qd_chess, qdd_chess, ...
    q_chess_actual, qd_chess_actual, qdd_chess_actual, tau_chess, link_lengths);
```

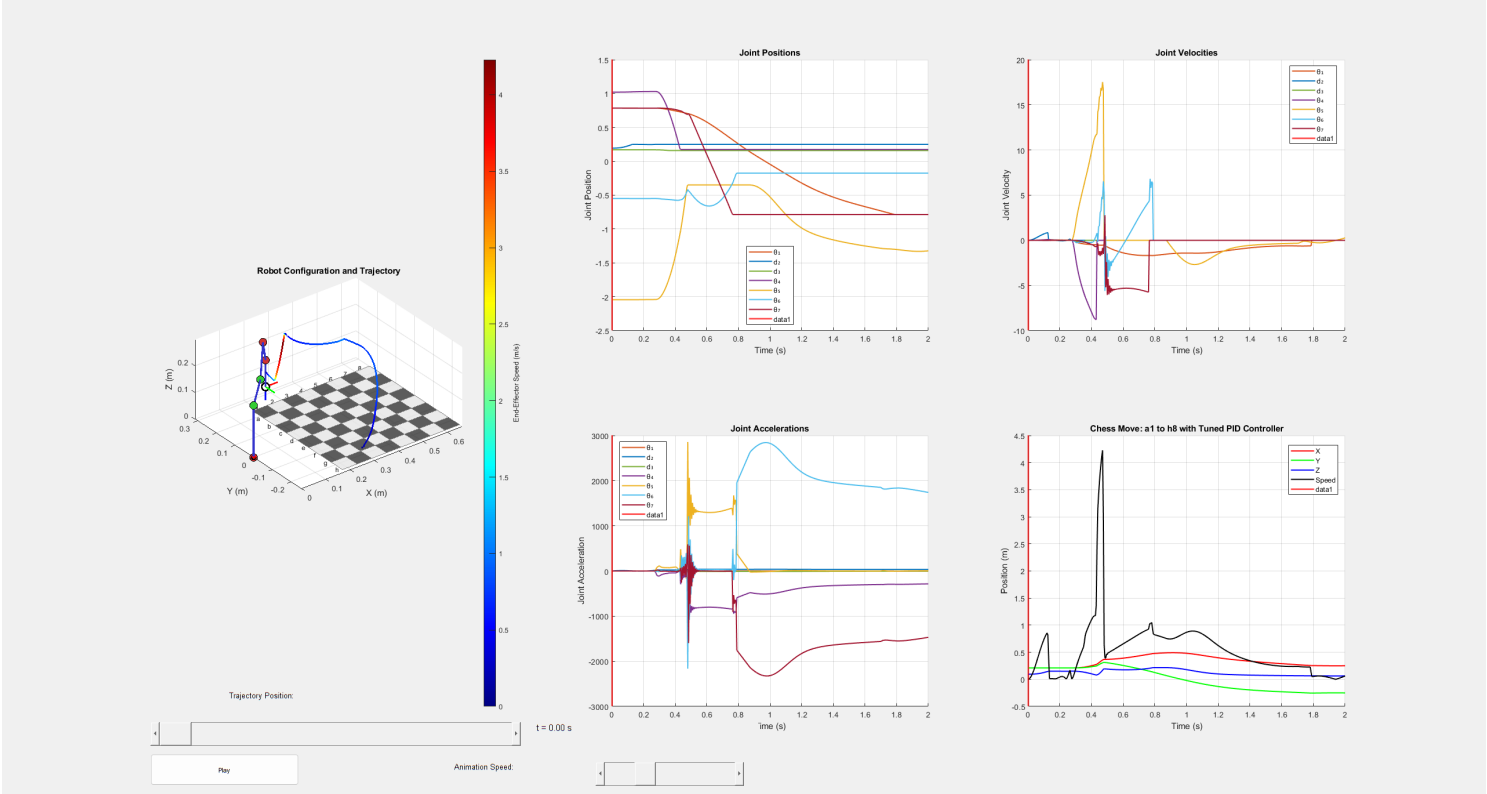



```
Controller Performance Metrics:
Max End-Effector Error: 0.4108 m
Mean End-Effector Error: 0.2247 m
RMS End-Effector Error: 0.2581 m

Maximum Position Errors:
Joint θ₁: 26.57 deg
Joint d₂: 0.0950 m
Joint d₃: 0.2641 m
Joint θ₄: 48.17 deg
Joint θ₅: 95.40 deg
Joint θ₆: 70.00 deg
Joint θ₇: 76.80 deg
```

```
sgtitle('Chess Move with Tuned PID Controller');
```




```
% Visualize the trajectory itself
chess_params = struct('show_board', true, 'square_size', 0.06, 'board_offset',
[0.18; 0.24; 0]);
visualizeTrajectory(q_chess_actual, qd_chess_actual, qdd_chess_actual, t_chess,
link_lengths, chess_params);
title(sprintf('Chess Move: %s to %s with Tuned PID Controller', start_square,
end_square));
```




```
fprintf('\nPID Controller Tuning Tests Completed\n');
```

```
PID Controller Tuning Tests Completed
```