ROB599_HW3_P4

Simiulating a PD Controller for Robot Arm with Moving Trajectory.

Contents

Cleanup

```
clear
clc
close all
```

Define Numerical Parameters of the System

Inertia Terms

```
param.m1 = 7.848;
param.m2 = 4.49;

param.I1 = 0.176;
param.I2 = 0.0411;

% Geometry Terms
param.l1 = 0.3;
param.lc1 = 0.1554;
param.lc2 = 0.0341;

% Fundamental Constants
param.g = 9.81;

% Gains
param.kp1 = 50;
param.kd1 = 10;

param.kp2 = 50;
param.kd2 = 10;

% Limits
param.tau1Max = 50;
param.tau1Min = -50;

param.tau2Max = 50;
param.tau2Min = -50;
```

Define Initial Simulation Prameters

```
% Initial Conditions
t = linspace(0,4,100000)';
x0 = [0;0;0;0];
tau = [0; 0];
```

Generate Target Trajectory

Cubic Polynomial Trajectory Waypoints

```
t_waypoints = [0; 2; 4];
q_waypoints = [0; pi/2; 0];

t_dot_waypoints = [0; 2; 4];
q_dot_waypoints = [0; 0; 0];

% Generate the Cubic Trajectories
[q, qd, qdd, pp] = cubicpolytraj(q_waypoints', t_waypoints', t, 'VelocityBoundaryCondition', q_dot_waypoints');

% Import the Trajectory into State Space
q1d_vec = q';
```

```
q1d_dot_vec = qd';
q1d_dot_dot_vec = qdd';

q2d_vec = q';
q2d_dot_vec = qd';
q2d_dot_dot_vec = qdd';

% Generate Stamped Target State Trajectory
x_target = [q1d_vec, q1d_dot_vec, q2d_vec, q2d_dot_vec];
t_target = t;

stamped_x_target = [x_target, t_target]';
```

Run Simulation

```
[tout, xout] = ode45(@(t, x) manipulator(t, x, @PDControllerGravComp, param, ...
   stamped_x_target), t, x0);

% Compute Torques
tau_values = postComputeTorques(tout, xout, @manipulator, @PDControllerGravComp, param, stamped_x_target);
```

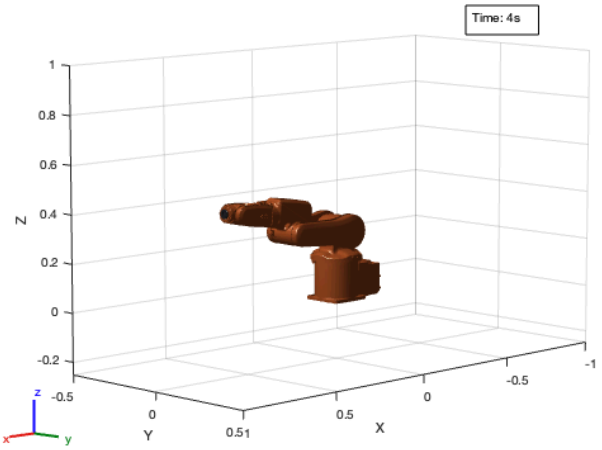
Postprocess Data

Compute the Errors

```
error_vals_1 = computeErrors(xout(:,1), x_target(:,1));
error_vals_2 = computeErrors(xout(:,2),x_target(:,2));

error_vals_3 = computeErrors(xout(:,3), x_target(:,3));
error_vals_4 = computeErrors(xout(:,4), x_target(:,4));

error_vals =[error_vals_1, error_vals_2, error_vals_3, error_vals_4];

% Calculate accelerations
dt = diff(tout);
[q1_dot_dot, q2_dot_dot] = savitzkyGolayDerivative(tout, xout(:,2), xout(:,4));

% Calculate acceleration errors
e1_dot_dot = computeErrors(q1_dot_dot, q1d_dot_dot_vec);
e2_dot_dot = computeErrors(q2_dot_dot, q2d_dot_dot_vec);

% Generate the Error Target Vector
zero_vector = getZeroVec(tout);
```

Animation

```
robotAnimation(tout, xout);
```



Plot the Results

This section plots desired outputs.

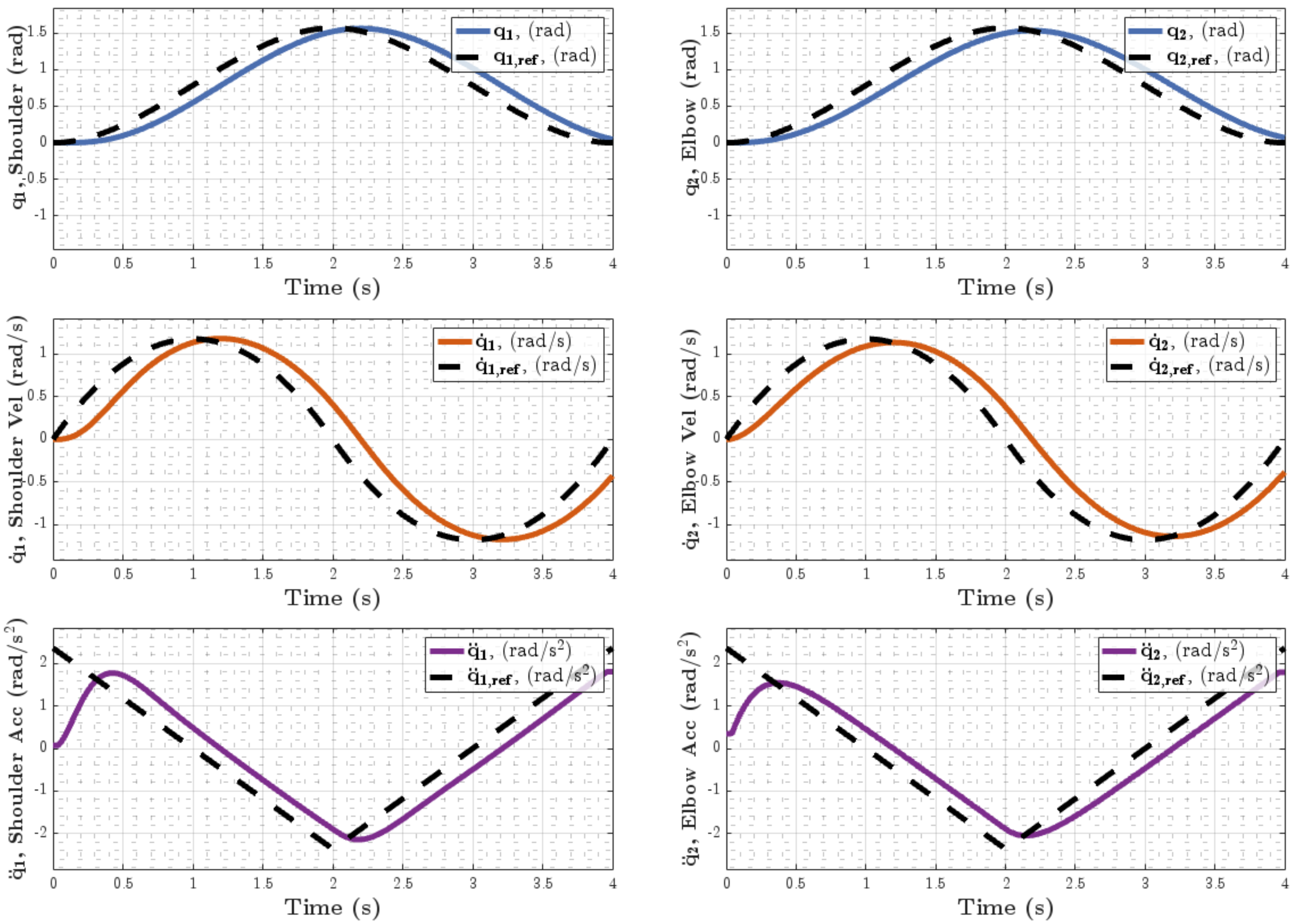
```
angle_pose_color = [0.2980, 0.4471, 0.6902];
ref_color = [0, 0, 0];
velocity_color = [0.8359, 0.3682, 0.0784];
torque_color = [0.4667, 0.6745, 0.1882];
acceleration_color = [0.4940, 0.1840, 0.5560];
```

Plot the System States and Reference

```
figure('Position', [0, 0, 1200, 1000]);

tLayout = tiledlayout(3,2,'Padding','Compact');
tLayout.Title.String = "Figure 3.1. Robot Arm State Evolution. Cubic Trajectory Tracking. PD Controller w Gravity Comp. Kpi = 50. Kdi = 10." + newline;
tLayout.Title.FontSize = 20;
tLayout.Title.FontWeight = 'bold';

% Poses
% Plot q1 and q1ref
nexttile;
plot(tout, xout(:,1), 'Color', angle_pose_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{q_1}$, (rad)');
hold on;
plot(t', x_target(:,1), 'Color', ref_color, 'LineStyle', '--', ...
    'LineWidth', 5, 'DisplayName', '$\mathbf{q_{1,ref}}$, (rad)');
hold off;
setSubplotProperties(gca);
y_lbl_handle = ylabel('\textbf{$\mathbf{q_1}$, Shoulder (rad)}', ...
    'FontSize', 18, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.17;
y_lbl_handle.Position(2) = 0.35;

% Plot q2 and q2ref
nexttile;
plot(tout, xout(:,3), 'Color', angle_pose_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{q_2}$, (rad)');
hold on;
plot(t', x_target(:,3), 'Color', ref_color, 'LineStyle', '--', ...
    'LineWidth', 5, 'DisplayName', '$\mathbf{q_{2,ref}}$, (rad)');
hold off;
setSubplotProperties(gca);
y_lbl_handle = ylabel('\textbf{$\mathbf{q_2}$, Elbow (rad)}', ...
    'FontSize', 18, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.17;
y_lbl_handle.Position(2) = 0.35;

% Set common y-axis limits for angle plots
[ymin, ymax] = getCommonYlim([xout(:,1); x_target(:,1)], [xout(:,3); x_target(:,2)]);
nexttile(1); ylim([ymin, ymax]);
nexttile(2); ylim([ymin, ymax]);

% Velocities
% Plot q1dot
nexttile;
plot(tout, xout(:,2), 'Color', velocity_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{\dot{q}_1}$, (rad/s)');
hold on;
plot(t', x_target(:,2), 'Color', ref_color, 'LineStyle', '--', ...
    'LineWidth', 5, 'DisplayName', '$\mathbf{\dot{q}_{1,ref}}$, (rad/s)');
hold off;
setSubplotProperties(gca);
y_lbl_handle = ylabel('\textbf{$\mathbf{\dot{q}_1}$, Shoulder Vel (rad/s)}', ...
    'FontSize', 18, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.17;

% Plot q2dot
nexttile;
plot(tout, xout(:,4), 'Color', velocity_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{\dot{q}_2}$, (rad/s)');
setSubplotProperties(gca);
hold on;
plot(t', x_target(:,2), 'Color', ref_color, 'LineStyle', '--', ...
    'LineWidth', 5, 'DisplayName', '$\mathbf{\dot{q}_{2,ref}}$, (rad/s)');
hold off;
y_lbl_handle = ylabel('\textbf{$\mathbf{\dot{q}_2}$, Elbow Vel (rad/s)}', ...
    'FontSize', 18, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.17;

% Set common y-axis limits for angular velocity plots
[ymin, ymax] = getCommonYlim(xout(:,2), xout(:,4));
nexttile(3); ylim([ymin, ymax]);
nexttile(4); ylim([ymin, ymax]);


% Accelerations
nexttile;
plot(tout, q1_dot_dot, 'Color', acceleration_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{\ddot{q}_1}$, (rad/s$^2$)');
hold on;
plot(t', q1d_dot_dot_vec, 'Color', ref_color, 'LineStyle', '--', ...
    'LineWidth', 5, 'DisplayName', '$\mathbf{\ddot{q}_{1,ref}}$, (rad/s$^2$)');
hold off;
setSubplotProperties(gca);
y_lbl_handle = ylabel('\textbf{$\mathbf{\ddot{q}_1}$, Shoulder Acc (rad/s$^2$)}', ...
    'FontSize', 18, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.17;

nexttile;
plot(tout, q2_dot_dot, 'Color', acceleration_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{\ddot{q}_2}$, (rad/s$^2$)');
hold on;
```

```
plot(t', q2d_dot_dot_vec, 'Color', ref_color, 'LineStyle', '--', ...
    'LineWidth', 5, 'DisplayName', '$\mathbf{\ddot{q}_{2,ref}}$, (rad/s$^2$)');
hold off;
setSubplotProperties(gca);
y_lbl_handle = ylabel('\textbf{$\mathbf{\ddot{q}_2}$, Elbow Acc (rad/s$^2$)}', ...
    'FontSize', 18, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.17;

% Set common y-axis limits for acceleration plots
[ymin, ymax] = getCommonYlim([q1_dot_dot; q1d_dot_dot_vec], [q2_dot_dot; q2d_dot_dot_vec]);
nexttile(5); ylim([ymin, ymax]);
nexttile(6); ylim([ymin, ymax]);

%print('ROB599-HW#3-Problem4-Fig3.1.png', '-dpng', '-r300');
```

Figure 3.1. Robot Arm State Evolution. Cubic Trajectory Tracking. PD Controller w Gravity Comp. Kpi = 50. Kdi = 10.

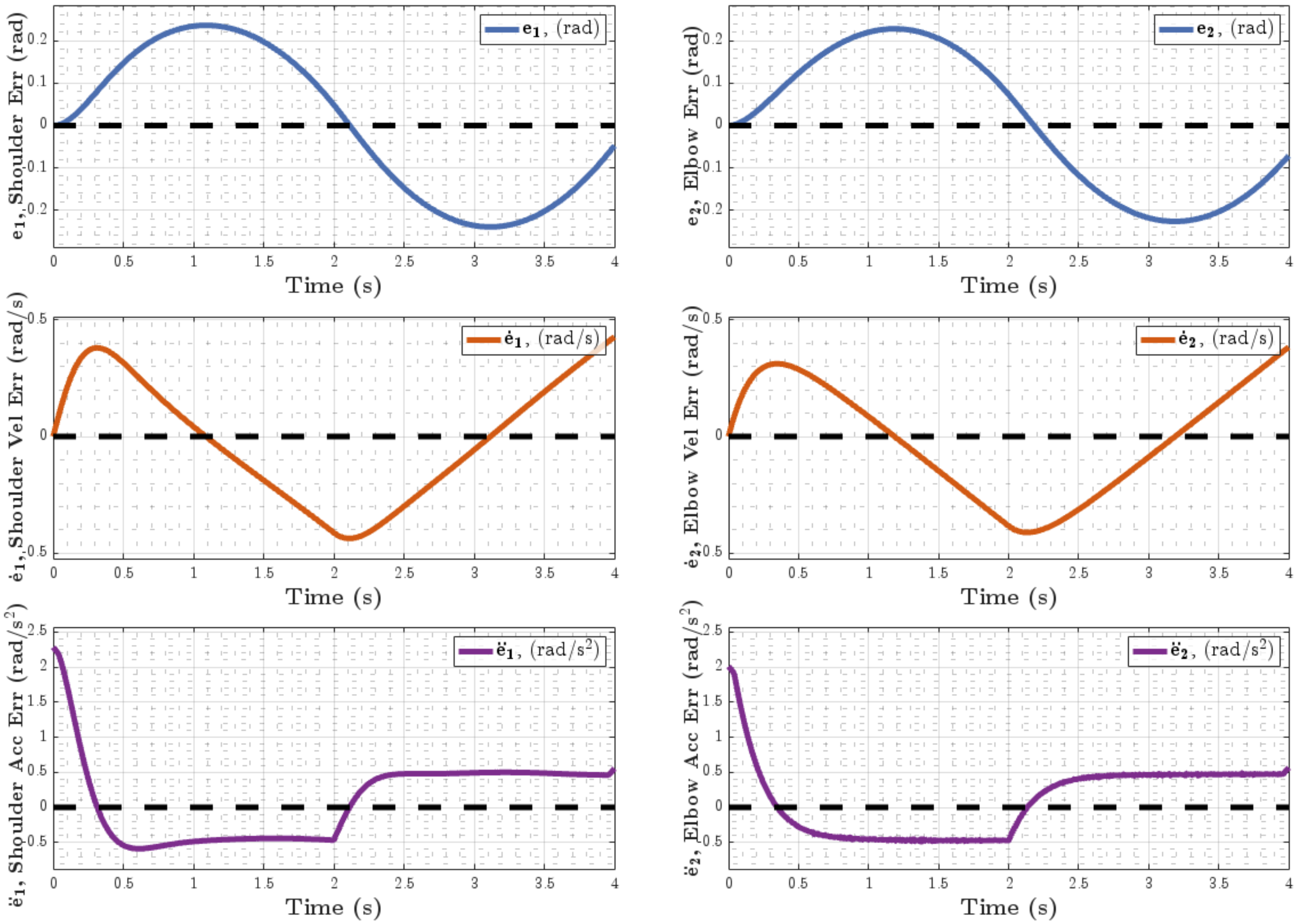


Plot the System Errors

```
figure('Position', [0, 0, 1200, 1000]);

tLayout = tiledlayout(3,2,'Padding','Compact');
tLayout.Title.String = "Figure 3.2. Robot Arm Errors Evolution. Cubic Trajectory Tracking. PD Controller w Gravity Comp. Kpi = 50. Kdi = 10." + newline;
tLayout.Title.FontSize = 20;
tLayout.Title.FontWeight = 'bold';

% Error
% Plot e1
nexttile;
plot(tout, error_vals(:,1), 'Color', angle_pose_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{e_1}$, (rad)');
hold on;
plot(tout, zero_vector, 'Color', ref_color, 'LineStyle', '--', ...
    'LineWidth', 5, 'HandleVisibility', 'off');
hold off;
setSubplotProperties(gca);
y_lbl_handle = ylabel('\textbf{$\mathbf{e_1}$, Shoulder Err (rad)}', ...
    'FontSize', 18, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.17;
```

```
% Plot e2
nexttile;
plot(tout, error_vals(:,3), 'Color', angle_pose_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{e_2}$, (rad)');
hold on;
plot(tout, zero_vector, 'Color', ref_color, 'LineStyle', '--', ...
    'LineWidth', 5, 'HandleVisibility', 'off');
hold off;
setSubplotProperties(gca);
y_lbl_handle = ylabel('\textbf{$\mathbf{e_2}$, Elbow Err (rad)}', ...
    'FontSize', 18, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.17;

% Set common y-axis limits for angle plots
[ymin, ymax] = getCommonYlim(error_vals(:,1), error_vals(:,3));
nexttile(1); ylim([ymin, ymax]);
nexttile(2); ylim([ymin, ymax]);


% Error Derivative
% Plot e1 derivative
nexttile;
plot(tout, error_vals(:,2), 'Color', velocity_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{\dot{e}_1}$, (rad/s)');
hold on;
plot(tout, zero_vector, 'Color', ref_color, 'LineStyle', '--', ...
    'LineWidth', 5, 'HandleVisibility', 'off');
hold off;
setSubplotProperties(gca);
y_lbl_handle = ylabel('\textbf{$\mathbf{\dot{e}_1}$, Shoulder Vel Err (rad/s)}', ...
    'FontSize', 18, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.17;

% Plot e2 derivative
nexttile;
plot(tout, error_vals(:,4), 'Color', velocity_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{\dot{e}_2}$, (rad/s)');
hold on;
plot(tout, zero_vector, 'Color', ref_color, 'LineStyle', '--', ...
    'LineWidth', 5, 'HandleVisibility', 'off');
hold off;
setSubplotProperties(gca);
y_lbl_handle = ylabel('\textbf{$\mathbf{\dot{e}_2}$, Elbow Vel Err (rad/s)}', ...
    'FontSize', 18, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.17;
y_lbl_handle.Position(2) = 0.0;

% Set common y-axis limits for angle plots
[ymin, ymax] = getCommonYlim(error_vals(:,2), error_vals(:,4));
nexttile(3); ylim([ymin, ymax]);
nexttile(4); ylim([ymin, ymax]);

% Error Acceleration
% e1_dot_dot
nexttile;
plot(tout, e1_dot_dot, 'Color', acceleration_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{\ddot{e}_1}$, (rad/s$^2$)');
hold on;
plot(tout, zero_vector, 'Color', ref_color, 'LineStyle', '--', ...
    'LineWidth', 5, 'HandleVisibility', 'off');
hold off;
setSubplotProperties(gca);
y_lbl_handle = ylabel('\textbf{$\mathbf{\ddot{e}_1}$, Shoulder Acc Err (rad/s$^2$)}', ...
    'FontSize', 18, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.17;

% e2_dot_dot
nexttile;
plot(tout, e2_dot_dot, 'Color', acceleration_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{\ddot{e}_2}$, (rad/s$^2$)');
hold on;
plot(tout, zero_vector, 'Color', ref_color, 'LineStyle', '--', ...
    'LineWidth', 5, 'HandleVisibility', 'off');
hold off;
setSubplotProperties(gca);
y_lbl_handle = ylabel('\textbf{$\mathbf{\ddot{e}_2}$, Elbow Acc Err (rad/s$^2$)}', ...
    'FontSize', 18, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.17;

% Set common y-axis limits for acceleration error plots
[ymin, ymax] = getCommonYlim(e1_dot_dot, e2_dot_dot);
nexttile(5); ylim([ymin, ymax]);
nexttile(6); ylim([ymin, ymax]);

%print('ROB599-HW#3-Problem4-Fig3.2.png', '-dpng', '-r300');
```

Figure 3.2. Robot Arm Errors Evolution. Cubic Trajectory Tracking. PD Controller w Gravity Comp. Kpi = 50. Kdi = 10.

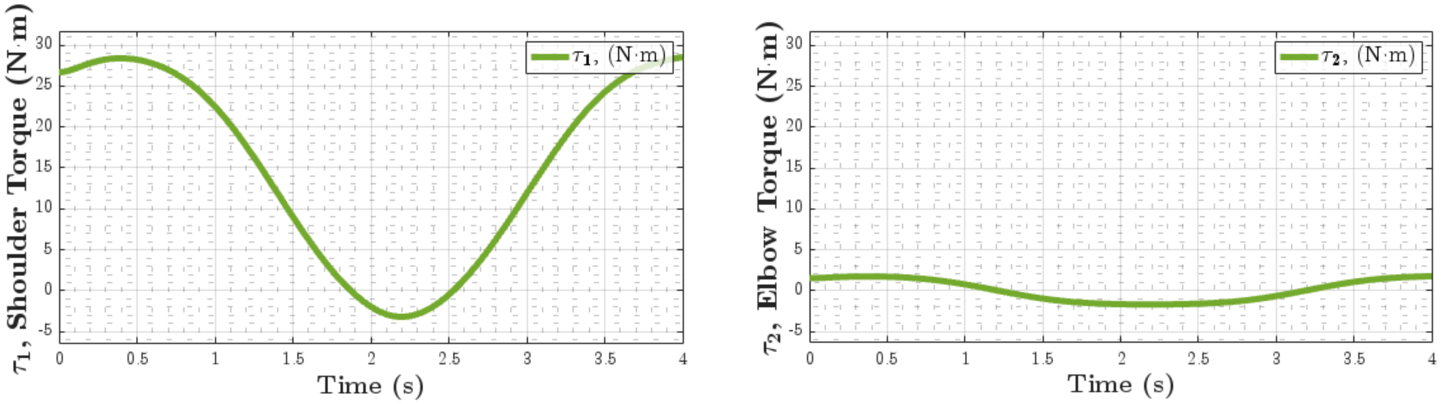


Plot the Robot Arm Input Evolution

```
figure('Position', [0, 0, 1200, 1000]);

tLayout = tiledlayout(1,2,'Padding','Compact');
tLayout.Title.String = "Figure 3.3. Robot Arm Input Evolution. Cubic Trajectory Tracking. PD Controller w Gravity Comp. Kpi = 50. Kdi = 10." + newline;
tLayout.Title.FontSize = 20;
tLayout.Title.FontWeight = 'bold';

% Plot tau1
nexttile;
plot(tout, tau_values(:,1), 'Color', torque_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{\tau_1}$, (N$\mathbf{\cdot}$m)');
ax = gca;
setSubplotProperties(ax);
y_lbl_handle = ylabel('\textbf{$\mathbf{\tau_1}$, Shoulder Torque (N$\mathbf{\cdot}$m)}', ...
    'FontSize', 22, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.15;

% Plot tau2
nexttile;
plot(tout, tau_values(:,2), 'Color', torque_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{\tau_2}$, (N$\mathbf{\cdot}$m)');
ax = gca;
setSubplotProperties(ax);
y_lbl_handle = ylabel('\textbf{$\mathbf{\tau_2}$, Elbow Torque (N$\mathbf{\cdot}$m)}', ...
    'FontSize', 22, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.15;
y_lbl_handle.Position(2) = 12.5;

% Set common y-axis limits for torque plots
[ymin, ymax] = getCommonYlim(tau_values(:,1), tau_values(:,2));
nexttile(1); ylim([ymin, ymax]);
nexttile(2); ylim([ymin, ymax]);

% Adjust subplot aspect ratios
nexttile(1); pbaspect([1 0.5 1]);
nexttile(2); pbaspect([1 0.5 1]);
```

```
print('ROB599-HW#3-Problem4-Fig3.3.png', '-dpng', '-r300');
```

Figure 3.3. Robot Arm Input Evolution. Cubic Trajectory Tracking. PD Controller w Gravity Comp. Kpi = 50. Kdi = 10.



Combined Tall Plot

```
figure('Position', [0, 0, 1200, 1200]);

tLayout = tiledlayout(7,2,'Padding','Compact');
tLayout.Title.String = "Figure 3. Robot Arm. Cubic Trajectory Tracking. PD Controller w Gravity Comp. Kpi = 50. Kdi = 10." + newline;
tLayout.Title.FontSize = 15;
tLayout.Title.FontWeight = 'bold';

% Plots (1,1), (1,2)
% Plot q1 and q1ref
[ymin, ymax] = getCommonYlim([xout(:,1); x_target(:,1)], [xout(:,3); x_target(:,2)]);
nexttile(1); ylim([ymin, ymax]);
nexttile(2); ylim([ymin, ymax]);

nexttile(1);
plot(tout, xout(:,1), 'Color', angle_pose_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{q_1}$, (rad)');
hold on;
plot(t', x_target(:,1), 'Color', ref_color, 'LineStyle', '--', ...
    'LineWidth', 5, 'DisplayName', '$\mathbf{q_{1,ref}}$, (rad)');
hold off;
setSubplotProperties(gca);
y_lbl_handle = ylabel('\textbf{$\mathbf{q_1}$, Shoulder (rad)}', ...
    'FontSize', 30, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.12;
y_lbl_handle.Position(2) = 0.8;
legend('FontSize', 24, 'Location', 'northeast', 'Interpreter', 'latex');

% Plot q2 and q2ref
nexttile(2);
plot(tout, xout(:,3), 'Color', angle_pose_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{q_2}$, (rad)');
hold on;
plot(t', x_target(:,3), 'Color', ref_color, 'LineStyle', '--', ...
    'LineWidth', 5, 'DisplayName', '$\mathbf{q_{2,ref}}$, (rad)');
hold off;
setSubplotProperties(gca);
y_lbl_handle = ylabel('\textbf{$\mathbf{q_2}$, Elbow (rad)}', ...
    'FontSize', 30, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.12;
y_lbl_handle.Position(2) = 0.8;
legend('FontSize', 24, 'Location', 'northeast', 'Interpreter', 'latex');


% Plots (2,1), (2,2)
% Plot e1
[ymin, ymax] = getCommonYlim(error_vals(:,1), error_vals(:,3));
nexttile(3); ylim([ymin, ymax]);
nexttile(4); ylim([ymin, ymax]);

nexttile(3);
plot(tout, error_vals(:,1), 'Color', angle_pose_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{e_1}$, (rad)');
hold on;
plot(tout, zero_vector, 'Color', ref_color, 'LineStyle', '--', ...
    'LineWidth', 5, 'HandleVisibility', 'off');
hold off;
setSubplotProperties(gca);
y_lbl_handle = ylabel('\textbf{$\mathbf{e_1}$, Shoulder Err (rad)}', ...
    'FontSize', 30, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.12;
legend('FontSize', 24, 'Location', 'northeast', 'Interpreter', 'latex');

% Plot e2
nexttile(4);
plot(tout, error_vals(:,3), 'Color', angle_pose_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{e_2}$, (rad)');
hold on;
plot(tout, zero_vector, 'Color', ref_color, 'LineStyle', '--', ...
    'LineWidth', 5, 'HandleVisibility', 'off');
hold off;
setSubplotProperties(gca);
y_lbl_handle = ylabel('\textbf{$\mathbf{q_2}$, Elbow Err (rad)}', ...
    'FontSize', 30, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.12;
legend('FontSize', 24, 'Location', 'northeast', 'Interpreter', 'latex');


% Plots (3,1), (3,2)
% Plot q1dot
[ymin, ymax] = getCommonYlim(xout(:,2), xout(:,4));
nexttile(5); ylim([ymin, ymax]);
nexttile(6); ylim([ymin, ymax]);

nexttile(5);
plot(tout, xout(:,2), 'Color', velocity_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{\dot{q}_1}$, (rad/s)');
hold on;
plot(t', x_target(:,2), 'Color', ref_color, 'LineStyle', '--', ...
    'LineWidth', 5, 'DisplayName', '$\mathbf{\dot{q}_{1,ref}}$, (rad/s)');
hold off;
setSubplotProperties(gca);
y_lbl_handle = ylabel('\textbf{$\mathbf{\dot{q}_1}$, Shoulder Vel (rad/s)}', ...
    'FontSize', 30, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.12;
legend('FontSize', 24, 'Location', 'northeast', 'Interpreter', 'latex');

% Plot q2dot
nexttile(6);
plot(tout, xout(:,4), 'Color', velocity_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{\dot{q}_2}$, (rad/s)');
setSubplotProperties(gca);
hold on;
plot(t', x_target(:,2), 'Color', ref_color, 'LineStyle', '--', ...
    'LineWidth', 5, 'DisplayName', '$\mathbf{\dot{q}_{2,ref}}$, (rad/s)');
hold off;
y_lbl_handle = ylabel('\textbf{$\mathbf{\dot{q}_2}$, Elbow Vel (rad/s)}', ...
    'FontSize', 30, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.12;
legend('FontSize', 24, 'Location', 'northeast', 'Interpreter', 'latex');


% Plots (4,1), (4,2)
% e1 derivative
[ymin, ymax] = getCommonYlim(error_vals(:,2), error_vals(:,4));
nexttile(7); ylim([ymin, ymax]);
nexttile(8); ylim([ymin, ymax]);

nexttile(7);
plot(tout, error_vals(:,2), 'Color', velocity_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{\dot{e}_2}$, (rad/s)');
hold on;
plot(tout, zero_vector, 'Color', ref_color, 'LineStyle', '--', ...
    'LineWidth', 5, 'HandleVisibility', 'off');
hold off;
setSubplotProperties(gca);
```

```
y_lbl_handle = ylabel('\textbf{$\mathbf{\dot{e}_1}$, Shoulder Vel Err (rad/s)}', ...
    'FontSize', 30, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.12;
legend('FontSize', 24, 'Location', 'northeast', 'Interpreter', 'latex');

% e2 derivative
nexttile(8);
plot(tout, error_vals(:,4), 'Color', velocity_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{\dot{e}_2}$, (rad/s)');
hold on;
plot(tout, zero_vector, 'Color', ref_color, 'LineStyle', '--', ...
    'LineWidth', 5, 'HandleVisibility', 'off');
hold off;
setSubplotProperties(gca);
y_lbl_handle = ylabel('\textbf{$\mathbf{\dot{e}_2}$, Elbow Vel Err (rad/s)}', ...
    'FontSize', 30, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.12;
legend('FontSize', 24, 'Location', 'northeast', 'Interpreter', 'latex');


% Plots (5,1), (5,2)
% Accelerations
[ymin, ymax] = getCommonYlim([q1_dot_dot; q1d_dot_dot_vec], [q2_dot_dot; q2d_dot_dot_vec]);
nexttile(9); ylim([ymin, ymax]);
nexttile(10); ylim([ymin, ymax]);

% q1_dot_dot
nexttile(9);
plot(tout, q1_dot_dot, 'Color', acceleration_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{\ddot{q}_1}$, (rad/s$^2$)');
hold on;
plot(t', q1d_dot_dot_vec, 'Color', ref_color, 'LineStyle', '--', ...
    'LineWidth', 5, 'DisplayName', '$\mathbf{\ddot{q}_{1,ref}}$, (rad/s$^2$)');
hold off;
setSubplotProperties(gca);
y_lbl_handle = ylabel('\textbf{$\mathbf{\ddot{q}_1}$, Shoulder Acc (rad/s$^2$)}', ...
    'FontSize', 30, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.12;
legend('FontSize', 24, 'Location', 'northeast', 'Interpreter', 'latex');

% q2_dot_dot
nexttile(10);
plot(tout, q2_dot_dot, 'Color', acceleration_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{\ddot{q}_2}$, (rad/s$^2$)');
hold on;
plot(t', q2d_dot_dot_vec, 'Color', ref_color, 'LineStyle', '--', ...
    'LineWidth', 5, 'DisplayName', '$\mathbf{\ddot{q}_{2,ref}}$, (rad/s$^2$)');
hold off;
setSubplotProperties(gca);
y_lbl_handle = ylabel('\textbf{$\mathbf{\ddot{q}_2}$, Elbow Acc (rad/s$^2$)}', ...
    'FontSize', 30, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.12;
legend('FontSize', 24, 'Location', 'northeast', 'Interpreter', 'latex');


% Plots (6,1), (6,2)
% e1_dot_dot
[ymin, ymax] = getCommonYlim(e1_dot_dot, e2_dot_dot);
nexttile(11); ylim([ymin, ymax]);
nexttile(12); ylim([ymin, ymax]);

nexttile(11);
plot(tout, e1_dot_dot, 'Color', acceleration_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{\ddot{e}_1}$, (rad/s$^2$)');
hold on;
plot(tout, zero_vector, 'Color', ref_color, 'LineStyle', '--', ...
    'LineWidth', 5, 'HandleVisibility', 'off');
hold off;
setSubplotProperties(gca);
y_lbl_handle = ylabel('\textbf{$\mathbf{\ddot{e}_1}$, Shoulder Acc Err (rad/s$^2$)}', ...
    'FontSize', 30, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.12;
legend('FontSize', 24, 'Location', 'northeast', 'Interpreter', 'latex');

% e2_dot_dot
nexttile(12);
plot(tout, e2_dot_dot, 'Color', acceleration_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{\ddot{e}_2}$, (rad/s$^2$)');
hold on;
plot(tout, zero_vector, 'Color', ref_color, 'LineStyle', '--', ...
    'LineWidth', 5, 'HandleVisibility', 'off');
hold off;
setSubplotProperties(gca);
y_lbl_handle = ylabel('\textbf{$\mathbf{\ddot{e}_2}$, Elbow Acc Err (rad/s$^2$)}', ...
    'FontSize', 30, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.12;
legend('FontSize', 24, 'Location', 'northeast', 'Interpreter', 'latex');


% Plots for Torques (7,1), (7,2)
[ymin, ymax] = getCommonYlim(tau_values(:,1), tau_values(:,2));
nexttile(13); ylim([ymin, ymax]);
nexttile(14); ylim([ymin, ymax]);

% tau1
nexttile(13);
plot(tout, tau_values(:,1), 'Color', torque_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{\tau_1}$, (N$\mathbf{\cdot}$m)');
setSubplotProperties(gca);
y_lbl_handle = ylabel('\textbf{$\mathbf{\tau_1}$, Shoulder Trq (N$\mathbf{\cdot}$m)}', ...
    'FontSize', 30, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.12;
legend('FontSize', 24, 'Location', 'northeast', 'Interpreter', 'latex');

% tau2
nexttile(14);
plot(tout, tau_values(:,2), 'Color', torque_color, 'LineWidth', 5, ...
    'DisplayName', '$\mathbf{\tau_2}$, (N$\mathbf{\cdot}$m)');
setSubplotProperties(gca);
y_lbl_handle = ylabel('\textbf{$\mathbf{\tau_2}$, Elbow Trq (N$\mathbf{\cdot}$m)}', ...
    'FontSize', 30, 'Interpreter', 'latex');
y_lbl_handle.Position(1) = -0.12;
y_lbl_handle.Position(2) = 0.0;
legend('FontSize', 24, 'Location', 'northeast', 'Interpreter', 'latex');

% Save the Plot
%set(gcf, 'PaperUnits', 'inches');
%set(gcf, 'PaperPosition', [0 0 36 48]);
%print('ROB599-HW#3-Problem4.png', '-dpng', '-r300');
```

Helper Functions

Computes the Torque Values at Give State Vector

```
function tau_values = postComputeTorques(tout, xout, model_ref, controller_ref, param, ref)

    num_steps = length(tout);
    tau_values = zeros(num_steps, 2);
    for i = 1:num_steps
        [~, tau] = model_ref(tout(i), xout(i,:)', controller_ref, param, ref);
        tau_values(i,:) = tau';
    end
end

% Computes the Error Vector
function error_vals = computeErrors(x_actual, x_ref)
    error_vals = x_ref - x_actual;
end

% Generates a Zero Vector
function zero_vector = getZeroVec(t_out)
    zero_vector = zeros(size(t_out));
end

% Returns Y-axis Limits for Two Sets of Data
function [ymin, ymax] = getCommonYlim(data1, data2)
    ymin = min(min(data1), min(data2));
    ymax = max(max(data1), max(data2));
    range = ymax - ymin;
    ymin = ymin - 0.1 * range;
    ymax = ymax + 0.1 * range;
end

% Sets Subplot Properties
function setSubplotProperties(ax)

    grid(ax, 'on');
    grid(ax, 'minor');

    ax.TickLabelInterpreter = 'latex';
    ax.FontSize = 14;

    xlabel(ax, '\textbf{Time (s)}', 'FontSize', 20, 'Interpreter', 'latex');
    lgd = legend(ax, 'FontSize', 18, 'Location', 'northeast', 'Interpreter', 'latex');
    % Set semi-transparent background
    lgd.BoxFace.ColorType = 'truecoloralpha';
    lgd.BoxFace.ColorData = uint8([255 255 255 200]');
end


function [accel1, accel2] = savitzkyGolayDerivative(t, vel1, vel2)
    % Parameters for Savitzky-Golay filter
    window_length = 2001;  % Must be odd
    polynomial_order = 1;

    % Compute accelerations using Savitzky-Golay filter
    accel1 = gradient(smooth(vel1, window_length, 'sgolay', polynomial_order), t);
    accel2 = gradient(smooth(vel2, window_length, 'sgolay', polynomial_order), t);
end
```

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