**2. Perform PD control simulation.**

clc

clear all

close all

syms time

m1=10;

m2=5;

l=0.5;

tt01=30\*pi/180;

tt02=150\*pi/180;

ttf1=150\*pi/180;

ttf2=30\*pi/180;

a01=pi/6;

a02=5\*pi/6;

a21=pi;

a22=-pi;

a31=-4\*pi/3;

a32=4\*pi/3;

g=9.81;

i=1;

deltat=0.01;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%% P\_D Controller %%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

tt1\_r=30\*pi/180;

tt2\_r=150\*pi/180;

dtt1\_r=0;

dtt2\_r=0;

e1=0;

e2=0;

Kp1=9000;

Kp2=7800;

Kv1=0.1;

Kv2=2.5;

hold off;

for t=0:deltat:1

tt1=a01+a21\*t\*t+a31\*t^3;

tt2=a02+a22\*t\*t+a32\*t^3;

dtt1=2\*a21\*t+3\*a31\*t^2;

dtt2=2\*a22\*t+3\*a32\*t^2;

ddtt1=2\*a21+6\*a31\*t;

ddtt2=2\*a22+6\*a32\*t;

tque1=-Kv1\*dtt1\_r+Kp1\*e1;

tque2=-Kv2\*dtt2\_r+Kp2\*e2;

T=[tque1;tque2];

M=[l^2\*m2+2\*l^2\*m2\*cos(tt2\_r)+l^2\*(m1+m2) l^2\*m2+l^2\*m2\*cos(tt2\_r);l^2\*m2+l^2\*m2\*cos(tt2\_r) l^2\*m2];

V=[-m2\*l^2\*sin(tt2\_r)\*dtt2\_r^2-2\*m2\*l^2\*sin(tt2\_r)\*dtt1\_r\*dtt2\_r;m2\*l^2\*sin(tt2\_r)\*dtt1^2];

G=[m2\*l\*g\*cos(tt1\_r+tt2\_r)+(m1+m2)\*l\*g\*cos(tt1\_r);m2\*l\*g\*cos(tt1\_r+tt2\_r)];

Minv=M^-1;

ddtt=Minv\*(T-V-G)

ddtt1\_r=ddtt(1)

ddtt2\_r=ddtt(2)

dtt1\_r=dtt1\_r+deltat\*ddtt1\_r;

dtt2\_r=dtt2\_r+deltat\*ddtt2\_r;

tt1\_r=tt1\_r+dtt1\_r\*deltat+0.5\*deltat^2\*ddtt1\_r;

tt2\_r=tt2\_r+dtt2\_r\*deltat+0.5\*deltat^2\*ddtt2\_r;

e1=tt1-tt1\_r;

e2=tt2-tt2\_r;

figure(1)

plot(t,tt1,'blue\*');

hold on

plot(t,tt1\_r,'red\*');

hold on

plot(t,e1,'black\*')

legend({'Desired', 'Real', 'Error'}, 'FontSize', 12);

title('PD Joint#1');

figure(2)

plot(t,tt2,'blue\*');

hold on

plot(t,tt2\_r,'red\*');

hold on

plot(t,e2,'black\*');

legend({'Desired', 'Real', 'Error'}, 'FontSize', 12);

title('PD Joint#2');

figure(3)

plot(t,e1,'red\*')

hold on

plot(t,e2,'blue\*');

legend({'Error#1', 'Error#2'}, 'FontSize', 12);

title('PD Error');

i=i+1;

end

The results obtained:

Graphical user interface, chart

Description automatically generated

Graphical user interface, application

Description automatically generated

Graphical user interface, chart

Description automatically generated

**3. Perform PD + gravity control simulation.**

Code in Matlab

tt1\_r=30\*pi/180;

tt2\_r=150\*pi/180;

dtt1\_r=0;

dtt2\_r=0;

e1=0;

e2=0;

Kp1=9000;

Kp2=7800;

Kv1=0.1;

Kv2=2.5;

for t=0:deltat:1

tt1=a01+a21\*t\*t+a31\*t^3;

tt2=a02+a22\*t\*t+a32\*t^3;

dtt1=2\*a21\*t+3\*a31\*t^2;

dtt2=2\*a22\*t+3\*a32\*t^2;

ddtt1=2\*a21+6\*a31\*t;

ddtt2=2\*a22+6\*a32\*t;

g1=m2\*l\*g\*cos(tt1+tt2)+(m1+m2)\*l\*g\*cos(tt1);

g2=m2\*l\*g\*cos(tt1+tt2);

tque1=g1-Kv1\*dtt1\_r+Kp1\*e1;

tque2=g2-Kv2\*dtt2\_r+Kp2\*e2;

T=[tque1;tque2];

M=[l^2\*m2+2\*l^2\*m2\*cos(tt2\_r)+l^2\*(m1+m2) l^2\*m2+l^2\*m2\*cos(tt2\_r);l^2\*m2+l^2\*m2\*cos(tt2\_r) l^2\*m2];

V=[-m2\*l^2\*sin(tt2\_r)\*dtt2\_r^2-2\*m2\*l^2\*sin(tt2\_r)\*dtt1\_r\*dtt2\_r;m2\*l^2\*sin(tt2\_r)\*dtt1^2];

G=[m2\*l\*g\*cos(tt1\_r+tt2\_r)+(m1+m2)\*l\*g\*cos(tt1\_r);m2\*l\*g\*cos(tt1\_r+tt2\_r)];

Minv=M^-1;

ddtt=Minv\*(T-V-G)

ddtt1\_r=ddtt(1)

ddtt2\_r=ddtt(2)

dtt1\_r=dtt1\_r+deltat\*ddtt1\_r;

dtt2\_r=dtt2\_r+deltat\*ddtt2\_r;

tt1\_r=tt1\_r+dtt1\_r\*deltat+0.5\*deltat^2\*ddtt1\_r;

tt2\_r=tt2\_r+dtt2\_r\*deltat+0.5\*deltat^2\*ddtt2\_r;

e1=tt1-tt1\_r;

e2=tt2-tt2\_r;

figure(4)

plot(t,tt1,'blue\*');

hold on

plot(t,tt1\_r,'red\*');

hold on

plot(t,e1,'black\*')

legend({'Desired', 'Real', 'Error'}, 'FontSize', 12);

title('PD + Gravity (Joint#1)');

figure(5)

plot(t,tt2,'blue\*');

hold on

plot(t,tt2\_r,'red\*');

hold on

plot(t,e2,'black\*')

legend({'Desired', 'Real', 'Error'}, 'FontSize', 12);

title('PD + Gravity (Joint#2)');

figure(6)

plot(t,e1,'red\*')

hold on

plot(t,e2,'\*')

hold on

legend({'Desired', 'Real', 'Error'}, 'FontSize', 12);

title('PD + Gravity (Error)');

i=i+1;

end

Graphical user interface, chart

Description automatically generated

Graphical user interface, application

Description automatically generated

Graphical user interface, chart, line chart

Description automatically generated

**4. Perform computed torque control simulation.**

Code in Matlab

tt1\_r=30\*pi/180;

tt2\_r=150\*pi/180;

dtt1\_r=0;

dtt2\_r=0;

e1=0;

e2=0;

de1=0;

de2=0;

Kp1=7800;

Kp2=5800;

Kv1=0.1;

Kv2=0.5;

for t=0:deltat:1

tt1=a01+a21\*t\*t+a31\*t^3;

tt2=a02+a22\*t\*t+a32\*t^3;

dtt1=2\*a21\*t+3\*a31\*t^2;

dtt2=2\*a22\*t+3\*a32\*t^2;

ddtt1=2\*a21+6\*a31\*t;

ddtt2=2\*a22+6\*a32\*t;

tque\_c1=ddtt1+Kp1\*e1+Kv1\*de1

tque\_c2=ddtt2+Kp2\*e2+Kv2\*de2

alpha=[l^2\*m2+2\*l^2\*m2\*cos(tt2)+l^2\*(m1+m2) l^2\*m2+l^2\*m2\*cos(tt2);l^2\*m2+l^2\*m2\*cos(tt2) l^2\*m2];

M=alpha;

V=[-m2\*l^2\*sin(tt2\_r)\*dtt2\_r^2-2\*m2\*l^2\*sin(tt2\_r)\*dtt1\_r\*dtt2\_r;m2\*l^2\*sin(tt2\_r)\*dtt1^2];

G=[m2\*l\*g\*cos(tt1\_r+tt2\_r)+(m1+m2)\*l\*g\*cos(tt1\_r);m2\*l\*g\*cos(tt1\_r+tt2\_r)];

beta=V+G;

T=alpha\*[tque\_c1;tque\_c2]+beta

ddtt=M\(T-V-G);

ddtt1\_r=ddtt(1);

ddtt2\_r=ddtt(2);

dtt1\_r=dtt1\_r+deltat\*ddtt1\_r;

dtt2\_r=dtt2\_r+deltat\*ddtt2\_r;

tt1\_r=tt1\_r+dtt1\_r\*deltat+0.5\*deltat^2\*ddtt1\_r;

tt2\_r=tt2\_r+dtt2\_r\*deltat+0.5\*deltat^2\*ddtt2\_r;

e1=tt1-tt1\_r;

e2=tt2-tt2\_r;

de1=dtt1-dtt1\_r;

de2=dtt2-dtt2\_r;

figure(7)

plot(t,tt1,'blue\*');

hold on

plot(t,tt1\_r,'red\*');

hold on

plot(t,e1,'black\*')

legend({'Desired', 'Real', 'Error'}, 'FontSize', 12);

title('Torque Control (Joint#1)');

figure(8)

plot(t,tt2,'blue\*');

hold on

plot(t,tt2\_r,'red\*');

hold on

plot(t,e2,'black\*')

legend({'Desired', 'Real', 'Error'}, 'FontSize', 12);

title('Torque Control (Joint#2)');

figure(9)

plot(t,e1,'red\*')

hold on

plot(t,e2,'blue\*')

legend({'Error#1', 'Error#2'}, 'FontSize', 12);

title('Torque Control (Error)');

i=i+1;

end

Graphical user interface

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Graphical user interface, application

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Graphical user interface

Description automatically generated

**5. Compare errors of 3 cases above.**

Graphical user interface, chart

Description automatically generatedGraphical user interface, chart, line chart

Description automatically generatedGraphical user interface

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