**MSE 4401A: Robotic Manipulators – 2018 Assignment #6**

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**Procedure:**

1. Choose a control system for this assignment. My choice is the inverse dynamics control. 2. Generate the inner loop control code and the code mimic robot block. The inner loop code and robot block code is modified from assignment 5. We need to use the equation below to do the calculation. In the inner loop code, we use position velocity and acceleration to calculate torque. In the robot block, we use position velocity and torque to calculate the acceleration.

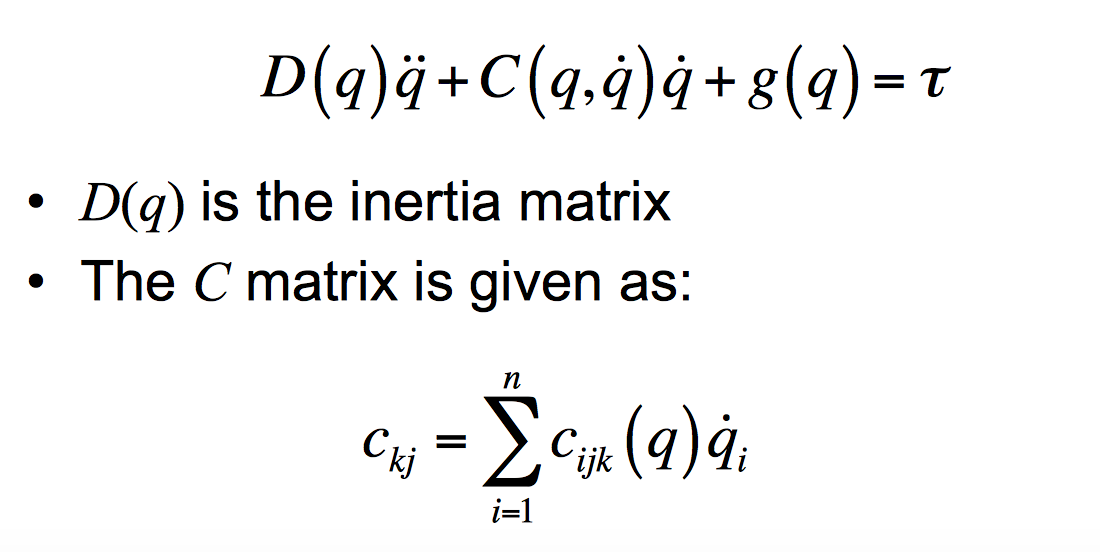


figure 1: relation between torque and acceleration.

3. Get the variable of each joints from assignment 4. The first joint variable is angular position, the second joint variable is distance, and the last joint variable is angular position.

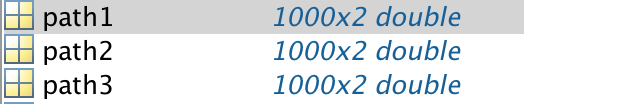


figure 2: the paths variable from workspace.

4. Create path blocks as input signal to the inverse dynamic control.

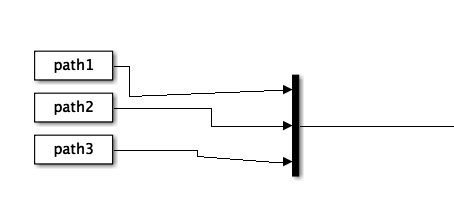


figure 3: input signal block.

5. Set the damping ratio for feedback. And write a code based on the equation below. And in my results. When the damping ratio is 20, the system has the best performance. K1 K0 are diagonal position and velocity gain matrices. But here, we need to test the damping ratio. I showed it in my results.

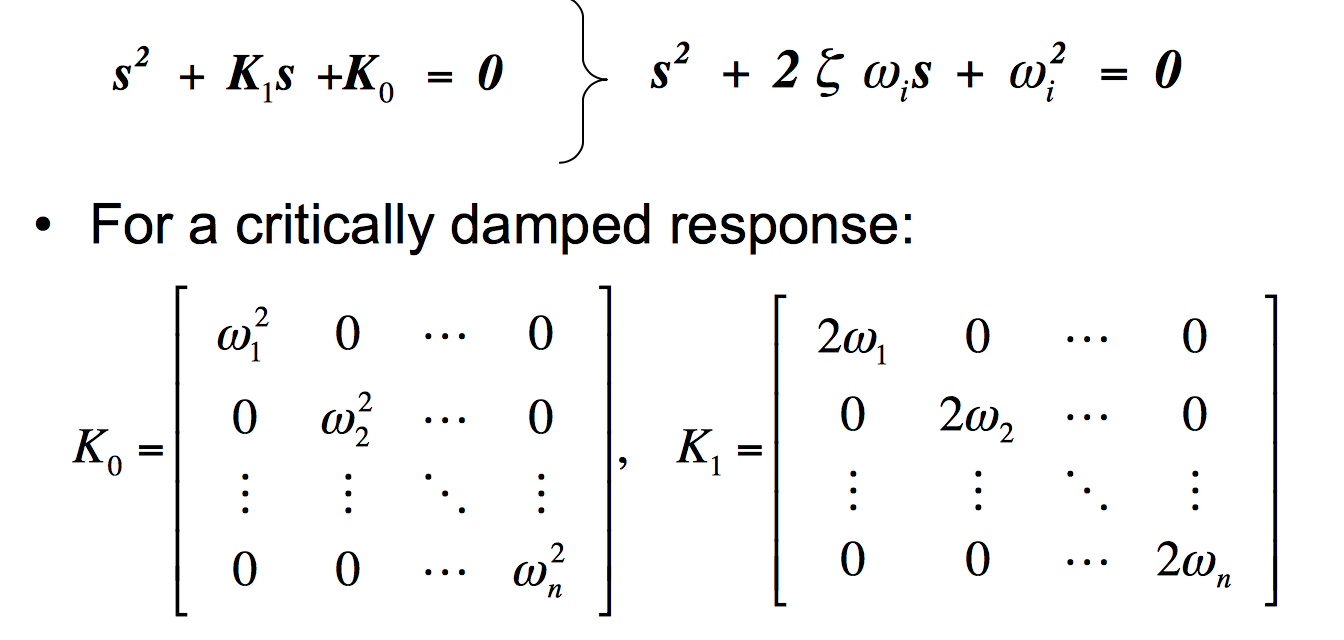


figure 4: damped response

6. Before run the Simulink, run the assignment 4 code to get the path1 path 2 path 3 variables. It takes a long time to get result, so I set the testing time as 4 second. And set the last integral block to get the initial position of each joint.

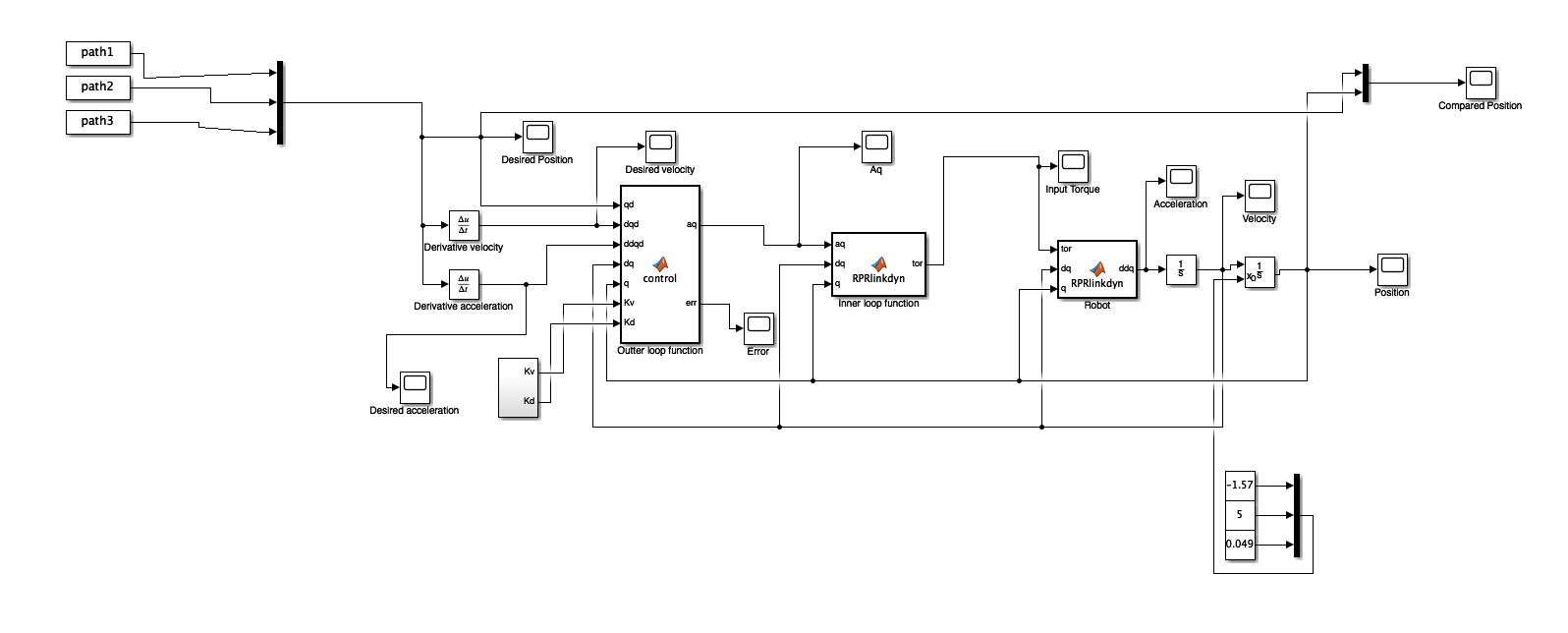


figure5: the total inverse dynamics control block

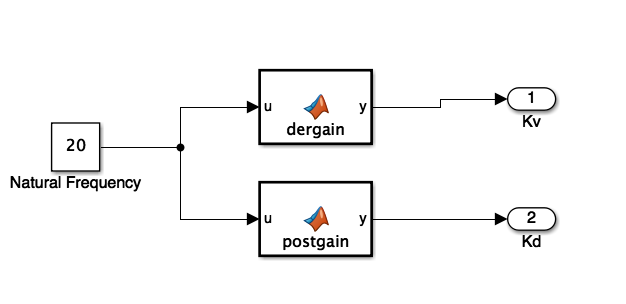


figure6: subsystem to generate K1 and K0 for inverse dynamic control

Result 1: The best result when set natural frequency is equal to 20.

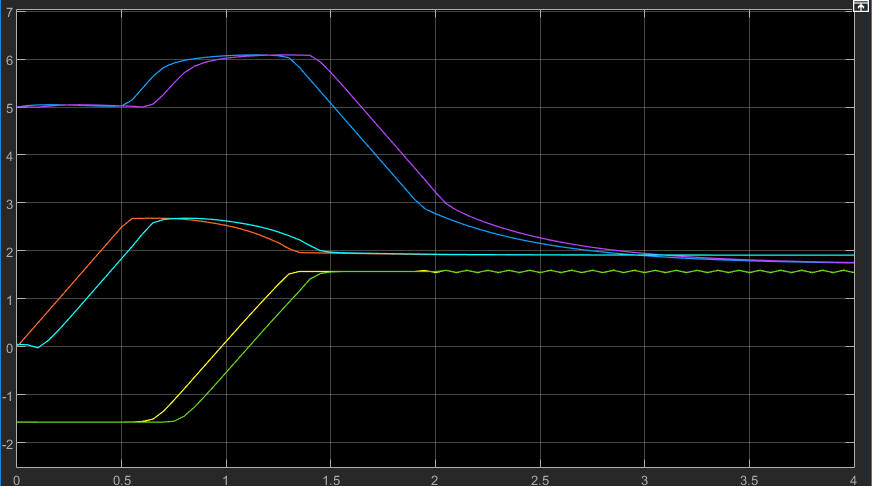


figure 7: input position and output position comparing when natural frequency is equal to 20.

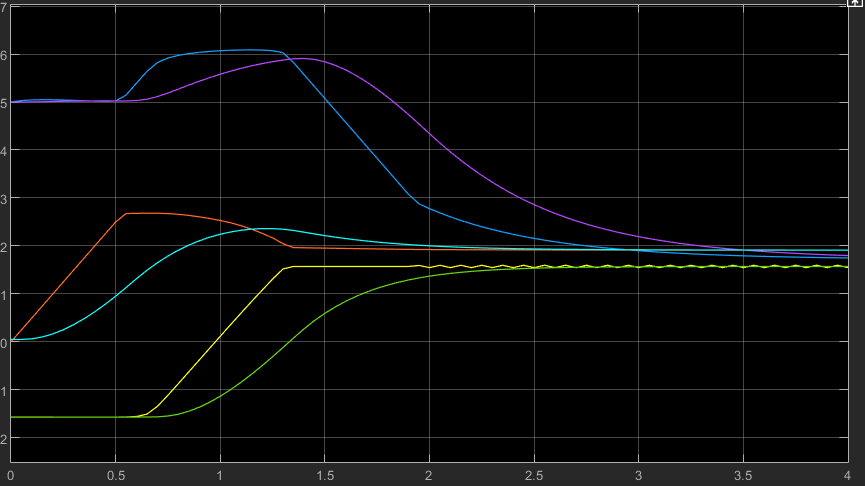


figure 8: input position and output position comparing natural frequency is equal to 4.

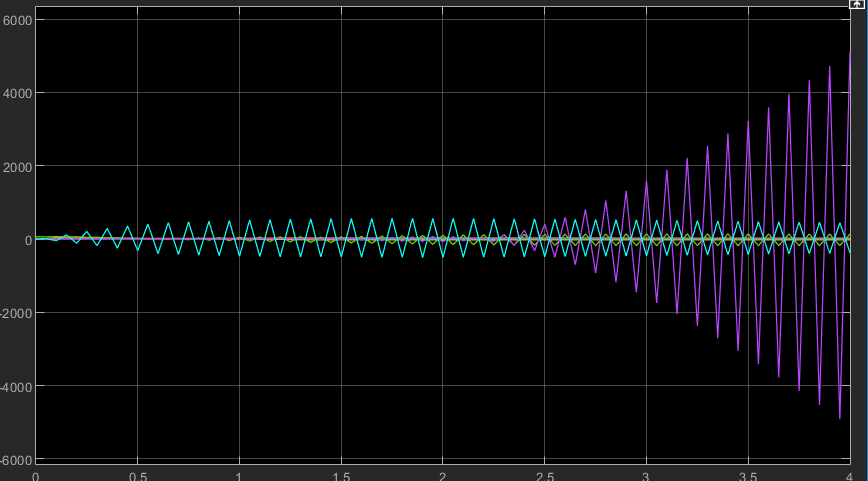


figure 9: input position and output position comparing natural frequency is equal to 50.

**Question & Answer:**

1. a)  Design and model a control system of your choice in Simulink using the arm’s dynamic model (developed in Assignment 5). **[30 points]**

**answer:** The answer is showed in the procedure part.

1. b)  Discuss why the controller implemented was chosen. **[20 points]**

**answer:** The inverse dynamic has many advantages. It is easy to design, and easy to select the natural frequency for diagonal position and velocity gain matrices. So when we test the inverse dynamic control, we can try to set different value of natural frequency to get the best performance. Compared to PID control, it needs three PID controllers for each joint. Besides, we know the exact model of this robotic manipulator, which is a condition for inverse dynamic control. From the result, we can get the conclusion that inverse dynamic control is robust and stable because it can track the desired path within a very small error.

1. c)  Simulate the motion of the controller arm along the trajectory selected in Assignment 4, and incorporate a time scale so that the velocity of the motion is known. Provide all the relevant plots for the three joints (position, velocity, torque, etc.). **[30 points]**

**answer:** for the path of each joint, I set a 1000 x 2 matrix. The first column is time, and the second column is position. Because it is too much, so I put them in appendix.

1. d)  Discuss the results obtained. Would a different controller have achieved better results?

**answer:** When change the natural frequency into 20, the result is good. The error is very small. From figure 7, we can find the output path tracks the desired path within very small uncertainty. The response is very robust and fast. Overall, it is a very good control system for the RPR robotic manipulator. For each controller, the MATLAB calculation is very slow. After simplifying the inner loop function, it may have better performance in the real situation. The different controller may have better results, however, for this assignment, the inverse dynamic control can meet our requirement which is giving a good tracking for the original trajectory.

**Appendix:**

1. modified assignment 4 mainfile.m

|  |
| --- |
| %  % we need get the variables of each joint, so I set path1 path2 path3  clear all;  clc;  figure  hold on  axis([-40 65 -50 50 0 50])  xlabel('x axis')  ylabel('y axis')  zlabel('z axis')  % the  obstacle is in pisitions [0,0,25];[-10,-10,30];[20,30,10]  % make all this sphere with a radiu of 3  [x,y,z] = sphere(20);  surf(3\*x+0,3\*y+0,3\*z+25);  surf(3\*x-10,3\*y-10,3\*z+30);  surf(3\*x+20,3\*y+30,3\*z+10);  % path planning      %set variable e for the parabolic well potential constant  e{1}=1;  e{2}=1;  e{3}=1;    %set the range d to be 1 for attractive force  d=10;  % set the variable for repulsive force  n{1}=20;  n{2}=20;  n{3}=20;  % define a radius of influence p0 of an obstacle  p0=10;        % assign a starting point to be [60 0 5]  Ts=[60 0 5];  % the ending point is [-20 0 30]  Tf=[-20 0 30];    %using inverse to get the qs and qf  qs=invkinRPR(Ts);  qcurr=qs;  qf=invkinRPR(Tf);  %assign a starting point to be qs=[-pi/2,10,0]  a1=qs(1);  b1=qs(2);  c1=qs(3);  [x,y,z]=sphere(10);  l2=30;l3=30;  surf(x-sin(a1)\*(l3\*cos(c1)+l2), y+cos(a1)\*(l3\*cos(c1)+l2),z+abs(l3\*sin(c1)+b1));  %the ending point is qf=[pi/2,5,pi/2]  a2=qf(1);  b2=qf(2);  c2=qf(3);  surf(x-sin(a2)\*(l3\*cos(c2)+l2),y+cos(a2)\*(l3\*cos(c2)+l2),z+abs(l3\*sin(c2)+b2));        %store values in steps matrix and keep track using counter  count = 1;  steps = [];  steps(count,:)= qcurr;    % region of convergence  range=5.5;  %step size of ith interation  stepsize=0.05;   [null,null,T]=fkinRPR(qcurr);   o=T(1:3,4);  %  % % [null,null,T1]=fkinRPR(qf);  % % o1=T1(1:3,4);  [null,null,T1]=fkinRPR(qf);   o1=T1(1:3,4);  Qvalue=[];  for i= 1:1000      ttorque= potentialfield(qcurr,qf,e,d,n,p0);      qstep = stepsize\*transpose(ttorque/norm(ttorque));      qtemp = qcurr + qstep;      steps(count,:) = qtemp;      count = count + 1;      qcurr = qtemp;      path1(i,:)=[i\*0.01, qcurr(1)];      path2(i,:)=[i\*0.01, qcurr(2)];      path3(i,:)=[i\*0.01, qcurr(3)];  end    for i=1:size(steps)          [null,null,T]=fkinRPR(steps(i,:));      o=T(1:3,4);      plot3(o(1),o(2),o(3),'y\*');      %plot the 03 point    end |

2. Inner loop function

This function is modified from assignment 5.

|  |
| --- |
| function [Tor]=innerfunction(qq,dq,ddq)    syms y1 y2 y3 v1 v2 v3 a1 a2 a3    q =[y1,y2,y3];  % q= position of each joint    qv= [v1,v2,v3]; % qv= velocity of each joint    qa= [a1,a2,a3]; %qa = acceleration of each joint    %variable  unit m kg kgm^2  x1 =q(1);  x2=1.5708;  x3=q(3);  l1=q(2);    l2=0.05;% the unit is m, 5 cm = 0.05 m  l3=0.05;  lc1=l1/2;  lc2=l1;  lc3=l1+sin(x3)\*(l3/2);  ml1=0.25;  ml2=0.25;  ml3=0.25;  Il1=0.005;  g=9.81;    lc = [0 0.05 0.05];  A01 = [      cos(q(1)) -sin(q(1)) 0 0 ;      sin(q(1)) cos(q(1)) 0 0;      0 0 1 0;      0 0 0 1      ];  A12 = [      0 0 1 0;      1 0 0 lc(2);      0 1 0 q(2);      0 0 0 1;      ];  A23 = [      cos(q(3)) 0 -sin(q(3)) lc(3)\*cos(q(3));      sin(q(3)) 0 cos(q(3)) lc(3)\*sin(q(3));      0 -1 0 0;      0 0 0 1;      ];  T\_2 = A01 \* A12;  T\_3 = T\_2 \* A23;  lc = [0 0.05 0.025];  A23 = [      cos(q(3)) 0 -sin(q(3)) lc(3)\*cos(q(3));      sin(q(3)) 0 cos(q(3)) lc(3)\*sin(q(3));      0 -1 0 0;      0 0 0 1;      ];  Tc\_3 = T\_2 \* A23;  lc = [0 0.025 0];  A12 = [      0 0 1 0;      1 0 0 lc(2);      0 1 0 q(2);      0 0 0 1;      ];  Tc\_2=A01\*A12;      z0 = [0;0;1];  z1=A01(1:3,3);  % this is for z1  z2=T\_2(1:3,3);  % this is for z2  z3=T\_3(1:3,3); % this is for z3  R1=A01(1:3,1:3);  R2=T\_2(1:3,1:3);  R3=T\_3(1:3,1:3);    o0 = [0;0;0];  o1 = A01(1:3, 4);  o2 = T\_2(1:3, 4);  o3 = T\_3(1:3, 4);  oc1 = A01(1:3, 4);  oc2 = Tc\_2(1:3, 4);  oc3 = Tc\_3(1:3, 4);    Jvc={};  Jvc{1}=[cross(z0, oc1-o0), [0;0;0], [0;0;0]];  Jvc{2}=[cross(z0, oc2-o0), z1, [0;0;0]];  Jvc{3}=[cross(z0, oc3-o0), z1, cross(z2, oc3-o2)];  Jwc={};  Jwc{1}=[z0, [0;0;0], [0;0;0]];  Jwc{2}=[z0, [0;0;0], [0;0;0]];  Jwc{3}=[z0, [0;0;0], z2];    %kinetic linear energy  % kl=1/2 \* qv\*(ml1\*Jvc{1}'\*Jvc{1}+ml2\*Jvc{2}'\*Jvc{2} + ml3\*Jvc{3}'\*Jvc{3})\*qv';    I=[0 0 0; 0 0 0;0 0 Il1]; % the inertia is same for I1 I2 I3    % kw=1/2 \* qv\*(Jwc{1}'\*R1\*I\*R1'\*Jwc{1}+Jwc{2}'\*R2\*I\*R2'\*Jwc{2}+Jwc{3}'\*R3\*I\*R3'\*Jwc{3})\*qv';    %inertia matrix D(q)  D= ml1\*Jvc{1}'\*Jvc{1}+ml2\*Jvc{2}'\*Jvc{2} + ml3\*Jvc{3}'\*Jvc{3}+...  Jwc{1}'\*R1\*I\*R1'\*Jwc{1}+Jwc{2}'\*R2\*I\*R2'\*Jwc{2}+Jwc{3}'\*R3\*I\*R3'\*Jwc{3};      %Christoffel Symbols  % cijk=1/2\*(ddkj/dqi+ddki/dqj-ddij/dqk) 1-3      for j=1:3          for i=1:3              ck1(i,j)=1/2\*(diff(D(1,j),q(i))+diff(D(1,i),q(j))-diff(D(i,j),q(1)));          end      end         for j=1:3          for i=1:3              ck2(i,j)=1/2\*(diff(D(2,j),q(i))+diff(D(2,i),q(j))-diff(D(i,j),q(2)));          end      end     for j=1:3          for i=1:3              ck3(i,j)=1/2\*(diff(D(3,j),q(i))+diff(D(3,i),q(j))-diff(D(i,j),q(3)));          end      end  C=sym(zeros(3,3));            C(1,1)=ck1(1,1)\*qv(1)+ck1(2,1)\*qv(2)+ck1(3,1)\*qv(3);              C(1,2)=ck2(1,2)\*qv(1)+ck2(2,2)\*qv(2)+ck2(3,2)\*qv(3);              C(1,3)=ck2(1,3)\*qv(1)+ck2(2,3)\*qv(2)+ck2(3,3)\*qv(3);  % potential energy  p1=l1/2\*ml1\*g;  % first centre of mass  p2=l1\*ml2\*g;  p3=(lc3)\*ml3\*g;  P=p1+p2+p3;  %gk  g1=diff(P,y1);      % dP/dq1  g2= diff(P,y2);       %dP/dl1  g3= diff(P,y3);             %dP/dx3    g13=[g1, g2 g3]';  % when k=1            y1=qq(1);  y2=qq(2);  y3=qq(3);  v1=dq(1); v2=dq(2); v3=dq(3); a1=ddq(1); a2=ddq(2); a3=ddq(3);    torque=D\*qa'+C\*qv'+g13;  Tor= zeros(3,1);  Tor=double(subs(torque));    end |

3. robot function

it is modified from the inner loop function, take position, velocity and torque as input, then generate output.

|  |
| --- |
| function [qa]=robot(qq,dq,tor)    syms y1 y2 y3 v1 v2 v3 a1 a2 a3    q =[y1,y2,y3];  % q= position of each joint    qv= [v1,v2,v3]; % qv= velocity of each joint    qa= [a1,a2,a3]; %qa = acceleration of each joint    %variable  unit m kg kgm^2  x1 =q(1);  x2=1.5708;  x3=q(3);  l1=q(2);    l2=0.05;% the unit is m, 5 cm = 0.05 m  l3=0.05;  lc1=l1/2;  lc2=l1;  lc3=l1+sin(x3)\*(l3/2);  ml1=0.25;  ml2=0.25;  ml3=0.25;  Il1=0.005;  Il2=0.005;  Il3=0.005;  g=9.81;  lc = [0 0.05 0.05];  A01 = [      cos(q(1)) -sin(q(1)) 0 0 ;      sin(q(1)) cos(q(1)) 0 0;      0 0 1 0;      0 0 0 1      ];  A12 = [      0 0 1 0;      1 0 0 lc(2);      0 1 0 q(2);      0 0 0 1;      ];  A23 = [      cos(q(3)) 0 -sin(q(3)) lc(3)\*cos(q(3));      sin(q(3)) 0 cos(q(3)) lc(3)\*sin(q(3));      0 -1 0 0;      0 0 0 1;      ];  T\_2 = A01 \* A12;  T\_3 = T\_2 \* A23;  lc = [0 0.05 0.025];  A23 = [      cos(q(3)) 0 -sin(q(3)) lc(3)\*cos(q(3));      sin(q(3)) 0 cos(q(3)) lc(3)\*sin(q(3));      0 -1 0 0;      0 0 0 1;      ];  Tc\_3 = T\_2 \* A23;  lc = [0 0.025 0];  A12 = [      0 0 1 0;      1 0 0 lc(2);      0 1 0 q(2);      0 0 0 1;      ];  Tc\_2=A01\*A12;      z0 = [0;0;1];  z1=A01(1:3,3);  % this is for z1  z2=T\_2(1:3,3);  % this is for z2  z3=T\_3(1:3,3); % this is for z3  R1=A01(1:3,1:3);  R2=T\_2(1:3,1:3);  R3=T\_3(1:3,1:3);    o0 = [0;0;0];  o1 = A01(1:3, 4);  o2 = T\_2(1:3, 4);  o3 = T\_3(1:3, 4);  oc1 = A01(1:3, 4);  oc2 = Tc\_2(1:3, 4);  oc3 = Tc\_3(1:3, 4);    Jvc={};  Jvc{1}=[cross(z0, oc1-o0), [0;0;0], [0;0;0]];  Jvc{2}=[cross(z0, oc2-o0), z1, [0;0;0]];  Jvc{3}=[cross(z0, oc3-o0), z1, cross(z2, oc3-o2)];  Jwc={};  Jwc{1}=[z0, [0;0;0], [0;0;0]];  Jwc{2}=[z0, [0;0;0], [0;0;0]];  Jwc{3}=[z0, [0;0;0], z2];    I=[0 0 0; 0 0 0;0 0 Il1]; % the inertia is same for I1 I2 I3    % kw=1/2 \* qv\*(Jwc{1}'\*R1\*I\*R1'\*Jwc{1}+Jwc{2}'\*R2\*I\*R2'\*Jwc{2}+Jwc{3}'\*R3\*I\*R3'\*Jwc{3})\*qv';    %inertia matrix D(q)  D= ml1\*Jvc{1}'\*Jvc{1}+ml2\*Jvc{2}'\*Jvc{2} + ml3\*Jvc{3}'\*Jvc{3}+...  Jwc{1}'\*R1\*I\*R1'\*Jwc{1}+Jwc{2}'\*R2\*I\*R2'\*Jwc{2}+Jwc{3}'\*R3\*I\*R3'\*Jwc{3};      %Christoffel Symbols  % cijk=1/2\*(ddkj/dqi+ddki/dqj-ddij/dqk) 1-3      for j=1:3          for i=1:3              ck1(i,j)=1/2\*(diff(D(1,j),q(i))+diff(D(1,i),q(j))-diff(D(i,j),q(1)));          end      end         for j=1:3          for i=1:3              ck2(i,j)=1/2\*(diff(D(2,j),q(i))+diff(D(2,i),q(j))-diff(D(i,j),q(2)));          end      end     for j=1:3          for i=1:3              ck3(i,j)=1/2\*(diff(D(3,j),q(i))+diff(D(3,i),q(j))-diff(D(i,j),q(3)));          end      end  C=sym(zeros(3,3));            C(1,1)=ck1(1,1)\*qv(1)+ck1(2,1)\*qv(2)+ck1(3,1)\*qv(3);              C(1,2)=ck2(1,2)\*qv(1)+ck2(2,2)\*qv(2)+ck2(3,2)\*qv(3);              C(1,3)=ck2(1,3)\*qv(1)+ck2(2,3)\*qv(2)+ck2(3,3)\*qv(3);  % potential energy  p1=l1/2\*ml1\*g;  % first centre of mass  p2=l1\*ml2\*g;  p3=(lc3)\*ml3\*g;  P=p1+p2+p3;  %gk  g1=diff(P,y1);      % dP/dq1  g2= diff(P,y2);       %dP/dl1  g3= diff(P,y3);             %dP/dx3    g13=[g1, g2 g3]';  % when k=1    y1=qq(1);  y2=qq(2);  y3=qq(3);  v1=dq(1); v2=dq(2); v3=dq(3);  ddq =inv(D)\*(tor-C\*qv'-g13);  qa = zeros(3,1);  qa=double(subs(ddq));    end |

4. the code in inner loop block

|  |
| --- |
| function tor = RPRlinkdyn(aq,dq,q)  coder.extrinsic('innerfunction');  tor = zeros(3,1);  tor=innerfunction(q,dq,aq);    end |

5. the code in robot block

|  |
| --- |
| function ddq = RPRlinkdyn(tor,dq,q)  coder.extrinsic('robot');  ddq = zeros(3,1);  ddq=robot(q,dq,tor);  end |

6. the code in outer loop control

|  |
| --- |
| function [aq,err] = control(qd,dqd,ddqd,dq,q,Kv,Kd)  % controls example for MSE 4401    aq = ddqd-Kd\*(q-qd)-Kv\*(dq-dqd);  err = [qd-q]; |

7.the code in dergain

|  |
| --- |
| function y = dergain(u)    y = [2\*u 0 0      0 2\*u 0      0 0 2\*u]; |

8. the code in postgain

|  |
| --- |
| function y = postgain(u)    y = [u\*u 0 0      0 u\*u 0      0 0 u\*u]; |

9. path 1 path 2 and path 3 table:

|  |  |  |
| --- | --- | --- |
| 0.0100000000000000 -1.57079768348412  0.0200000000000000 -1.57079910095301  0.0300000000000000 -1.57080057655499  0.0400000000000000 -1.57080210826254  0.0500000000000000 -1.57080369452222  0.0600000000000000 -1.57080533415442  0.0700000000000000 -1.57080702628263  0.0800000000000000 -1.57080877028249  0.0900000000000000 -1.57081056574481  0.100000000000000 -1.57081241244830  0.110000000000000 -1.57081431033947  0.120000000000000 -1.57081625951805  0.130000000000000 -1.57081826022650  0.140000000000000 -1.57082031284305  0.150000000000000 -1.57082241787753  0.160000000000000 -1.57082457596981  0.170000000000000 -1.57082678789057  0.180000000000000 -1.57082905454429  0.190000000000000 -1.57083137697472  0.200000000000000 -1.57083375637265  0.210000000000000 -1.57083619408648  0.220000000000000 -1.57083869163584  0.230000000000000 -1.57084125072875  0.240000000000000 -1.57084387328292  0.250000000000000 -1.57084656145210  0.260000000000000 -1.57084931765846  0.270000000000000 -1.57085214463242  0.280000000000000 -1.57085504546172  0.290000000000000 -1.57085802365201  0.300000000000000 -1.57086108320204  0.310000000000000 -1.57086422869738  0.320000000000000 -1.57086746542820  0.330000000000000 -1.57087079953806  0.340000000000000 -1.57087423821369  0.350000000000000 -1.57087778992925  0.360000000000000 -1.57088146476379  0.370000000000000 -1.57088527481889  0.380000000000000 -1.57088923477479  0.390000000000000 -1.57089336264183  0.400000000000000 -1.57089768079181  0.410000000000000 -1.57090221739936  0.420000000000000 -1.57090700849783  0.430000000000000 -1.57091210098124  0.440000000000000 -1.57091755710849  0.450000000000000 -1.57092346148091  0.460000000000000 -1.57092699080100  0.470000000000000 -1.57092476475602  0.480000000000000 -1.57090976152112  0.490000000000000 -1.57086625853073  0.500000000000000 -1.57076163879800  0.510000000000000 -1.57054744167375  0.520000000000000 -1.57021145746103  0.530000000000000 -1.56980868550581  0.540000000000000 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