```
close all
clear
clc

% PROBLEM 4 - 4.1

% create figure
figure
axis([-6, 6, -6, 6])
grid on
hold on

% save as a video file
v = VideoWriter('Problem4.mp4', 'MPEG-4');
v.FrameRate = 7;
open(v);

epsilon = 0.1;
%initial joint values
theta = [pi/8; pi/8; pi/8; pi/8; pi/8];
L = 1;

omega = [0;0;1];

q1 = [0;0;0];
q2 = [L;0;0];
q3 = [2*L;0;0];
q4 = [3*L;0;0];
q5 = [4*L;0;0];

S1 = [omega; -cross(omega, q1)];
S2 = [omega; -cross(omega, q2)];
S3 = [omega; -cross(omega, q3)];
S4 = [omega; -cross(omega, q4)];
S5 = [omega; -cross(omega, q5)];

S_eq = [S1, S2, S3, S4, S5];
M = [eye(3), [5*L;0;0]; 0 0 0 1];

% T with initial joint positions
T_0 = fk(M, S_eq, theta)
```

```
T_0 = 4×4
   -0.3827   -0.9239         0    1.6310
    0.9239   -0.3827         0    3.9375
         0         0    1.0000         0
         0         0         0    1.0000
```

```
R_0 = T_0(1:3, 1:3);
JS = double(JacS(S_eq, theta)) %Space Jacobian
```

```
JS = 6×5
         0         0         0         0         0
         0         0         0         0         0
    1.0000    1.0000    1.0000    1.0000    1.0000
         0    0.3827    1.0898    2.0137    3.0137
         0   -0.9239   -1.6310   -2.0137   -2.0137
         0         0         0         0         0
```

```
Jb = double(adjointM(inv(T_0))*JS) %Body Jacobian
```

```
Jb = 6×5
         0         0         0         0         0
         0         0         0         0         0
    1.0000    1.0000    1.0000    1.0000    1.0000
    3.0137    2.0137    1.0898    0.3827         0
    3.0137    3.0137    2.6310    1.9239    1.0000
         0         0         0         0         0
```

```
J_geometric = double([R_0, zeros(3); zeros(3), R_0] * Jb) %Geometric Jacobian
```

```
J_geometric = 6×5
         0         0         0         0         0
         0         0         0         0         0
    1.0000    1.0000    1.0000    1.0000    1.0000
   -3.9375   -3.5549   -2.8478   -1.9239   -0.9239
    1.6310    0.7071   -0.0000   -0.3827   -0.3827
         0         0         0         0         0
```

```
X = [r2axisangle(R_0);T_0(1:3,4)]
```

```
X = 6×1
         0
         0
    1.9635
    1.6310
    3.9375
         0
```

```
% Problem part 4.1
% Given desired Transformation matrices T_d
T_d = [rotz(0), [3;-1;0]; 0 0 0 1]
```

```
T_d = 4×4
     1     0     0     3
     0     1     0    -1
     0     0     1     0
     0     0     0     1
```

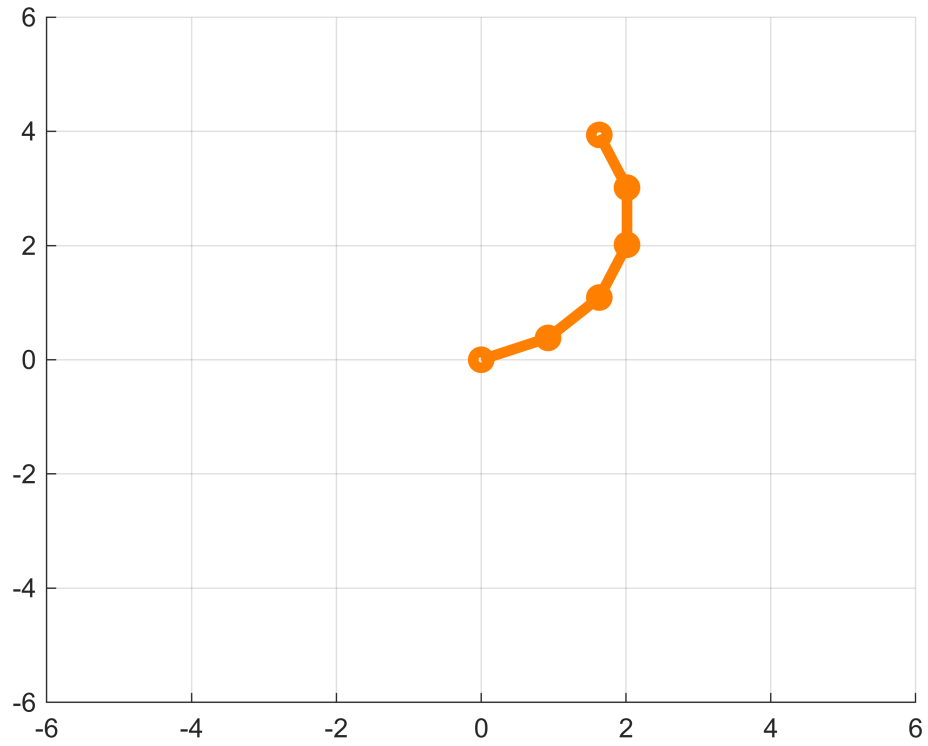
```
R_d = T_d(1:3, 1:3);
Xd = [r2axisangle(R_d);T_d(1:3,4)]
```

```
Xd = 6×1
     0
     0
     0
     3
    -1
     0
```

```
V = Xd - X
```

```
V = 6×1
         0
         0
   -1.9635
    1.3690
   -4.9375
         0
```

```
while norm(Xd - X) > epsilon
% plot the robot
% 1. get the position of each link
    p0 = [0; 0];
    p1 = [L*cos(theta(1)); L*sin(theta(1))]; % (x,y) position of end of first link
    p2 = [L*cos(theta(1) + theta(2)) + p1(1); L*sin(theta(1) + theta(2)) + p1(2)];
% (x,y) position of end of second link
    p3 = [L*cos(theta(1) + theta(2) + theta(3)) + p2(1); L*sin(theta(1) + theta(2)
+ theta(3)) + p2(2)]; % (x,y) position of end of third link
    p4 = [L*cos(theta(1) + theta(2) + theta(3) + theta(4)) + p3(1); L*sin(theta(1)
+ theta(2) + theta(3) + theta(4)) + p3(2)]; % (x,y) position of end of fourth link
    p_v = [L*cos(theta(1) + theta(2) + theta(3) + theta(4) + theta(5)) + p4(1);
L*sin(theta(1) + theta(2) + theta(3) + theta(4) + theta(5)) + p4(2)];% (x,y)
position of end-effector
    P_v = [p0, p1, p2, p3, p4, p_v];
% 2. draw the robot and save the frame

    cla;
    plot(P_v(1,:), P_v(2,:), 'o-', 'color',[1, 0.5, 0],'linewidth',4)
    drawnow
    frame = getframe(gcf);
    writeVideo(v, frame);

% your code here
    V = Xd - X;
    JS = double(JacS(S_eq, theta)); % Updated Space Jacobian
    Jb = double(adjointM(inv(T_0))*JS); %Updated Body Jacobian
    J_geometric = double([R_0, zeros(3); zeros(3), R_0] * Jb); %Updated Geometric
Jacobian

    %Here, we set b vector as the following: b = [-theta(1);0;0;0;0]
    delta_theta = double(pinv(J_geometric)*V +(eye(5) -
pinv(J_geometric)*J_geometric)*[-theta(1);0;0;0;0])

    %Updating theta until the while loop is satisfied to get the desired inverse
kinematics (joint positions), thus simulating the robot
    theta = double(0.1 * delta_theta + theta)
    T_0 = fk(M, S_eq, theta)
    R_0 = T_0(1:3, 1:3);
    X = [r2axisangle(R_0);T_0(1:3,4)];

end
```




```
Warning: The video's width and height has been padded to be a multiple of two as required by the H.264 codec.
delta_theta = 5×1
   -4.6393
    1.9469
    4.0018
    1.6052
   -4.8780
theta = 5×1
   -0.0712
    0.5874
    0.7929
    0.5532
   -0.0951
T_0 = 4×4
   -0.1951   -0.9808         0    1.6435
    0.9808   -0.1951         0    3.3269
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -2.7151
    0.6912
    2.2999
    0.6800
   -2.7232
theta = 5×1
   -0.3427
    0.6565
    1.0229
    0.6212
   -0.3674
T_0 = 4×4
   -0.0196   -0.9998         0    1.7279
    0.9998   -0.0196         0    2.8711
         0         0    1.0000         0
```

```
         0         0         0    1.0000
delta_theta = 5×1
   -2.0783
    0.2118
    1.7237
    0.5041
   -1.9517
theta = 5×1
   -0.5506
    0.6777
    1.1952
    0.6716
   -0.5626
T_0 = 4×4
    0.1390   -0.9903         0    1.8183
    0.9903    0.1390         0    2.4750
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -1.6548
   -0.1139
    1.3376
    0.4444
   -1.4447
theta = 5×1
   -0.7160
    0.6663
    1.3290
    0.7161
   -0.7071
T_0 = 4×4
    0.2788   -0.9603         0    1.9075
    0.9603    0.2788         0    2.1232
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -1.3231
   -0.3500
    1.0349
    0.4233
   -1.0734
theta = 5×1
   -0.8484
    0.6313
    1.4325
    0.7584
   -0.8144
T_0 = 4×4
    0.3999   -0.9166         0    1.9933
    0.9166    0.3999         0    1.8084
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -1.0459
   -0.5164
    0.7842
    0.4133
   -0.7946
theta = 5×1
   -0.9529
    0.5797
    1.5109
    0.7997
   -0.8939
```

```
T_0 = 4×4
    0.5032   -0.8642         0    2.0750
    0.8642    0.5032         0    1.5256
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.8091
   -0.6245
    0.5748
    0.4023
   -0.5870
theta = 5×1
   -1.0339
    0.5172
    1.5684
    0.8400
   -0.9526
T_0 = 4×4
    0.5905   -0.8070         0    2.1521
    0.8070    0.5905         0    1.2710
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.6070
   -0.6853
    0.4029
    0.3860
   -0.4357
theta = 5×1
   -1.0946
    0.4487
    1.6087
    0.8786
   -0.9962
T_0 = 4×4
    0.6636   -0.7481         0    2.2245
    0.7481    0.6636         0    1.0419
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.4366
   -0.7103
    0.2658
    0.3640
   -0.3282
theta = 5×1
   -1.1382
    0.3777
    1.6353
    0.9150
   -1.0290
T_0 = 4×4
    0.7244   -0.6894         0    2.2921
    0.6894    0.7244         0    0.8357
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.2951
   -0.7108
    0.1598
    0.3385
   -0.2531
theta = 5×1
   -1.1677
```

```
    0.3066
    1.6512
    0.9488
   -1.0543
T_0 = 4×4
    0.7747   -0.6324         0    2.3549
    0.6324    0.7747         0    0.6503
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.1796
   -0.6961
    0.0803
    0.3120
   -0.2013
theta = 5×1
   -1.1857
    0.2370
    1.6593
    0.9800
   -1.0744
T_0 = 4×4
    0.8161   -0.5779         0    2.4130
    0.5779    0.8161         0    0.4836
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.0867
   -0.6732
    0.0222
    0.2868
   -0.1652
theta = 5×1
   -1.1944
    0.1696
    1.6615
    1.0087
   -1.0909
T_0 = 4×4
    0.8501   -0.5266         0    2.4665
    0.5266    0.8501         0    0.3339
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.0131
   -0.6467
   -0.0193
    0.2641
   -0.1397
theta = 5×1
   -1.1957
    0.1050
    1.6596
    1.0351
   -1.1049
T_0 = 4×4
    0.8780   -0.4786         0    2.5156
    0.4786    0.8780         0    0.1994
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0448
   -0.6193
   -0.0483
```

```
    0.2447
   -0.1210
theta = 5×1
   -1.1912
    0.0430
    1.6547
    1.0596
   -1.1170
T_0 = 4×4
    0.9008   -0.4342         0    2.5606
    0.4342    0.9008         0    0.0786
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0897
   -0.5925
   -0.0683
    0.2286
   -0.1067
theta = 5×1
   -1.1822
   -0.0162
    1.6479
    1.0824
   -1.1277
T_0 = 4×4
    0.9194   -0.3933         0    2.6016
    0.3933    0.9194         0   -0.0298
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.1243
   -0.5671
   -0.0818
    0.2155
   -0.0952
theta = 5×1
   -1.1698
   -0.0729
    1.6397
    1.1040
   -1.1372
T_0 = 4×4
    0.9345   -0.3559         0    2.6391
    0.3559    0.9345         0   -0.1272
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.1507
   -0.5435
   -0.0906
    0.2050
   -0.0856
theta = 5×1
   -1.1547
   -0.1273
    1.6307
    1.1245
   -1.1457
T_0 = 4×4
    0.9469   -0.3216         0    2.6731
    0.3216    0.9469         0   -0.2147
         0         0    1.0000         0
         0         0         0    1.0000
```

```
delta_theta = 5×1
    0.1707
   -0.5215
   -0.0960
    0.1967
   -0.0773
theta = 5×1
   -1.1376
   -0.1794
    1.6211
    1.1442
   -1.1535
T_0 = 4×4
    0.9569   -0.2905         0    2.7041
    0.2905    0.9569         0   -0.2933
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.1856
   -0.5012
   -0.0993
    0.1901
   -0.0699
theta = 5×1
   -1.1191
   -0.2295
    1.6111
    1.1632
   -1.1605
T_0 = 4×4
    0.9650   -0.2621         0    2.7322
    0.2621    0.9650         0   -0.3640
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.1965
   -0.4825
   -0.1009
    0.1848
   -0.0631
theta = 5×1
   -1.0994
   -0.2778
    1.6011
    1.1816
   -1.1668
T_0 = 4×4
    0.9716   -0.2365         0    2.7577
    0.2365    0.9716         0   -0.4275
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.2043
   -0.4651
   -0.1015
    0.1805
   -0.0569
theta = 5×1
   -1.0790
   -0.3243
    1.5909
    1.1997
   -1.1725
T_0 = 4×4
```

```
    0.9770   -0.2132         0    2.7809
    0.2132    0.9770         0   -0.4846
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.2096
   -0.4490
   -0.1014
    0.1770
   -0.0511
theta = 5×1
   -1.0580
   -0.3692
    1.5808
    1.2174
   -1.1776
T_0 = 4×4
    0.9814   -0.1922         0    2.8018
    0.1922    0.9814         0   -0.5359
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.2131
   -0.4339
   -0.1009
    0.1741
   -0.0457
theta = 5×1
   -1.0367
   -0.4126
    1.5707
    1.2348
   -1.1821
T_0 = 4×4
    0.9849   -0.1731         0    2.8208
    0.1731    0.9849         0   -0.5821
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.2151
   -0.4199
   -0.1002
    0.1716
   -0.0406
theta = 5×1
   -1.0152
   -0.4546
    1.5607
    1.2520
   -1.1862
T_0 = 4×4
    0.9878   -0.1560         0    2.8379
    0.1560    0.9878         0   -0.6236
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.2159
   -0.4067
   -0.0994
    0.1693
   -0.0357
theta = 5×1
   -0.9936
   -0.4952
```

```
    1.5507
    1.2689
   -1.1898
T_0 = 4×4
    0.9901   -0.1405         0    2.8534
    0.1405    0.9901         0   -0.6610
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.2158
   -0.3942
   -0.0985
    0.1671
   -0.0311
theta = 5×1
   -0.9720
   -0.5347
    1.5409
    1.2856
   -1.1929
T_0 = 4×4
    0.9920   -0.1265         0    2.8674
    0.1265    0.9920         0   -0.6947
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.2150
   -0.3825
   -0.0978
    0.1651
   -0.0267
theta = 5×1
   -0.9506
   -0.5729
    1.5311
    1.3021
   -1.1956
T_0 = 4×4
    0.9935   -0.1139         0    2.8801
    0.1139    0.9935         0   -0.7249
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.2136
   -0.3713
   -0.0971
    0.1630
   -0.0225
theta = 5×1
   -0.9292
   -0.6100
    1.5214
    1.3184
   -1.1978
T_0 = 4×4
    0.9947   -0.1026         0    2.8916
    0.1026    0.9947         0   -0.7522
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.2119
   -0.3606
   -0.0965
    0.1610
```

```
   -0.0185
theta = 5×1
   -0.9080
   -0.6461
    1.5117
    1.3345
   -1.1997
T_0 = 4×4
    0.9957   -0.0924         0    2.9019
    0.0924    0.9957         0   -0.7767
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.2098
   -0.3504
   -0.0960
    0.1588
   -0.0146
theta = 5×1
   -0.8870
   -0.6811
    1.5021
    1.3504
   -1.2011
T_0 = 4×4
    0.9965   -0.0831         0    2.9112
    0.0831    0.9965         0   -0.7988
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.2074
   -0.3407
   -0.0957
    0.1566
   -0.0109
theta = 5×1
   -0.8663
   -0.7152
    1.4926
    1.3661
   -1.2022
T_0 = 4×4
    0.9972   -0.0748         0    2.9197
    0.0748    0.9972         0   -0.8187
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.2048
   -0.3313
   -0.0955
    0.1543
   -0.0073
theta = 5×1
   -0.8458
   -0.7483
    1.4830
    1.3815
   -1.2029
T_0 = 4×4
    0.9977   -0.0674         0    2.9273
    0.0674    0.9977         0   -0.8366
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
```

```
    0.2021
   -0.3222
   -0.0954
    0.1519
   -0.0038
theta = 5×1
   -0.8256
   -0.7805
    1.4735
    1.3967
   -1.2033
T_0 = 4×4
    0.9982   -0.0606         0    2.9342
    0.0606    0.9982         0   -0.8527
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.1993
   -0.3134
   -0.0955
    0.1493
   -0.0004
theta = 5×1
   -0.8057
   -0.8119
    1.4639
    1.4116
   -1.2034
T_0 = 4×4
    0.9985   -0.0546         0    2.9404
    0.0546    0.9985         0   -0.8672
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.1963
   -0.3049
   -0.0956
    0.1466
    0.0028
theta = 5×1
   -0.7860
   -0.8424
    1.4544
    1.4263
   -1.2031
T_0 = 4×4
    0.9988   -0.0491         0    2.9460
    0.0491    0.9988         0   -0.8802
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.1933
   -0.2966
   -0.0957
    0.1438
    0.0060
theta = 5×1
   -0.7667
   -0.8720
    1.4448
    1.4407
   -1.2025
T_0 = 4×4
    0.9990   -0.0442         0    2.9510
```

```
    0.0442    0.9990         0   -0.8920
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.1902
   -0.2885
   -0.0959
    0.1409
    0.0090
theta = 5×1
   -0.7477
   -0.9009
    1.4352
    1.4547
   -1.2016
T_0 = 4×4
    0.9992   -0.0398         0    2.9556
    0.0398    0.9992         0   -0.9026
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.1871
   -0.2806
   -0.0962
    0.1379
    0.0119
theta = 5×1
   -0.7290
   -0.9289
    1.4256
    1.4685
   -1.2004
T_0 = 4×4
    0.9994   -0.0358         0    2.9597
    0.0358    0.9994         0   -0.9122
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.1839
   -0.2729
   -0.0964
    0.1348
    0.0147
theta = 5×1
   -0.7106
   -0.9562
    1.4159
    1.4820
   -1.1989
T_0 = 4×4
    0.9995   -0.0322         0    2.9635
    0.0322    0.9995         0   -0.9208
         0         0    1.0000         0
         0         0         0    1.0000
```

```
close(v);
close all
```