```
close all
clear
clc

% PROBLEM 2 - 2.3

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

% save as a video file
v = VideoWriter('Problem3_3.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 2.3
% 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
```

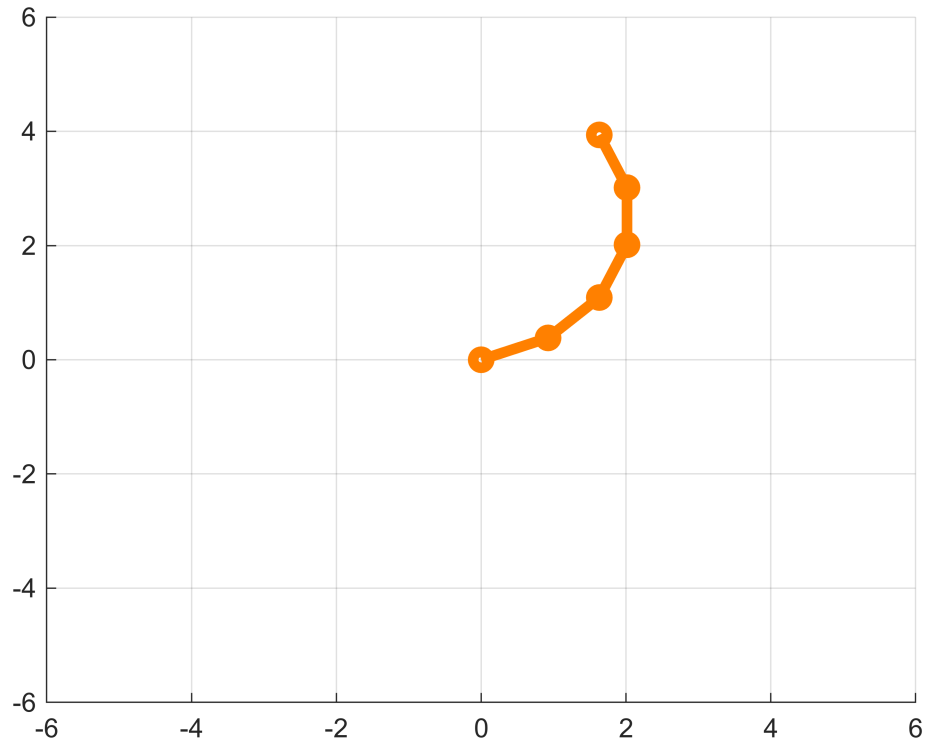
```
while norm(Xd - X) > epsilon
% plot the robot
% 1. get the position of each link
    p0 = [0; 0];
    p1 = [L*cos(theta(1)); L*sin(theta(1))]; % (x,y) position of end of first link
    p2 = [L*cos(theta(1) + theta(2)) + p1(1); L*sin(theta(1) + theta(2)) + p1(2)];
% (x,y) position of end of second 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
    delta_theta = double(pinv(J_geometric)*V +(eye(5) -
pinv(J_geometric)*J_geometric)*[0;0;0;0;0]) %null space is zero currently as we set
b = 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
   -4.5887
    1.8411
    4.0367
    1.6638
   -4.9164
theta = 5×1
   -0.0662
    0.5768
    0.7964
    0.5591
   -0.0989
T_0 = 4×4
   -0.1951   -0.9808         0    1.6449
    0.9808   -0.1951         0    3.3255
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -2.7155
    0.7023
    2.2931
    0.6734
   -2.7205
theta = 5×1
   -0.3377
    0.6470
    1.0257
    0.6264
   -0.3710
T_0 = 4×4
   -0.0196   -0.9998         0    1.7293
    0.9998   -0.0196         0    2.8699
         0         0    1.0000         0
```

```
         0         0         0    1.0000
delta_theta = 5×1
   -2.1361
    0.3178
    1.6832
    0.4558
   -1.9111
theta = 5×1
   -0.5513
    0.6788
    1.1940
    0.6720
   -0.5621
T_0 = 4×4
    0.1390   -0.9903         0    1.8192
    0.9903    0.1390         0    2.4747
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -1.7715
    0.0709
    1.2706
    0.3662
   -1.3675
theta = 5×1
   -0.7285
    0.6859
    1.3211
    0.7086
   -0.6989
T_0 = 4×4
    0.2788   -0.9603         0    1.9079
    0.9603    0.2788         0    2.1242
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -1.4943
   -0.1020
    0.9487
    0.3223
   -0.9629
theta = 5×1
   -0.8779
    0.6757
    1.4159
    0.7408
   -0.7951
T_0 = 4×4
    0.3999   -0.9166         0    1.9934
    0.9166    0.3999         0    1.8105
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -1.2619
   -0.2193
    0.6853
    0.2927
   -0.6562
theta = 5×1
   -1.0041
    0.6538
    1.4845
    0.7701
   -0.8608
```

```
T_0 = 4×4
    0.5032   -0.8642         0    2.0749
    0.8642    0.5032         0    1.5284
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -1.0576
   -0.2898
    0.4688
    0.2627
   -0.4277
theta = 5×1
   -1.1099
    0.6248
    1.5313
    0.7964
   -0.9035
T_0 = 4×4
    0.5905   -0.8070         0    2.1522
    0.8070    0.5905         0    1.2740
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.8756
   -0.3218
    0.2946
    0.2270
   -0.2633
theta = 5×1
   -1.1974
    0.5926
    1.5608
    0.8191
   -0.9299
T_0 = 4×4
    0.6636   -0.7481         0    2.2249
    0.7481    0.6636         0    1.0445
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.7151
   -0.3251
    0.1594
    0.1857
   -0.1501
theta = 5×1
   -1.2689
    0.5601
    1.5767
    0.8377
   -0.9449
T_0 = 4×4
    0.7244   -0.6894         0    2.2928
    0.6894    0.7244         0    0.8376
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.5763
   -0.3097
    0.0588
    0.1424
   -0.0759
theta = 5×1
   -1.3266
```

```
    0.5291
    1.5826
    0.8519
   -0.9525
T_0 = 4×4
    0.7747   -0.6324         0    2.3560
    0.6324    0.7747         0    0.6513
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.4589
   -0.2839
   -0.0129
    0.1006
   -0.0296
theta = 5×1
   -1.3725
    0.5008
    1.5813
    0.8620
   -0.9554
T_0 = 4×4
    0.8161   -0.5779         0    2.4145
    0.5779    0.8161         0    0.4836
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.3617
   -0.2540
   -0.0617
    0.0634
   -0.0022
theta = 5×1
   -1.4086
    0.4754
    1.5752
    0.8683
   -0.9556
T_0 = 4×4
    0.8501   -0.5266         0    2.4683
    0.5266    0.8501         0    0.3330
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.2825
   -0.2239
   -0.0932
    0.0321
    0.0129
theta = 5×1
   -1.4369
    0.4530
    1.5658
    0.8715
   -0.9544
T_0 = 4×4
    0.8780   -0.4786         0    2.5178
    0.4786    0.8780         0    0.1977
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.2188
   -0.1957
   -0.1121
```

```
    0.0071
    0.0204
theta = 5×1
   -1.4588
    0.4334
    1.5546
    0.8722
   -0.9523
T_0 = 4×4
    0.9008   -0.4342         0    2.5631
    0.4342    0.9008         0    0.0762
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.1681
   -0.1703
   -0.1221
   -0.0119
    0.0234
theta = 5×1
   -1.4756
    0.4164
    1.5424
    0.8710
   -0.9500
T_0 = 4×4
    0.9194   -0.3933         0    2.6044
    0.3933    0.9194         0   -0.0328
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.1281
   -0.1481
   -0.1260
   -0.0259
    0.0238
theta = 5×1
   -1.4884
    0.4016
    1.5298
    0.8684
   -0.9476
T_0 = 4×4
    0.9345   -0.3559         0    2.6421
    0.3559    0.9345         0   -0.1307
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.0966
   -0.1289
   -0.1257
   -0.0356
    0.0229
theta = 5×1
   -1.4980
    0.3887
    1.5173
    0.8649
   -0.9453
T_0 = 4×4
    0.9469   -0.3216         0    2.6764
    0.3216    0.9469         0   -0.2186
         0         0    1.0000         0
         0         0         0    1.0000
```

```
delta_theta = 5×1
   -0.0720
   -0.1123
   -0.1225
   -0.0420
    0.0214
theta = 5×1
   -1.5052
    0.3774
    1.5050
    0.8607
   -0.9432
T_0 = 4×4
    0.9569   -0.2905         0    2.7075
    0.2905    0.9569         0   -0.2974
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.0529
   -0.0981
   -0.1176
   -0.0457
    0.0196
theta = 5×1
   -1.5105
    0.3676
    1.4932
    0.8561
   -0.9412
T_0 = 4×4
    0.9650   -0.2621         0    2.7358
    0.2621    0.9650         0   -0.3683
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.0380
   -0.0859
   -0.1116
   -0.0475
    0.0178
theta = 5×1
   -1.5143
    0.3590
    1.4821
    0.8514
   -0.9394
T_0 = 4×4
    0.9716   -0.2365         0    2.7614
    0.2365    0.9716         0   -0.4320
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.0265
   -0.0754
   -0.1050
   -0.0478
    0.0161
theta = 5×1
   -1.5170
    0.3515
    1.4716
    0.8466
   -0.9378
T_0 = 4×4
```

```
    0.9770   -0.2132         0    2.7847
    0.2132    0.9770         0   -0.4891
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.0177
   -0.0663
   -0.0982
   -0.0471
    0.0145
theta = 5×1
   -1.5188
    0.3449
    1.4618
    0.8419
   -0.9364
T_0 = 4×4
    0.9814   -0.1922         0    2.8057
    0.1922    0.9814         0   -0.5405
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.0110
   -0.0585
   -0.0912
   -0.0456
    0.0130
theta = 5×1
   -1.5199
    0.3390
    1.4526
    0.8373
   -0.9351
T_0 = 4×4
    0.9849   -0.1731         0    2.8247
    0.1731    0.9849         0   -0.5867
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.0060
   -0.0517
   -0.0844
   -0.0436
    0.0117
theta = 5×1
   -1.5205
    0.3339
    1.4442
    0.8329
   -0.9339
T_0 = 4×4
    0.9878   -0.1560         0    2.8419
    0.1560    0.9878         0   -0.6282
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.0022
   -0.0458
   -0.0779
   -0.0413
    0.0106
theta = 5×1
   -1.5207
    0.3293
```

```
    1.4364
    0.8288
   -0.9328
T_0 = 4×4
    0.9901   -0.1405         0    2.8575
    0.1405    0.9901         0   -0.6656
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0006
   -0.0407
   -0.0716
   -0.0388
    0.0095
theta = 5×1
   -1.5206
    0.3252
    1.4293
    0.8249
   -0.9319
T_0 = 4×4
    0.9920   -0.1265         0    2.8715
    0.1265    0.9920         0   -0.6991
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0026
   -0.0362
   -0.0656
   -0.0363
    0.0086
theta = 5×1
   -1.5204
    0.3216
    1.4227
    0.8213
   -0.9310
T_0 = 4×4
    0.9935   -0.1139         0    2.8842
    0.1139    0.9935         0   -0.7293
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0040
   -0.0322
   -0.0601
   -0.0337
    0.0078
theta = 5×1
   -1.5200
    0.3184
    1.4167
    0.8179
   -0.9303
T_0 = 4×4
    0.9947   -0.1026         0    2.8956
    0.1026    0.9947         0   -0.7565
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0049
   -0.0287
   -0.0549
   -0.0312
```

```
    0.0070
theta = 5×1
   -1.5195
    0.3155
    1.4112
    0.8148
   -0.9296
T_0 = 4×4
    0.9957   -0.0924         0    2.9059
    0.0924    0.9957         0   -0.7809
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0055
   -0.0256
   -0.0500
   -0.0287
    0.0063
theta = 5×1
   -1.5189
    0.3129
    1.4062
    0.8119
   -0.9289
T_0 = 4×4
    0.9965   -0.0831         0    2.9152
    0.0831    0.9965         0   -0.8028
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0058
   -0.0229
   -0.0455
   -0.0264
    0.0057
theta = 5×1
   -1.5183
    0.3107
    1.4016
    0.8093
   -0.9283
T_0 = 4×4
    0.9972   -0.0748         0    2.9236
    0.0748    0.9972         0   -0.8226
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0060
   -0.0204
   -0.0414
   -0.0242
    0.0052
theta = 5×1
   -1.5177
    0.3086
    1.3975
    0.8069
   -0.9278
T_0 = 4×4
    0.9977   -0.0674         0    2.9312
    0.0674    0.9977         0   -0.8404
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
```

```
    0.0059
   -0.0183
   -0.0376
   -0.0221
    0.0047
theta = 5×1
   -1.5171
    0.3068
    1.3937
    0.8047
   -0.9274
T_0 = 4×4
    0.9982   -0.0606         0    2.9381
    0.0606    0.9982         0   -0.8563
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0058
   -0.0164
   -0.0341
   -0.0202
    0.0042
theta = 5×1
   -1.5165
    0.3051
    1.3903
    0.8026
   -0.9269
T_0 = 4×4
    0.9985   -0.0546         0    2.9442
    0.0546    0.9985         0   -0.8707
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0056
   -0.0147
   -0.0310
   -0.0184
    0.0038
theta = 5×1
   -1.5160
    0.3037
    1.3872
    0.8008
   -0.9266
T_0 = 4×4
    0.9988   -0.0491         0    2.9498
    0.0491    0.9988         0   -0.8837
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0053
   -0.0131
   -0.0280
   -0.0168
    0.0035
theta = 5×1
   -1.5155
    0.3024
    1.3844
    0.7991
   -0.9262
T_0 = 4×4
    0.9990   -0.0442         0    2.9548
```

```
    0.0442    0.9990         0   -0.8953
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0050
   -0.0118
   -0.0254
   -0.0152
    0.0031
theta = 5×1
   -1.5150
    0.3012
    1.3819
    0.7976
   -0.9259
T_0 = 4×4
    0.9992   -0.0398         0    2.9593
    0.0398    0.9992         0   -0.9058
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0047
   -0.0106
   -0.0230
   -0.0138
    0.0028
theta = 5×1
   -1.5145
    0.3001
    1.3796
    0.7962
   -0.9256
T_0 = 4×4
    0.9994   -0.0358         0    2.9633
    0.0358    0.9994         0   -0.9152
         0         0    1.0000         0
         0         0         0    1.0000
```

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