```
close all
clear
clc

% PROBLEM 2 - 2.1

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

% save as a video file
v = VideoWriter('Problem3_1.mp4', 'MPEG-4');
v.FrameRate = 6;
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 2.1
% Given desired Transformation matrices T_d
T_d = [rotz(pi/4), [3;2;0]; 0 0 0 1]
```

```
T_d = 4×4
    0.9999   -0.0137         0    3.0000
    0.0137    0.9999         0    2.0000
         0         0    1.0000         0
         0         0         0    1.0000
```

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

```
Xd = 6×1
         0
         0
    0.0137
    3.0000
    2.0000
         0
```

```
V = Xd - X
```

```
V = 6×1
         0
         0
   -1.9498
    1.3690
   -1.9375
         0
```

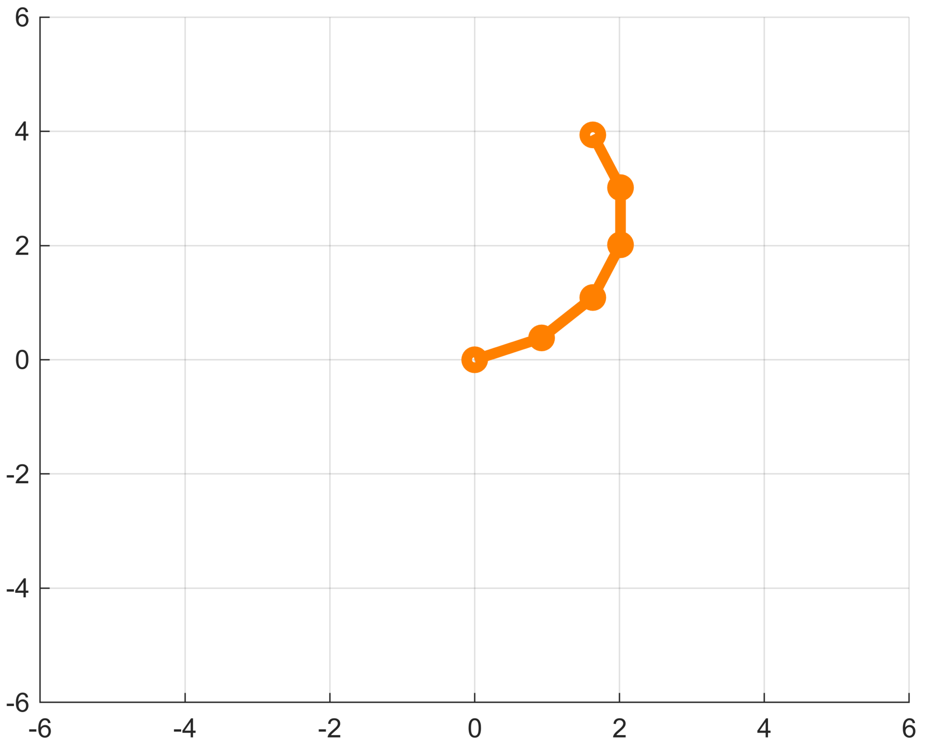
```
while norm(Xd - X) > epsilon
% plot the robot
% 1. get the position of each link
    p0 = [0; 0];
    p1 = [L*cos(theta(1)); L*sin(theta(1))]; % (x,y) position of end of first link
    p2 = [L*cos(theta(1) + theta(2)) + p1(1); L*sin(theta(1) + theta(2)) + p1(2)];
% (x,y) position of end of second 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
   -2.3195
    1.0891
    2.0912
    0.5342
   -3.3447
theta = 5×1
    0.1607
    0.5016
    0.6018
    0.4461
    0.0582
T_0 = 4×4
   -0.1964   -0.9805         0    1.7420
    0.9805   -0.1964         0    3.6992
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -1.5031
    0.6907
    1.3850
    0.0910
   -2.4183
theta = 5×1
    0.0104
    0.5707
    0.7403
    0.4552
   -0.1836
T_0 = 4×4
   -0.0222   -0.9998         0    1.8560
    0.9998   -0.0222         0    3.5071
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -1.0924
    0.5115
    1.0160
   -0.0841
   -1.9303
theta = 5×1
   -0.0988
    0.6218
    0.8419
    0.4468
   -0.3766
T_0 = 4×4
    0.1353   -0.9908         0    1.9625
    0.9908    0.1353         0    3.3417
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.8189
    0.3986
    0.7632
   -0.1735
   -1.5907
theta = 5×1
   -0.1807
    0.6617
    0.9182
    0.4295
   -0.5357
T_0 = 4×4
    0.2743   -0.9617         0    2.0603
    0.9617    0.2743         0    3.1968
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.6208
    0.3181
    0.5753
   -0.2203
   -1.3315
theta = 5×1
   -0.2428
    0.6935
    0.9758
    0.4074
   -0.6689
T_0 = 4×4
    0.3947   -0.9188         0    2.1493
    0.9188    0.3947         0    3.0692
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.4725
    0.2568
    0.4312
   -0.2423
   -1.1246
theta = 5×1
   -0.2900
    0.7192
    1.0189
    0.3832
   -0.7813
```

```
T_0 = 4×4
    0.4977   -0.8674         0    2.2302
    0.8674    0.4977         0    2.9562
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.3596
    0.2085
    0.3193
   -0.2489
   -0.9555
theta = 5×1
   -0.3260
    0.7400
    1.0508
    0.3583
   -0.8769
T_0 = 4×4
    0.5847   -0.8112         0    2.3036
    0.8112    0.5847         0    2.8560
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.2731
    0.1694
    0.2324
   -0.2459
   -0.8153
theta = 5×1
   -0.3533
    0.7569
    1.0740
    0.3337
   -0.9584
T_0 = 4×4
    0.6577   -0.7533         0    2.3702
    0.7533    0.6577         0    2.7669
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.2066
    0.1374
    0.1649
   -0.2369
   -0.6981
theta = 5×1
   -0.3740
    0.7707
    1.0905
    0.3100
   -1.0282
T_0 = 4×4
    0.7185   -0.6955         0    2.4306
    0.6955    0.7185         0    2.6876
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.1554
    0.1111
    0.1127
   -0.2243
   -0.5995
theta = 5×1
   -0.3895
```

```
    0.7818
    1.1018
    0.2876
   -1.0882
T_0 = 4×4
    0.7690   -0.6393         0    2.4853
    0.6393    0.7690         0    2.6168
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.1160
    0.0894
    0.0728
   -0.2099
   -0.5162
theta = 5×1
   -0.4011
    0.7907
    1.1091
    0.2666
   -1.1398
T_0 = 4×4
    0.8106   -0.5856         0    2.5350
    0.5856    0.8106         0    2.5536
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.0856
    0.0716
    0.0423
   -0.1946
   -0.4456
theta = 5×1
   -0.4096
    0.7979
    1.1133
    0.2472
   -1.1843
T_0 = 4×4
    0.8449   -0.5349         0    2.5799
    0.5349    0.8449         0    2.4970
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.0622
    0.0569
    0.0194
   -0.1793
   -0.3856
theta = 5×1
   -0.4159
    0.8036
    1.1153
    0.2292
   -1.2229
T_0 = 4×4
    0.8731   -0.4876         0    2.6206
    0.4876    0.8731         0    2.4464
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.0442
    0.0450
    0.0025
   -0.1643
   -0.3345
theta = 5×1
   -0.4203
    0.8081
    1.1155
    0.2128
   -1.2564
T_0 = 4×4
    0.8962   -0.4437         0    2.6575
    0.4437    0.8962         0    2.4010
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.0305
    0.0352
   -0.0099
   -0.1500
   -0.2908
theta = 5×1
   -0.4233
    0.8116
    1.1145
    0.1978
   -1.2854
T_0 = 4×4
    0.9151   -0.4033         0    2.6909
    0.4033    0.9151         0    2.3604
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.0200
    0.0273
   -0.0187
   -0.1366
   -0.2534
theta = 5×1
   -0.4253
    0.8143
    1.1126
    0.1841
   -1.3108
T_0 = 4×4
    0.9305   -0.3663         0    2.7211
    0.3663    0.9305         0    2.3239
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.0120
    0.0209
   -0.0248
   -0.1241
   -0.2213
theta = 5×1
   -0.4265
    0.8164
    1.1102
    0.1717
   -1.3329
T_0 = 4×4
    0.9431   -0.3324         0    2.7483
    0.3324    0.9431         0    2.2912
         0         0    1.0000         0
         0         0         0    1.0000
```

```
delta_theta = 5×1
   -0.0060
    0.0157
   -0.0287
   -0.1125
   -0.1937
theta = 5×1
   -0.4271
    0.8180
    1.1073
    0.1605
   -1.3523
T_0 = 4×4
    0.9534   -0.3016         0    2.7730
    0.3016    0.9534         0    2.2618
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
   -0.0015
    0.0116
   -0.0310
   -0.1019
   -0.1699
theta = 5×1
   -0.4273
    0.8192
    1.1042
    0.1503
   -1.3693
T_0 = 4×4
    0.9619   -0.2736         0    2.7953
    0.2736    0.9619         0    2.2354
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0017
    0.0083
   -0.0321
   -0.0921
   -0.1492
theta = 5×1
   -0.4271
    0.8200
    1.1010
    0.1411
   -1.3842
T_0 = 4×4
    0.9687   -0.2481         0    2.8155
    0.2481    0.9687         0    2.2117
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0041
    0.0058
   -0.0323
   -0.0833
   -0.1314
theta = 5×1
   -0.4267
    0.8206
    1.0977
    0.1328
   -1.3973
T_0 = 4×4
```

```
    0.9743   -0.2251         0    2.8336
    0.2251    0.9743         0    2.1904
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0057
    0.0038
   -0.0318
   -0.0752
   -0.1158
theta = 5×1
   -0.4261
    0.8209
    1.0946
    0.1252
   -1.4089
T_0 = 4×4
    0.9789   -0.2043         0    2.8501
    0.2043    0.9789         0    2.1713
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0068
    0.0022
   -0.0309
   -0.0679
   -0.1023
theta = 5×1
   -0.4254
    0.8212
    1.0915
    0.1185
   -1.4191
T_0 = 4×4
    0.9827   -0.1854         0    2.8649
    0.1854    0.9827         0    2.1541
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0074
    0.0010
   -0.0296
   -0.0612
   -0.0905
theta = 5×1
   -0.4247
    0.8213
    1.0885
    0.1123
   -1.4282
T_0 = 4×4
    0.9857   -0.1684         0    2.8782
    0.1684    0.9857         0    2.1386
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0078
    0.0001
   -0.0281
   -0.0552
   -0.0802
theta = 5×1
   -0.4239
    0.8213
    1.0857
    0.1068
   -1.4362
T_0 = 4×4
    0.9882   -0.1531         0    2.8903
    0.1531    0.9882         0    2.1247
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0079
   -0.0005
   -0.0265
   -0.0498
   -0.0711
theta = 5×1
   -0.4231
    0.8212
    1.0831
    0.1018
   -1.4433
T_0 = 4×4
    0.9903   -0.1392         0    2.9012
    0.1392    0.9903         0    2.1122
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0078
   -0.0010
   -0.0248
   -0.0448
   -0.0632
theta = 5×1
   -0.4224
    0.8211
    1.0806
    0.0974
   -1.4496
T_0 = 4×4
    0.9919   -0.1267         0    2.9110
    0.1267    0.9919         0    2.1009
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0076
   -0.0013
   -0.0231
   -0.0404
   -0.0562
theta = 5×1
   -0.4216
    0.8210
    1.0783
    0.0933
   -1.4553
T_0 = 4×4
    0.9933   -0.1155         0    2.9198
    0.1155    0.9933         0    2.0908
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0073
   -0.0016
   -0.0214
   -0.0364
   -0.0500
theta = 5×1
   -0.4209
    0.8208
    1.0761
    0.0897
   -1.4602
T_0 = 4×4
    0.9944   -0.1053         0    2.9278
    0.1053    0.9944         0    2.0817
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0070
   -0.0017
   -0.0198
   -0.0328
   -0.0445
theta = 5×1
   -0.4202
    0.8207
    1.0742
    0.0864
   -1.4647
T_0 = 4×4
    0.9954   -0.0962         0    2.9350
    0.0962    0.9954         0    2.0735
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0066
   -0.0018
   -0.0182
   -0.0295
   -0.0397
theta = 5×1
   -0.4195
    0.8205
    1.0723
    0.0834
   -1.4687
T_0 = 4×4
    0.9961   -0.0880         0    2.9414
    0.0880    0.9961         0    2.0662
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
    0.0062
   -0.0018
   -0.0167
   -0.0266
   -0.0354
theta = 5×1
   -0.4189
    0.8203
    1.0707
    0.0808
   -1.4722
T_0 = 4×4
    0.9967   -0.0806         0    2.9473
    0.0806    0.9967         0    2.0595
         0         0    1.0000         0
         0         0         0    1.0000
delta_theta = 5×1
```

```
    0.0058
   -0.0018
   -0.0153
   -0.0239
   -0.0317
theta = 5×1
   -0.4183
    0.8201
    1.0691
    0.0784
   -1.4754
T_0 = 4×4
    0.9973   -0.0739         0    2.9525
    0.0739    0.9973         0    2.0536
         0         0    1.0000         0
         0         0         0    1.0000
```

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