Prob3. Generate trajectory using CartesianTrajectory.m

Using matlab generate trajectory by "CartesianTrajectory,m" in joint space and plot in CoppeliaSim.

- Generate trajectory in SE(3) matrix.
- Show output together with your MATLAB code.
- Plot the motion of Indy 7 manipulator by CoppeliaSim.

First import the matlab library.

```
% 20190348 Jungill Kang
addpath('..\mr')
clear; clc;
```

Observe CartesianTrajectory.m

```
*** CHAPTER 9: TRAJECTORY GENERATION ***
Takes Xstart: The initial end-effector configuration,
      Xend: The final end-effector configuration,
      Tf: Total time of the motion in seconds from rest to rest,
      N: The number of points N > 1 (Start and stop) in the discrete
         representation of the trajectory,
      method: The time-scaling method, where 3 indicates cubic
              (third-order polynomial) time scaling and 5 indicates
              quintic (fifth-order polynomial) time scaling.
Returns traj: The discretized trajectory as a list of N matrices in SE(3)
              separated in time by Tf/(N-1). The first in the list is
              Xstart and the Nth is Xend .
This function is similar to ScrewTrajectory, except the origin of the
end-effector frame follows a straight line, decoupled from the rotational
motion.
Example Input:

clear; clc;
Xstart = [[1, 0, 0, 1]; [0, 1, 0, 0]; [0, 0, 1, 1]; [0, 0, 0, 1]];
Xend = [[0, 0, 1, 0.1]; [1, 0, 0, 0]; [0, 1, 0, 4.1]; [0, 0, 0, 1]];
Tf = 5;
N = 4;
method = 5;
traj = CartesianTrajectory(Xstart, Xend, Tf, N, method)

Output:
traj =
   1.0000         0         0    1.0000
        0    1.0000         0         0
        0         0    1.0000    1.0000
        0         0         0    1.0000

   0.9366   -0.2140    0.2774    0.8111
   0.2774    0.9366   -0.2140         0
  -0.2140    0.2774    0.9366    1.6506
```

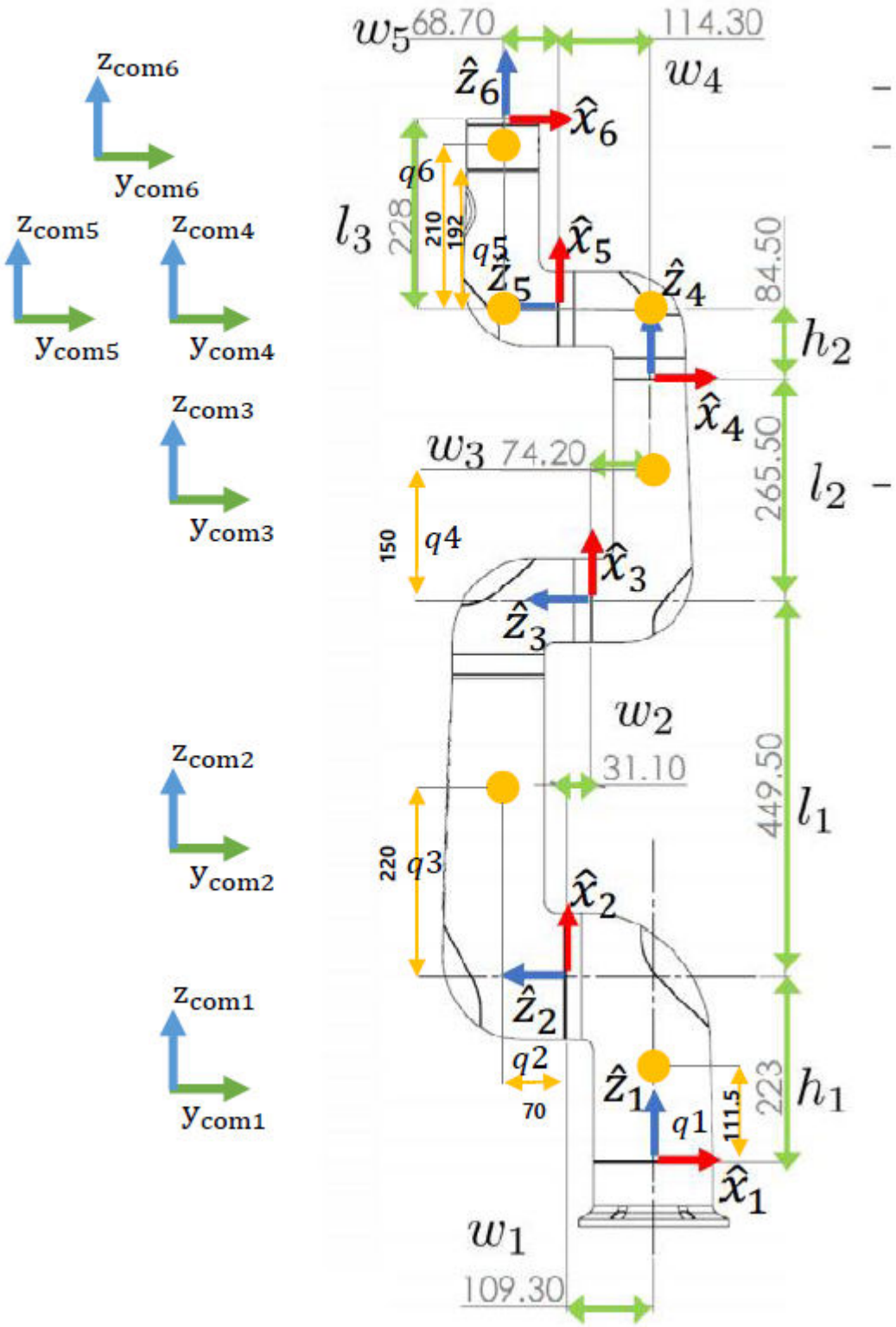
```
     0         0         0    1.0000

 0.2774   -0.2140    0.9366    0.2889
 0.9366    0.2774   -0.2140         0
-0.2140    0.9366    0.2774    3.4494
     0         0         0    1.0000

-0.0000    0.0000    1.0000    0.1000
 1.0000   -0.0000    0.0000         0
 0.0000    1.0000   -0.0000    4.1000
     0         0         0    1.0000
```

Now create code which create joint trajectory using 3rd order polynomial time scaling.

Starts from initial state to final state.

Use this properties below.

Indy7 Dynamic parameter



[Initial state]

with all joint variables set to zero.

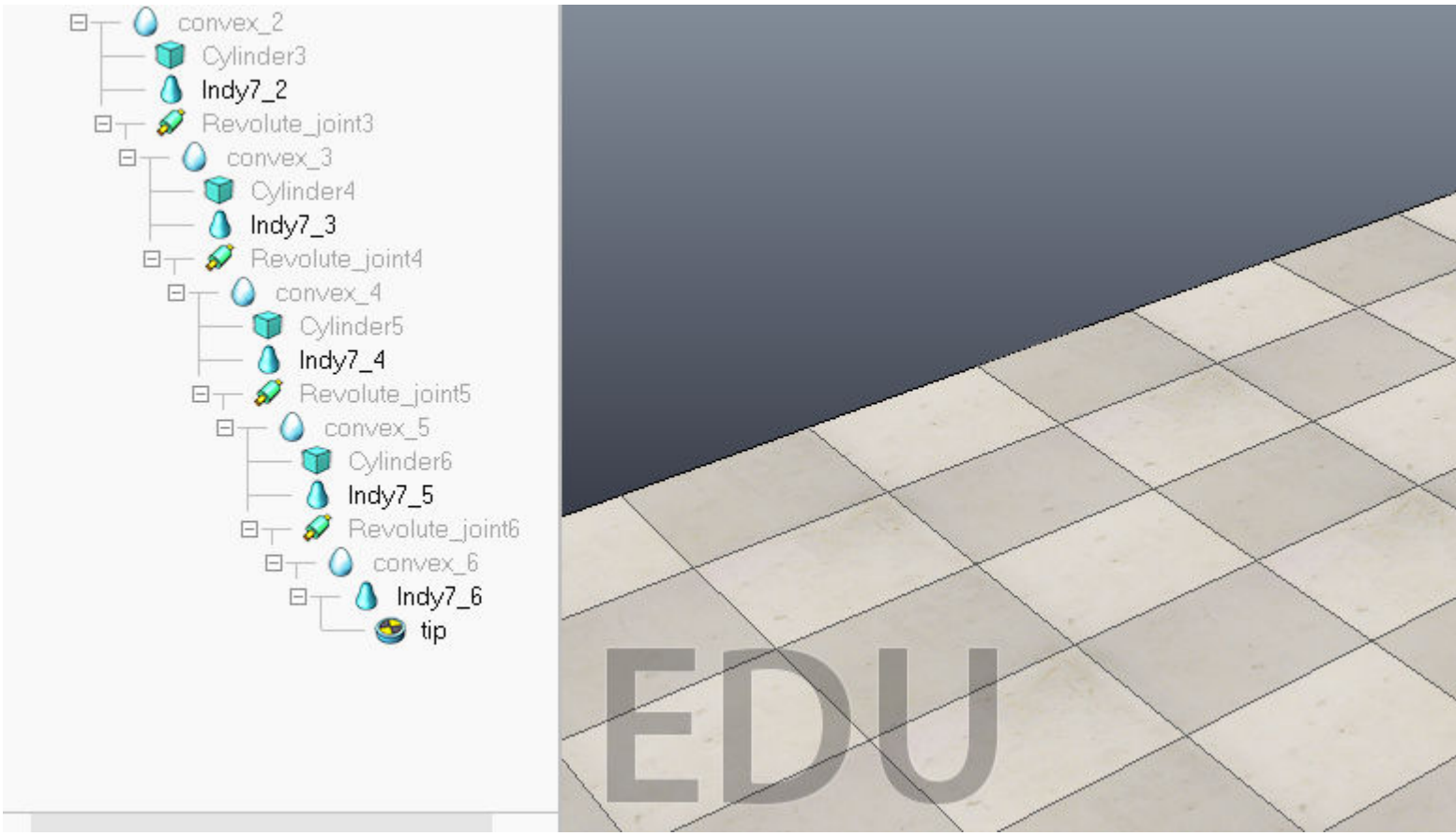
Xstart =

[[1 ,0, 0, 0];

[0, 1, 0, -W1+W2+W3-W4-W5];

[0, 0, 1, H1+L1+L2+H2+L3];

[0, 0, 0, 1]];



[Final state]

with theta 2 = pi/2.

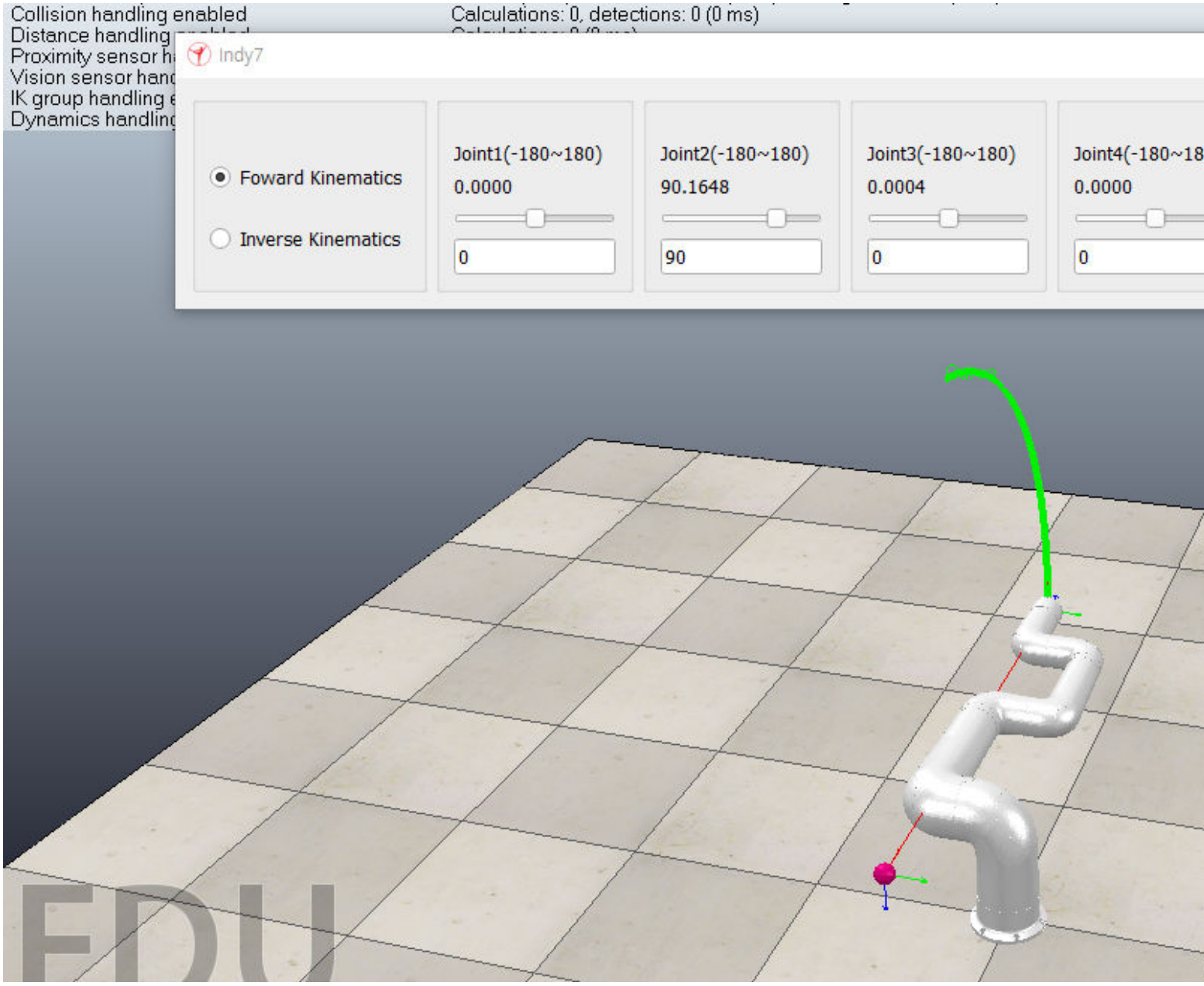
Xend =

[[0, 0, -1, -L1-L2-H2-L3];

[0, 1, 0, -W1+W2+W3-W4-W5];

[1, 0, 0, H1];

[0, 0, 0, 1]];



Implement with code.

And find the spatial screw axis.

These parameters are from above image.

```
clear; clc;

% length
L1 = 449.5 * 0.001;
L2 = 265.5 * 0.001;
L3 = 228 * 0.001;
H1 = 223 * 0.001;
H2 = 84.5 * 0.001;
W1 = 109.3 * 0.001;
```

```
W2 = 31.1 * 0.001;
W3 = 74.2 * 0.001;
W4 = 114.3 * 0.001;
W5 = 68.7 * 0.001;

% S list, screw axis list
Slist = [[0 ; 0; 1; 0; 0; 0;], ...
        [0; -1; 0; H1; 0; 0;], ...
        [0; -1; 0; L1+H1; 0; 0;], ...
        [0 ; 0; 1; -W1+W2+W3; 0; 0;], ...
        [0; -1; 0; H1+H2+L1+L2; 0; 0;], ...
        [0 ; 0; 1; -W1+W2+W3-W4-W5; 0; 0;]];

% Trajectory making
Xstart = [[1 ,0, 0, 0]; [0, 1, 0, -W1+W2+W3-W4-W5]; [0, 0, 1, H1+L1+L2+H2+L3]; [0, 0, 0, 1]];
Xend = [[0, 0, -1, -L1-L2-H2-L3]; [0, 1, 0, -W1+W2+W3-W4-W5]; [1, 0, 0, H1]; [0, 0, 0, 1]];
Tf = 4;
N = 100;
method = 3;
traj1 = CartesianTrajectory(Xstart, Xend, Tf, N, method);
traj2 = CartesianTrajectory(Xend, Xstart, Tf, N, method);
```

Here, traj1 is trajectroy starts from initial state to final state, and traj2 is trajectory for going back from final state to initial state.

We need to change the SE(3) matrix to joint variables.

For traj1

```
traj1thetalist = zeros(6, N);

% for trajectory making
M0 = Xstart;
thetalist0 = [0; 0; 0; 0; 0; 0;];
eomg = 0.01;
ev = 0.01;

for i = 1:N
    % create trajectory using IKinSpace.m
    T = cell2mat(traj1(i));

    [thetalist, success] = IKinSpace(Slist, M0, T, thetalist0, eomg, ev);

    if success == 1
        % update initial guess < -- previous step's result
        thetalist0 = thetalist;
        traj1thetalist(:, i) = thetalist;
    else
        traj1thetalist(:, i) = thetalist0;
```

```
        disp(i);
    end
end
```

For traj2

```
traj2thetalist = zeros(6, N);

M0 = Xstart;
% use thetalist from previous results.
eomg = 0.001;
ev = 0.0001;

% use Slist from previous results

for i = 1:N
    T = cell2mat(traj2(i));

    [thetalist, success] = IKinSpace(Slist, M0, T, thetalist0, eomg, ev);

    if success == 1
        % update initial guess < -- previous step's result
        thetalist0 = thetalist;
        traj2thetalist(:, i) = thetalist;
    else
        traj2thetalist(:, i) = thetalist0;
        disp(i);
    end
end
```

And change the trajectory from above

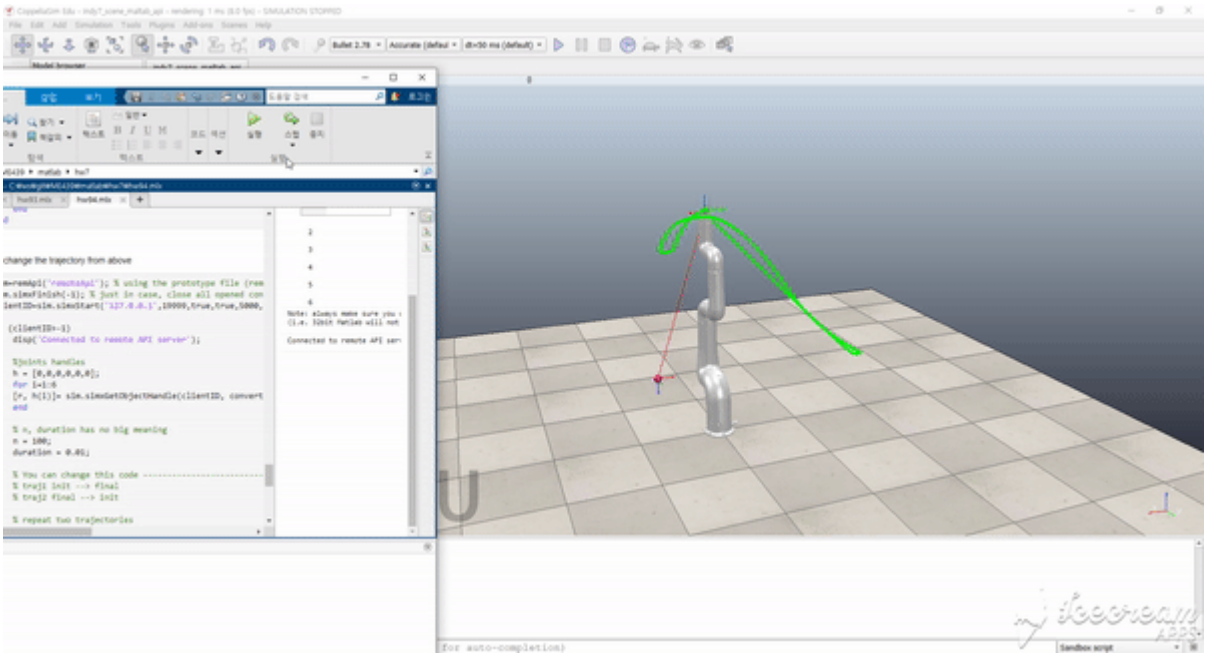
```
% sim=remApi('remoteApi'); % using the prototype file (remoteApiProto.m)
% sim.simxFinish(-1); % just in case, close all opened connections
% clientID=sim.simxStart('127.0.0.1',19999,true,true,5000,5);
%
% if (clientID>-1)
%     disp('Connected to remote API server');
%
%     %joints handles
%     h = [0,0,0,0,0,0];
%     for i=1:6
%     [r, h(i)]= sim.simxGetObjectHandle(clientID, convertStringsToChars("Revolute_joint"+strin
%     end
%
%     % n, duration has no big meaning
%     n = 100;
%     duration = 0.01;
%
%     % You can change this code ----------------------------------------
```

```
%     % traj1 init --> final
%     % traj2 final --> init
%
%     % repeat two trajectories
%     joint_pos_mat1 = traj1thetalist;
%     joint_pos_mat2 = traj2thetalist;
%
%
%     while true
%         for i=1:n
%             tstart = tic;
%             for j=1:6
%                 sim.simxSetJointTargetPosition(clientID, h(j), joint_pos_mat1(j, i), sim.simx
%             end
%             dt = toc(tstart);
%             if dt<duration
%                 pause(duration-dt);
%             end
%         end
%         pause(3);
%
%         for i=1:n
%             tstart = tic;
%             for j=1:6
%                 sim.simxSetJointTargetPosition(clientID, h(j), joint_pos_mat2(j, i), sim.simx
%             end
%             dt = toc(tstart);
%             if dt<duration
%                 pause(duration-dt);
%             end
%         end
%         pause(3);
%     end
%     % You can change this code ----------------------------------------
% else
%     disp('Failed connecting to remote API server');
% end
% sim.delete(); % call the destructor!
% disp('Program ended');
```

Result 1

실패한 결과이다.

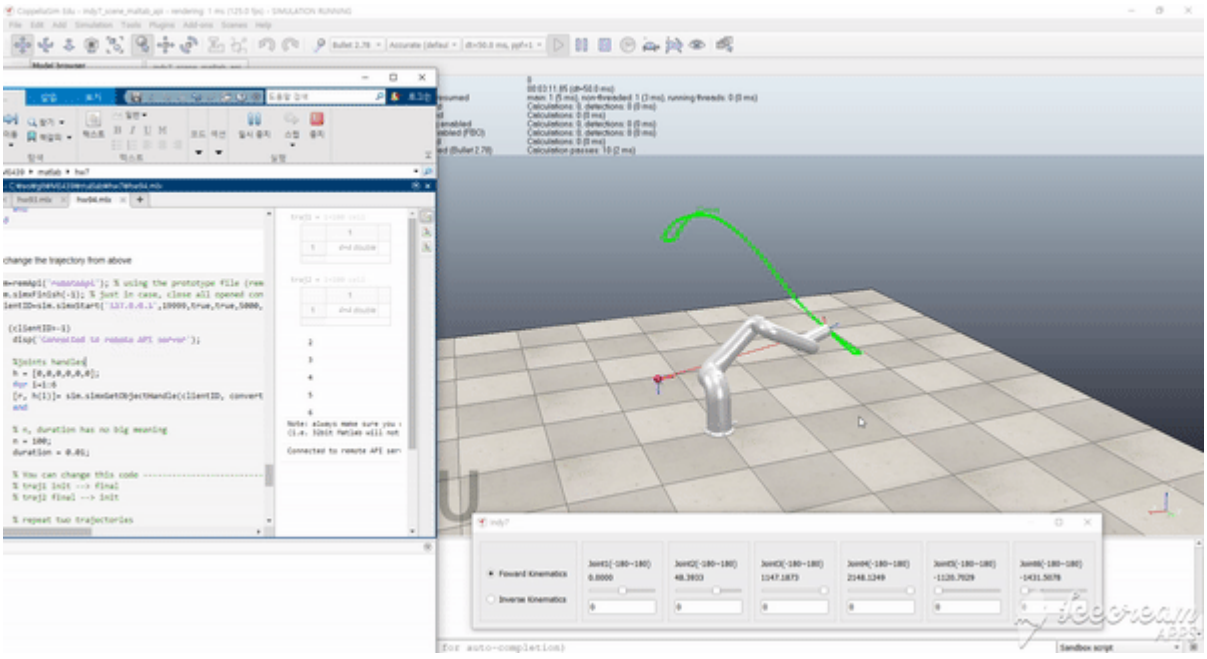
Results 2 참고해주세요!



Initially, robot tends to move randomly.

We predict this is because of jerk motion and other properties.

After a while trajectory looks like below.



When starting from initial condition, spiral motions are observated.

It might be caused from the singularity or jerk motion at the inital condition.

We can modify this problem by changing the interpolating time scaling to 5th order.

And if we observe we was able to see the angle difference more than 3.14 rad in one time step which is redundant.

ex)

thetalist =

-0.0000

-12.5479

31.3741

-0.0000

-18.8259

-0.0000

This means that the joint spin more than 1 time in each time steps.

We can reduce it to reduce singularity error.

Modified code

```
clear; clc;

% length
L1 = 449.5 * 0.001;
L2 = 265.5 * 0.001;
L3 = 228 * 0.001;
H1 = 223 * 0.001;
H2 = 84.5 * 0.001;
W1 = 109.3 * 0.001;
W2 = 31.1 * 0.001;
W3 = 74.2 * 0.001;
W4 = 114.3 * 0.001;
W5 = 68.7 * 0.001;
q1 = 111.5 * 0.001;
q2 = 70 * 0.001;
q3 = 220 * 0.001;
q4 = 150 * 0.001;
q5 = 192 * 0.001;
q6 = 210 * 0.001;
```

```
% S list, screw axis list
Slist = [[0 ; 0; 1; 0; 0; 0;], ...
        [0; -1; 0; H1; 0; 0;], ...
        [0; -1; 0; L1+H1; 0; 0;], ...
        [0 ; 0; 1; -W1+W2+W3; 0; 0;], ...
        [0; -1; 0; H1+H2+L1+L2; 0; 0;], ...
        [0 ; 0; 1; -W1+W2+W3-W4-W5; 0; 0;]];

% Trajectory making
Xstart = [[1 ,0, 0, 0]; [0, 1, 0, -W1+W2+W3-W4-W5]; [0, 0, 1, H1+L1+L2+H2+L3]; [0, 0, 0, 1]];

% Xend = [[0, 0, -1, -L1-L2-H2-L3]; [0, 1, 0, -W1+W2+W3-W4-W5]; [1, 0, 0, H1]; [0, 0, 0, 1]];
thetaend = [0; pi/2; 0; 0; 0; 0];
Xend = FKinSpace(Xstart,Slist,thetaend);

Tf = 4;
N = 200;
method = 5;
traj1 = CartesianTrajectory(Xstart, Xend, Tf, N, method)
```

```
traj1 = 1×200 cell
```

...

	1	2	3	4	5	6	7	8
1	4×4 double	4×4 double	4×4 double	4×4 double	4×4 double	4×4 double	4×4 double	4×4 double

```
traj2 = CartesianTrajectory(Xend, Xstart, Tf, N, method)
```

```
traj2 = 1×200 cell
```

...

	1	2	3	4	5	6	7	8
1	4×4 double	4×4 double	4×4 double	4×4 double	4×4 double	4×4 double	4×4 double	4×4 double

Convert to angle space.

For traj1

```
traj1thetalist = zeros(6, N);

% for trajectory making
M0 = Xstart;
thetalist0 = [0; 0; 0; 0; 0; 0;];
eomg = 0.001;
ev = 0.0001;

for i = 1:N
    % create trajectory using IKinSpace.m
    T = cell2mat(traj1(i));

    [thetalist, success] = IKinSpace(Slist, M0, T, thetalist0, eomg, ev);
```

```
    if success == 1
        % update initial guess < -- previous step's result
        for j = 1:6
            % error occurs, spin more than 2 * pi which means redundant
            % spins.
            if abs(thetalist0(j) - thetalist(j)) > 2 * pi
                if thetalist(j) < 0
                    % modular operation
                    thetalist0(j) = -1*mod(-thetalist(j), 2 * pi);
                    % ex) if the result of angle is 359 degree
                    % you can consider to spin -1 degree which is same.
                    % which can avoid singular error.
                    if thetalist0(j) < -pi
                        thetalist0(j)  = thetalist0(j) + 2*pi;
                    end
                else
                    thetalist0(j) = 1*mod(thetalist(j), 2 * pi);
                    if thetalist0(j) > pi
                        thetalist0(j)  = thetalist0(j) - 2*pi;
                    end
                end
            else
                thetalist0(j) = thetalist(j);
            end
        end

        traj1thetalist(:, i) = thetalist0;
    else
        traj1thetalist(:, i) = thetalist0;
        disp(i);
    end
end
```

For traj2

```
traj2thetalist = zeros(6, N);

M0 = Xstart;
% use thetalist from previous results.
eomg = 0.001;
ev = 0.0001;

% use Slist from previous results

for i = 1:N
    T = cell2mat(traj2(i));

    [thetalist, success] = IKinSpace(Slist, M0, T, thetalist0, eomg, ev);

    if success == 1
        % update initial guess < -- previous step's result
        for j = 1:6
```

```
            % error occurs
            if abs(thetalist0(j) - thetalist(j)) > 2 * pi
                if thetalist(j) < 0
                    thetalist0(j) = -1*mod(-thetalist(j), 2 * pi);
                    if thetalist0(j) < -pi
                        thetalist0(j)  = thetalist0(j) + 2*pi;
                    end
                else
                    thetalist0(j) = 1*mod(thetalist(j), 2 * pi);
                    if thetalist0(j) > pi
                        thetalist0(j)  = thetalist0(j) - 2*pi;
                    end
                end
            else
                thetalist0(j) = thetalist(j);
            end
        end

        traj2thetalist(:, i) = thetalist0;
    else
        traj2thetalist(:, i) = thetalist0;
        disp(i);
    end
end
```

And change the trajectory from above

```
sim=remApi('remoteApi'); % using the prototype file (remoteApiProto.m)
```

```
Note: always make sure you use the corresponding remoteApi library
(i.e. 32bit Matlab will not work with 64bit remoteApi, and vice-versa)
```

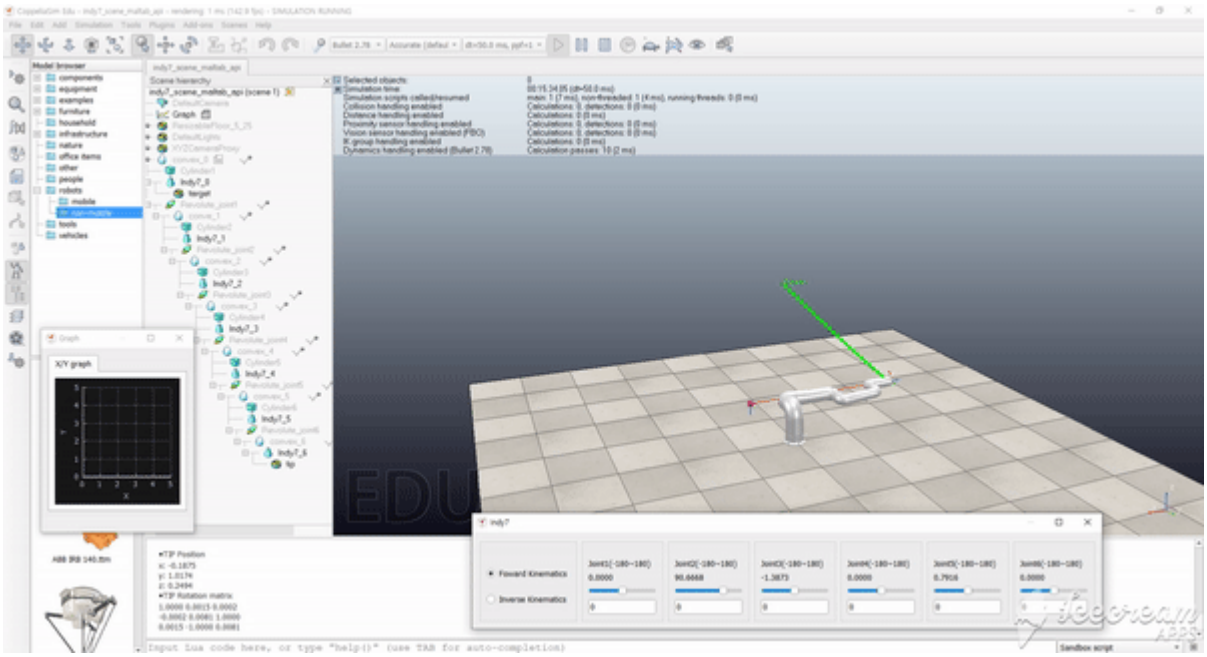
```
sim.simxFinish(-1); % just in case, close all opened connections
clientID=sim.simxStart('127.0.0.1',19999,true,true,5000,5);

if (clientID>-1)
    disp('Connected to remote API server');

    %joints handles
    h = [0,0,0,0,0,0];
    for i=1:6
    [r, h(i)]= sim.simxGetObjectHandle(clientID, convertStringsToChars("Revolute_joint"+string(
    end

    % n, duration has no big meaning
    n = N;
    duration = 0.01;

    % You can change this code ----------------------------------------
    % traj1 init --> final
    % traj2 final --> init
```

```
    % repeat two trajectories
    joint_pos_mat1 = traj1thetalist;
    joint_pos_mat2 = traj2thetalist;


    while true
        for i=1:n
            tstart = tic;
            for j=1:6
                sim.simxSetJointTargetPosition(clientID, h(j), joint_pos_mat1(j, i), sim.simx_
            end
            dt = toc(tstart);
            if dt<duration
                pause(duration-dt);
            end
        end
        pause(3);

        for i=1:n
            tstart = tic;
            for j=1:6
                sim.simxSetJointTargetPosition(clientID, h(j), joint_pos_mat2(j, i), sim.simx_
            end
            dt = toc(tstart);
            if dt<duration
                pause(duration-dt);
            end
        end
        pause(3);
    end
    % You can change this code ----------------------------------------
else
    disp('Failed connecting to remote API server');
end
```

```
Connected to remote API server
```

```
sim.delete(); % call the destructor!
disp('Program ended');
```

Results2



Now it follows straight line with no big error.