MAE C163B Project 3

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Contents

Jacobian Derivation

```
% VELOCITY PROPAGATION
close all; clear all; clc;

syms theta1 theta2 theta3 l1 l2 d1 d4

% Modified Denavit-Hartenberg (DH) parameters
alpha = [0, 0, 0, 0];
a = [0, l1, l2, 0];
d = [d1, 0, 0, -d4];
theta = [theta1, theta2, theta3, 0];
L(1) = Link('revolute', 'alpha', alpha(1), 'a', a(1), 'd', d(1), 'modified');
L(2) = Link('revolute', 'alpha', alpha(2), 'a', a(2), 'd', d(2), 'modified');
L(3) = Link('revolute', 'alpha', alpha(3), 'a', a(3), 'd', d(3), 'modified');
L(4) = Link('prismatic', 'alpha', alpha(4), 'a', a(4), 'theta', 0, 'modified');
scara_robot = SerialLink(L, 'name', 'scara_robot')

% Joint angles
syms theta1 theta2 theta3 d4
q = [theta1, theta2, theta3, d4];

% Transformation matrices
T01 = scara_robot.A(1, q);
T12 = scara_robot.A(2, q);
T23 = scara_robot.A(3, q);
T34 = scara_robot.A(4, q);
T04 = scara_robot.A([1 2 3 4], q);
T04 = simplify(T04)

% Calculate rotation matrices and positions for each link
[R01, P01] = tr2rt(T01);
[R12, P12] = tr2rt(T12);
[R23, P23] = tr2rt(T23);
[R34, P34] = tr2rt(T34);
[R10, ~] = tr2rt(inv(T01));
[R21, ~] = tr2rt(inv(T12));
[R32, ~] = tr2rt(inv(T23));
[R43, ~] = tr2rt(inv(T34));
[R04, P04] = tr2rt(T04);
[R02, P02] = tr2rt(simplify(T01*T12));
[R03, P03] = tr2rt(simplify(T01*T12*T23));

% Define joint velocities
syms dq1 dq2 dq3 dd4
dq = [dq1; dq2; dq3; dd4];

% Calculate angular velocities for each frame
w00 = [0; 0; 0];
w11 = simplify(R10*w00 + [0; 0; dq1]);
w22 = simplify(R21*w11 + [0; 0; dq2]);
w33 = simplify(R32*w22 + [0; 0; dq3]);
w44 = simplify(R43*w33 + [0; 0; 0]);

% Define velocities for frame {0}
v0 = [0; 0; 0];

% Calculate velocities for each link
v01 = cross(w00, P01) + v0;
v11 = simplify(R10*v01);
v12 = cross(w11, P12) + v11;
v22 = simplify(R21*v12);
v23 = cross(w22, P23) + v22;
v33 = simplify(R32*v23);
v34 = cross(w33, P34) + v33;
v44 = simplify(R43*v34 + [0; 0; dd4]);

% Calculate the Jacobian matrix
JV4 = simplify(jacobian(v44, dq)); % Linear velocity
JW4 = simplify(jacobian(w44, dq)); % Angular velocity
J4_VP = simplify([JV4; JW4]) % Combined velocity
```

```
% Jacobian expressed in frame {0}
JT = [R04, zeros(3,3);zeros(3,3), R04];
J0_VP = simplify(JT * J4_VP)

% FORCE PROPAGATION
syms f_x f_y f_z n_x n_y n_z
f_end = [f_x f_y f_z n_x n_y n_z];
f4 = [f_x;f_y;f_z];
f3 = R34 * f4;
f2 = R23 * f3;
f1 = R12 * f2; f1 = simplify(collect(f1, f_end));
n4 = [n_x; n_y; n_z];
n3 = R34*n4 + cross(P34,f3); n3 = simplify(collect(n3, f_end));
n2 = R23*n3 + cross(P23,f2); n2 = simplify(collect(n2, f_end));
n1 = R12*n2 + cross(P12,f1); n1 = simplify(collect(n1, f_end));

% Torque Matrix
tq1 = collect(transpose(n1) * [0;0;1], [f_x f_y f_z n_x n_y n_z]);
tq2 = collect(transpose(n2) * [0;0;1], [f_x f_y f_z n_x n_y n_z]);
tq3 = collect(transpose(n3) * [0;0;1], [f_x f_y f_z n_x n_y n_z]);
tq4 = collect(transpose(f4) * [0;0;1], [f_x f_y f_z n_x n_y n_z]);
TQ1 = equationsToMatrix(tq1, [f_x f_y f_z n_x n_y n_z]);
TQ2 = equationsToMatrix(tq2, [f_x f_y f_z n_x n_y n_z]);
TQ3 = equationsToMatrix(tq3, [f_x f_y f_z n_x n_y n_z]);
TQ4 = equationsToMatrix(tq4, [f_x f_y f_z n_x n_y n_z]);
JT = [R04, zeros(3,3); zeros(3,3), R04];
J4_FP_T = [TQ1; TQ2; TQ3; TQ4];
J4_FP = transpose(J4_FP_T);
J4_FP = simplify(JT * J4_FP)

% EXPLICIT METHOD
Jxyz1 = diff(P04, theta1);
Jxyz2 = diff(P04, theta2);
Jxyz3 = diff(P04, theta3);
Jxyz4 = diff(P04, d4);
Jxyz = [Jxyz1 Jxyz2 Jxyz3 Jxyz4];
Orn = [0; 0; theta1 + theta2 + theta3]; % roll pitch yaw
JOrn1 = diff(Orn, theta1); % derivative of rpy wrp theta 1
JOrn2 = diff(Orn, theta2);
JOrn3 = diff(Orn, theta3);
JOrn4 = diff(Orn, d4);
JOrn = [JOrn1 JOrn2 JOrn3 JOrn4];
Jdiff = [Jxyz; JOrn]

% Using Siciliano
Jxyzs1 = cross(R01(:,3), P04 - P01);
Jxyzs2 = cross(R02(:,3), P04 - P02);
Jxyzs3 = cross(R03(:,3), P04 - P03);
Jxyzs4 = R04(:,3);
Jxyzs = [Jxyzs1 Jxyzs2 Jxyzs3 Jxyzs4];
JOrns1 = R01(:,3);
JOrns2 = R02(:,3);
JOrns3 = R03(:,3);
JOrns4 = zeros(3,1);
JOrns = [JOrns1 JOrns2 JOrns3 JOrns4];
Jdiffs = [Jxyzs; JOrns]
```

```
scara_robot =

scara_robot:: 4 axis, RRRP, modDH, slowRNE, Symbolic
+---+-----------+-----------+-----------+-----------+-----------+
| j |     theta |         d |         a |     alpha |    offset |
+---+-----------+-----------+-----------+-----------+-----------+
|  1|         q1|         d1|          0|          0|          0|
|  2|         q2|          0|         l1|          0|          0|
|  3|         q3|          0|         l2|          0|          0|
|  4|          0|         q4|          0|          0|          0|
+---+-----------+-----------+-----------+-----------+-----------+


[cos(theta1 + theta2 + theta3), -sin(theta1 + theta2 + theta3), 0, l2*cos(theta1 + theta2) + l1*cos(theta1)]
[sin(theta1 + theta2 + theta3),  cos(theta1 + theta2 + theta3), 0, l2*sin(theta1 + theta2) + l1*sin(theta1)]
[                            0,                              0, 1,                                 d1 + d4]
[                            0,                              0, 0,                                      1]


J4_VP =

[sin(conj(theta3))*(l2 + l1*cos(conj(theta2))) + l1*cos(conj(theta3))*sin(conj(theta2)), l2*sin(conj(theta3)), 0, 0]
[cos(conj(theta3))*(l2 + l1*cos(conj(theta2))) - l1*sin(conj(theta2))*sin(conj(theta3)), l2*cos(conj(theta3)), 0, 0]
[                                                                                    0,                    0, 0, 1]
[                                                                                    0,                    0, 0, 0]
[                                                                                    0,                    0, 0, 0]
[                                                                                    1,                    1, 1, 0]
```

```
J0_VP =

[cos(theta1 + theta2 + theta3)*(sin(conj(theta3))*(l2 + l1*cos(conj(theta2))) + l1*cos(conj(theta3))*sin(conj(theta2))) - sin(theta1 + theta2 + theta3)*(cos(conj(th
[cos(theta1 + theta2 + theta3)*(cos(conj(theta3))*(l2 + l1*cos(conj(theta2))) - l1*sin(conj(theta2))*sin(conj(theta3))) + sin(theta1 + theta2 + theta3)*(sin(conj(th
[
[
[
[


J4_FP =

[- l2*sin(theta1 + theta2) - l1*sin(theta1), -l2*sin(theta1 + theta2), 0, 0]
[  l2*cos(theta1 + theta2) + l1*cos(theta1),  l2*cos(theta1 + theta2), 0, 0]
[                                        0,                        0, 0, 1]
[                                        0,                        0, 0, 0]
[                                        0,                        0, 0, 0]
[                                        1,                        1, 1, 0]


Jdiff =

[- l2*sin(theta1 + theta2) - l1*sin(theta1), -l2*sin(theta1 + theta2), 0, 0]
[  l2*cos(theta1 + theta2) + l1*cos(theta1),  l2*cos(theta1 + theta2), 0, 0]
[                                        0,                        0, 0, 1]
[                                        0,                        0, 0, 0]
[                                        0,                        0, 0, 0]
[                                        1,                        1, 1, 0]


Jdiffs =

[- l2*sin(theta1 + theta2) - l1*sin(theta1), -l2*sin(theta1 + theta2), 0, 0]
[  l2*cos(theta1 + theta2) + l1*cos(theta1),  l2*cos(theta1 + theta2), 0, 0]
[                                        0,                        0, 0, 1]
[                                        0,                        0, 0, 0]
[                                        0,                        0, 0, 0]
[                                        1,                        1, 1, 0]
```

Singularities

```
% POSE DEFINITION
J_reduced = [Jdiff(1:3,: ); Jdiff(6,:)];
find_singularity = simplify(det(J_reduced));
sol1 = solve(find_singularity == 0, theta2)
sol2 = solve([find_singularity == 0, theta2 ~= sol1], theta2)
sol3 = solve([find_singularity == 0, theta2 ~= sol1, theta2 ~= sol2], theta2)

% IMPLICATIONS
% The following are the implications of the singular configuration:
% 1) The manipulator loses one degree of freedom.
%    As a result, the end effector can only move along the tangent direction of the arm.
%    Movement along the radial direction is not possible.
% 2) In this singular configuration,
%    it is possible to apply a finite force to the end effector that does not produce any torque at the robot's joints.
%    Consequently, the manipulator can "lock up."
% 3) The determinant of the Jacobian matrix is zero.
% 4) theta2 = -pi so the manipulator folds back from the other direction
```

```
sol1 =

0


sol2 =

pi


sol3 =

-pi
```

Jacobian Ellipsoid

```
% From TA posted code:
close all; clear all; clc;
```

```
syms l1 l2 theta1 theta2
alpha = [0, 0];
a = [l1, l2];
d = [0, 0];
L(1) = Link('revolute', 'alpha', alpha(1), 'a', a(1), 'd', d(1), 'standard');
L(2) = Link('revolute', 'alpha', alpha(2), 'a', a(2), 'd', d(2), 'standard');
RR_robot = SerialLink(L, 'name', 'RR_robot');

% Define Jacobian Matrix
q_sym = [theta1 theta2];
T01 = RR_robot.A(1, q_sym);
T12 = RR_robot.A(2, q_sym);
T02 = simplify(T01*T12);
[R01, P01] = tr2rt(T01); R10 = transpose(R01);
[R12, P12] = tr2rt(T12); R21 = transpose(R12);
[R02, P02] = tr2rt(simplify(T01*T12));
Jxyz1 = diff(P02, theta1);
Jxyz2 = diff(P02, theta2);
Jxyz = [Jxyz1 Jxyz2];
roll = 0;
pitch = 0;
yaw = theta1 + theta2;
Orn = [roll; pitch; yaw];
JOrn1 = diff(Orn, theta1);
JOrn2 = diff(Orn, theta2);
JOrn = [JOrn1 JOrn2];
Jdiff = [Jxyz; JOrn]

% Define eigenvalues and eigenvectors for each config

% Config 1: L1 = 0.25, L2 = 0.75
config1 = subs(Jdiff, [l1,l2,theta1,theta2], [0.25, 0.75, 0, 0]);
% Get reduced Jacobian
Jconfig1 = config1(1:2, 1:2)
Jconfig1_T = transpose(Jconfig1);
% Get V1 and D1
[V1,D1] = eig(Jconfig1*Jconfig1_T)

% Config 2: L1 = 0.5, L2 = 0.5
config2 = subs(Jdiff, [l1,l2,theta1,theta2], [0.5, 0.5, 0, 0]);
% Get reduced Jacobian
Jconfig2 = config2(1:2, 1:2)
Jconfig2_T = transpose(Jconfig2);
% Get V2 and D2
[V2,D2] = eig(Jconfig2*Jconfig2_T)

% Config 3: L1 = 0.75, L2 = 0.25
config3 = subs(Jdiff, [l1,l2,theta1,theta2], [0.75, 0.25, 0, 0]);
% Get reduced Jacobian
Jconfig3 = config3(1:2, 1:2)
Jconfig3_T = transpose(Jconfig3);
% Get V3 and D3
[V3,D3] = eig(Jconfig3*Jconfig3_T)

% Plot

% Config 1
alpha = [0, 0];
a = [0.25, 0.75];
d = [0, 0];

L(1) = Link('revolute', 'alpha', alpha(1), 'a', a(1), 'd', d(1), 'standard');
L(2) = Link('revolute', 'alpha', alpha(2), 'a', a(2), 'd', d(2), 'standard');

RR_robot = SerialLink(L, 'name', 'RR_robot');

% can reach from 0.5 to 1
q1 = zeros(6,2);
% to reach x = 0.5, theta1 = pi, theta2 = 0
q1(1,:) = [pi, 0];
% to reach x = 1, theta1 = 0, theta2 = 0
q1(6,:) = [0, 0];

for i = 2:5
q1(i,:) = ik(0.25, 0.75, 0.5+(i-1)*0.1);
figure(i-1);
xlim([-inf inf]);
ylim([-inf inf]);
zlim([-inf inf]);
RR_robot.plot(q1(i,:))
RR_robot.fellipse(q1(i,:))
RR_robot.vellipse(q1(i,:))
% saveas(figure(i-1),sprintf('config1_%d.jpg',i-1))
end

% Config 2
alpha = [0, 0];
```

```
a = [0.5, 0.5];
d = [0, 0];

L(1) = Link('revolute', 'alpha', alpha(1), 'a', a(1), 'd', d(1), 'standard');
L(2) = Link('revolute', 'alpha', alpha(2), 'a', a(2), 'd', d(2), 'standard');

RR_robot2 = SerialLink(L, 'name', 'RR_robot');

% can reach from 0 to 1
q2 = zeros(11,2);
% to reach x = 0, theta1 = 0, theta2 = pi
q2(1,:) = [0, pi];
% to reach x = 1, theta1 = 0, theta2 = 0
q2(11,:) = [0, 0];

for i = 2:10
q2(i,:) = ik(0.5, 0.5, (i-1)*0.1);
figure(i-1);
xlim([-inf inf]);
ylim([-inf inf]);
zlim([-inf inf]);
RR_robot2.plot(q2(i,:))
RR_robot2.fellipse(q2(i,:))
RR_robot2.vellipse(q2(i,:))
% saveas(figure(i-1),sprintf('config2_%d.jpg',i-1))
end

% Config 3
alpha = [0, 0];
a = [0.75, 0.25];
d = [0, 0];
L(1) = Link('revolute', 'alpha', alpha(1), 'a', a(1), 'd', d(1), 'standard');
L(2) = Link('revolute', 'alpha', alpha(2), 'a', a(2), 'd', d(2), 'standard');

RR_robot3 = SerialLink(L, 'name', 'RR_robot');

% can reach from 0.5 to 1
q3 = zeros(6,2);
% to reach x = 0, theta1 = 0, theta2 = pi
q3(1,:) = [0, pi];
% to reach x = 1, theta1 = 0, theta2 = 0
q3(6,:) = [0, 0];

for i = 2:5
 q3(i,:) = ik(0.75, 0.25, 0.5+(i-1)*0.1);
 figure(i-1);
 xlim([-inf inf]);
 ylim([-inf inf]);
 zlim([-inf inf]);
 RR_robot3.plot(q3(i,:))
 RR_robot3.fellipse(q3(i,:))
 RR_robot3.vellipse(q3(i,:))
%  saveas(figure(i-1),sprintf('config3_%d.jpg',i-1))
end

% Best position for configurations

% Config 1
w1 = zeros(1, 4);
for i = 6:9
    w1(1, i-5) = w_func(0.25, 0.75, i*0.1);
end

max = w1(1,1);
for i = 1:4
if w1(1,i) > max
max = w1(1,i);
end
end
pos = find(w1 == max)

% ANSWER: best position for configuration 1 is x = 0.8

% Config 2
w2 = zeros(1, 9);
for i = 1:9
w2(1, i) = w_func(0.5, 0.5, i*0.1);
end

max = w2(1,1);
for i = 1:9
if w2(1,i) > max
max = w2(1,i);
end
end
pos = find(w2 == max)
```

```
% ANSWER: best position for configuration 2 is x = 0.7

% Config 3
w3 = zeros(1, 4);
for i = 6:9
 w3(1, i-5) = w_func(0.75, 0.25, i*0.1);
end
max = w3(1,1);
for i = 1:4
 if w3(1,i) > max
 max = w3(1,i);
 end
end
pos = find(w3 == max)

% ANSWER: best position for configuration 3 is x = 0.8
```

```
Jdiff =

[- l2*sin(theta1 + theta2) - l1*sin(theta1), -l2*sin(theta1 + theta2)]
[  l2*cos(theta1 + theta2) + l1*cos(theta1),  l2*cos(theta1 + theta2)]
[                                        0,                        0]
[                                        0,                        0]
[                                        0,                        0]
[                                        1,                        1]


Jconfig1 =

[0,   0]
[1, 3/4]


V1 =

[1, 0]
[0, 1]


D1 =

[0,     0]
[0, 25/16]


Jconfig2 =

[0,   0]
[1, 1/2]


V2 =

[1, 0]
[0, 1]


D2 =

[0,   0]
[0, 5/4]


Jconfig3 =

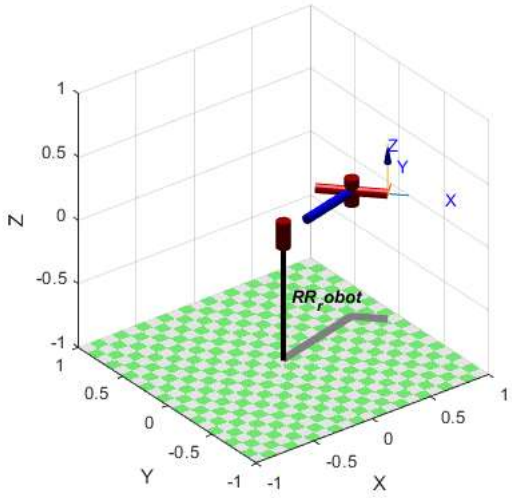
[0,   0]
[1, 1/4]

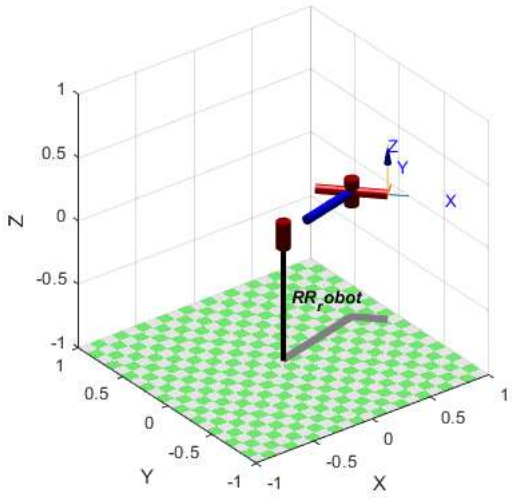

V3 =

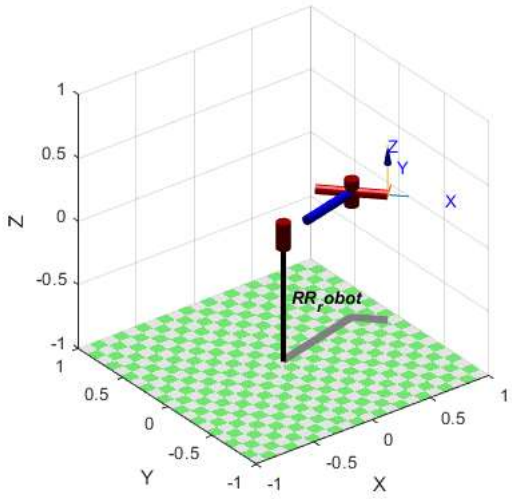
[1, 0]
[0, 1]

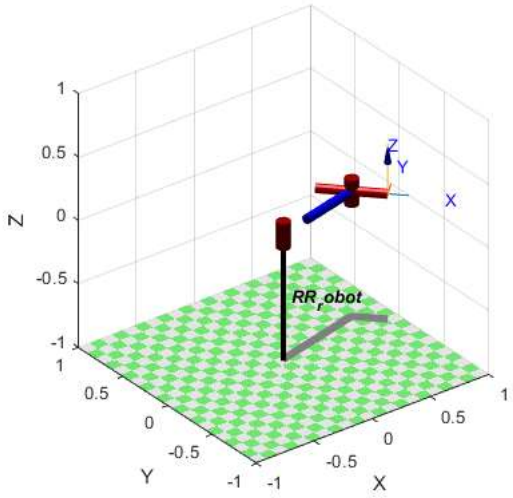

D3 =

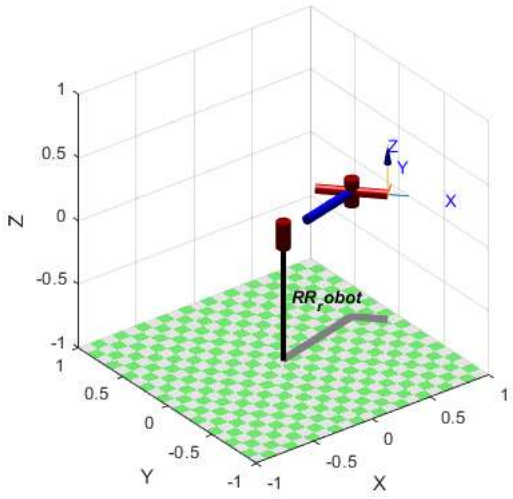
[0,     0]
[0, 17/16]
```

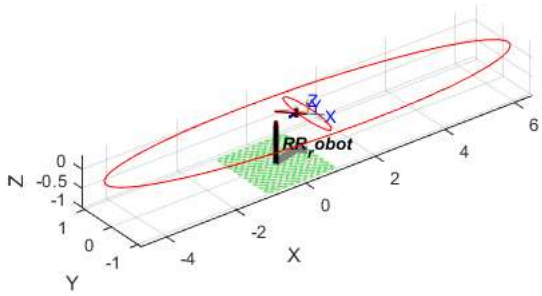

RRrobot
Z
Y
X

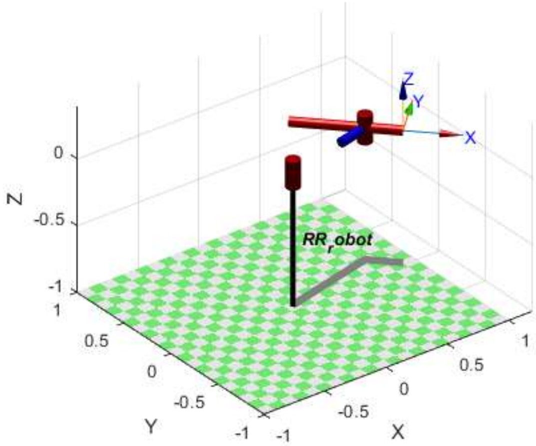

RRrobot
Z
Y
X

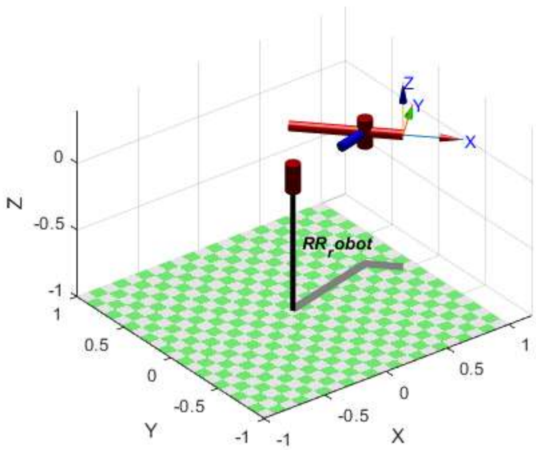

RRrobot
Z
Y
X

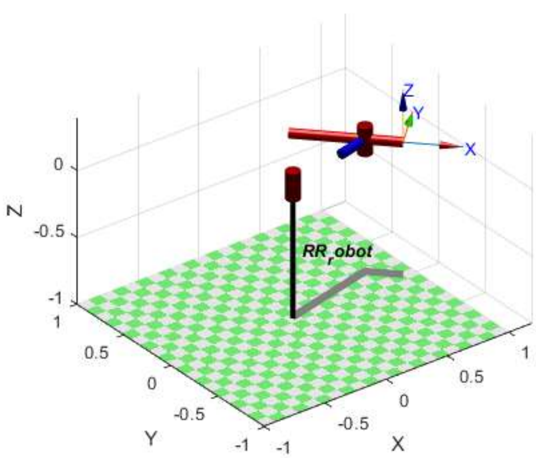

RRrobot
Z
Y
X


RRrobot
Z
Y
X


RRrobot
Z
Y
X







Arm Optimization

```
close all; clear all; clc;

% Brute Force
syms th1 th2 th3 L1 L2
% Modified DH parameters
```

```
alpha = [0, 0, 0, 0];
a = [0, L1, L2, 0];
d = [0.4, 0, 0, -0.15];
th = [th1, th2, th3, 0];
L(1) = Link('revolute', 'alpha', alpha(1), 'a', a(1), 'd', d(1), 'modified');
L(2) = Link('revolute', 'alpha', alpha(2), 'a', a(2), 'd', d(2), 'modified');
L(3) = Link('revolute', 'alpha', alpha(3), 'a', a(3), 'd', d(3), 'modified');
L(4) = Link('prismatic', 'alpha', alpha(4), 'a', a(4), 'theta', 0, 'modified');
SCARA = SerialLink(L, 'name', 'SCARA')

% Joint angle
syms q1 q2 q3 d4
q = [q1 q2 q3 0.15];
% Transformations, rotations, translations
T01 = SCARA.A(1,q);
T12 = SCARA.A(2,q);
T23 = SCARA.A(3,q);
T34 = SCARA.A(4,q);
T04 = SCARA.A([1 2 3 4],q);
T04 = simplify(T04)

[R01, P01] = tr2rt(T01); R10 = transpose(R01);
[R12, P12] = tr2rt(T12); R21 = transpose(R12);
[R23, P23] = tr2rt(T23); R32 = transpose(R23);
[R34, P34] = tr2rt(T34); R43 = transpose(R34);
[R04, P04] = tr2rt(T04);
[R02, P02] = tr2rt(simplify(T01*T12));
[R03, P03] = tr2rt(simplify(T01*T12*T23));
Jxyzs1 = cross(R01(:,3), P04 - P01);
Jxyzs2 = cross(R02(:,3), P04 - P02);
Jxyzs3 = cross(R03(:,3), P04 - P03);
Jxyzs4 = R04(:,3);
Jxyzs = [Jxyzs1 Jxyzs2 Jxyzs3 Jxyzs4]

JOrns1 = R01(:,3);
JOrns2 = R02(:,3);
JOrns3 = R03(:,3);
JOrns4 = zeros(3,1);
JOrns = [JOrns1 JOrns2 JOrns3 JOrns4];
Jdiffs = [Jxyzs; JOrns];
J0 = [Jdiffs(1:2,1:3); Jdiffs(6,1:3)]

J0T = transpose(J0);
JJT = simplify(J0*J0T)

l1 = [0.01:0.01:0.5];
l2 = [0.01:0.01:0.5];
h = 0.1;
w = 0.14;
d = 0.2;
count = 0;
kappa_array = [];
C= [];
l1_plot = [];
l2_plot = [];
X= linspace(d, d+w, 15);
Y= linspace(-h/2, h/2, 11);
for i=1:length(l1)
    for j=1:length(l2)
        kappa_array = [];
        if (abs(l1(i)-l2(j)) < d) && (l1(i)+l2(j) > ((d+w)^2 + (h/2)^2)^0.5)
            count = count+1;
            for m=1:length(X)
                for n=1:length(Y)
                    [theta] = inverseKinematicsScara3(X(m), Y(n), l1(i), l2(j));
                    JJTsubs = subs(JJT, [q1, q2, L1, L2], [theta(1), theta(2), l1(i), l2(j)]);
                    JJTsubs = vpa(JJTsubs);
                    lambda = eig(JJTsubs);
                    lambda_max = max(lambda);
                    lambda_min = min(lambda);
                    kappa = vpa((lambda_min/lambda_max)^0.5);
                    kappa_array = [kappa_array; kappa];
                end
            end
            C(count) = (sum(kappa_array)*min(kappa_array))/(l1(i)^3 + l2(j)^3);
            l1_plot(count) = l1(i);
            l2_plot(count) = l2(j);
            fprintf('Count = %d \t C-Value = %f \n',count, C(count));
        end
    end
end


% Plot values of Goal function
scatter3(l1_plot,l2_plot,C, 'filled', 'MarkerEdgeColor','k','MarkerFaceColor',[0 .75 .75])
xlabel('L1', 'FontWeight','bold')
ylabel('L2', 'FontWeight','bold')
```

```
zlabel('C', 'FontWeight','bold')

% Find optimal values
[Cmax,Imax] = max(C)
L1_max = l1_plot(Imax)
L2_max = l2_plot(Imax)

% Plot value of Ki for entire workspace for best and worst combinations
kappa_max = [];
for m=1:length(X)
    for n=1:length(Y)
        [theta] = inverseKinematicsScara3(X(m), Y(n), L1_max, L2_max);
        JJTsubs = subs(JJT, [q1, q2, L1, L2], [theta(1), theta(2), L1_max, L2_max]);
        JJTsubs = vpa(JJTsubs);
        lambda = eig(JJTsubs);
        lambda_max = max(lambda);
        lambda_min = min(lambda);
        kappa = vpa((lambda_min/lambda_max)^0.5);
        kappa_max(m,n) = kappa;
    end
end

surf(X,Y, kappa_max')
xlabel('X(m)', 'FontWeight','bold')
ylabel('Y(m)', 'FontWeight','bold')
zlabel('K', 'FontWeight','bold', 'FontSize', 14)

% Here, we can see that the plot is symmetric
% Based on the C_max, the best manipulability point is at x = 0.24
% while the worst manipulability point is at x = 0.20
```

```
SCARA =

SCARA:: 4 axis, RRRP, modDH, slowRNE, Symbolic
+---+-----------+-----------+-----------+-----------+-----------+
| j |     theta |         d |         a |     alpha |    offset |
+---+-----------+-----------+-----------+-----------+-----------+
|  1|         q1|        0.4|          0|          0|          0|
|  2|         q2|          0|         L1|          0|          0|
|  3|         q3|          0|         L2|          0|          0|
|  4|          0|         q4|          0|          0|          0|
+---+-----------+-----------+-----------+-----------+-----------+


[cos(q1 + q2 + q3), -sin(q1 + q2 + q3), 0, L2*cos(q1 + q2) + L1*cos(q1)]
[sin(q1 + q2 + q3),  cos(q1 + q2 + q3), 0, L2*sin(q1 + q2) + L1*sin(q1)]
[                0,                  0, 1,                        11/20]
[                0,                  0, 0,                            1]


Jxyzs =

[- L2*sin(q1 + q2) - L1*sin(q1), -L2*sin(q1 + q2), 0, 0]
[  L2*cos(q1 + q2) + L1*cos(q1),  L2*cos(q1 + q2), 0, 0]
[                             0,                0, 0, 1]


J0 =

[- L2*sin(q1 + q2) - L1*sin(q1), -L2*sin(q1 + q2), 0]
[  L2*cos(q1 + q2) + L1*cos(q1),  L2*cos(q1 + q2), 0]
[                             1,                1, 1]


JJT =

[             L2^2*sin(q1 + q2)^2 + (L2*sin(q1 + q2) + L1*sin(q1))^2, - sin(2*q1 + 2*q2)*L2^2 - L1*sin(2*q1 + q2)*L2 - (L1^2*sin(2*q1))/2, - 2*L2*sin(q1 + q2) - L1*
[- sin(2*q1 + 2*q2)*L2^2 - L1*sin(2*q1 + q2)*L2 - (L1^2*sin(2*q1))/2,              L2^2*cos(q1 + q2)^2 + (L2*cos(q1 + q2) + L1*cos(q1))^2,   2*L2*cos(q1 + q2) + L1*
[                                  - 2*L2*sin(q1 + q2) - L1*sin(q1),                                        2*L2*cos(q1 + q2) + L1*cos(q1),

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Count = 14      C-Value = 8.093066
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Count = 1034 C-Value = 7.976670
Count = 1035 C-Value = 7.870724
Count = 1036 C-Value = 7.717788
Count = 1037 C-Value = 7.522629
Count = 1038 C-Value = 7.290222
Count = 1039 C-Value = 7.025601
Count = 1040 C-Value = 6.733719
Count = 1041 C-Value = 6.419335
Count = 1042 C-Value = 6.086922
Count = 1043 C-Value = 0.000000
Count = 1044 C-Value = 1.905146
Count = 1045 C-Value = 2.834606
Count = 1046 C-Value = 3.606475
Count = 1047 C-Value = 4.284126
Count = 1048 C-Value = 4.887546
Count = 1049 C-Value = 5.424504
Count = 1050 C-Value = 5.898159
Count = 1051 C-Value = 6.309753
Count = 1052 C-Value = 6.659786
Count = 1053 C-Value = 6.948611
Count = 1054 C-Value = 7.176771
Count = 1055 C-Value = 7.345191
Count = 1056 C-Value = 7.455302
Count = 1057 C-Value = 7.509094
Count = 1058 C-Value = 7.509136
Count = 1059 C-Value = 7.458548

```
Count = 1060     C-Value = 7.360938
Count = 1061     C-Value = 7.220312
Count = 1062     C-Value = 7.040958
Count = 1063     C-Value = 6.827327
Count = 1064     C-Value = 6.583912
Count = 1065     C-Value = 6.315129
Count = 1066     C-Value = 6.025233
Count = 1067     C-Value = 0.000000
Count = 1068     C-Value = 1.803595
Count = 1069     C-Value = 2.679622
Count = 1070     C-Value = 3.404693
Count = 1071     C-Value = 4.039356
Count = 1072     C-Value = 4.602934
Count = 1073     C-Value = 5.103140
Count = 1074     C-Value = 5.543297
Count = 1075     C-Value = 5.924896
Count = 1076     C-Value = 6.248705
Count = 1077     C-Value = 6.515330
Count = 1078     C-Value = 6.725524
Count = 1079     C-Value = 6.880364
Count = 1080     C-Value = 6.981357
Count = 1081     C-Value = 7.030483
Count = 1082     C-Value = 7.030207
Count = 1083     C-Value = 6.983452
Count = 1084     C-Value = 6.893539
Count = 1085     C-Value = 6.764115
Count = 1086     C-Value = 6.599050
Count = 1087     C-Value = 6.402343
Count = 1088     C-Value = 6.178018
Count = 1089     C-Value = 5.930037
Count = 1090     C-Value = 0.000000
Count = 1091     C-Value = 1.707679
Count = 1092     C-Value = 2.533725
Count = 1093     C-Value = 3.215323
Count = 1094     C-Value = 3.810288
Count = 1095     C-Value = 4.337278
Count = 1096     C-Value = 4.803911
Count = 1097     C-Value = 5.213627
Count = 1098     C-Value = 5.568108
Count = 1099     C-Value = 5.868336
Count = 1100     C-Value = 6.115114
Count = 1101     C-Value = 6.309354
Count = 1102     C-Value = 6.452237
Count = 1103     C-Value = 6.545308
Count = 1104     C-Value = 6.590510
Count = 1105     C-Value = 6.590196
Count = 1106     C-Value = 6.547093
Count = 1107     C-Value = 6.464264
Count = 1108     C-Value = 6.345031
Count = 1109     C-Value = 6.192899
Count = 1110     C-Value = 6.011473
Count = 1111     C-Value = 5.804377
Count = 1112     C-Value = 1.617206
Count = 1113     C-Value = 2.396525
Count = 1114     C-Value = 3.037736
Count = 1115     C-Value = 3.596027
Count = 1116     C-Value = 4.089389
Count = 1117     C-Value = 4.525315
Count = 1118     C-Value = 4.907318
Count = 1119     C-Value = 5.237230
Count = 1120     C-Value = 5.516197
Count = 1121     C-Value = 5.745172
Count = 1122     C-Value = 5.925184
Count = 1123     C-Value = 6.057483
Count = 1124     C-Value = 6.143623
Count = 1125     C-Value = 6.185493
Count = 1126     C-Value = 6.185327
Count = 1127     C-Value = 6.145670
Count = 1128     C-Value = 6.069344
Count = 1129     C-Value = 5.959383
Count = 1130     C-Value = 5.818972
Count = 1131     C-Value = 5.651371
Warning: Using only the real component of complex data.

Cmax =

   40.6784


Imax =

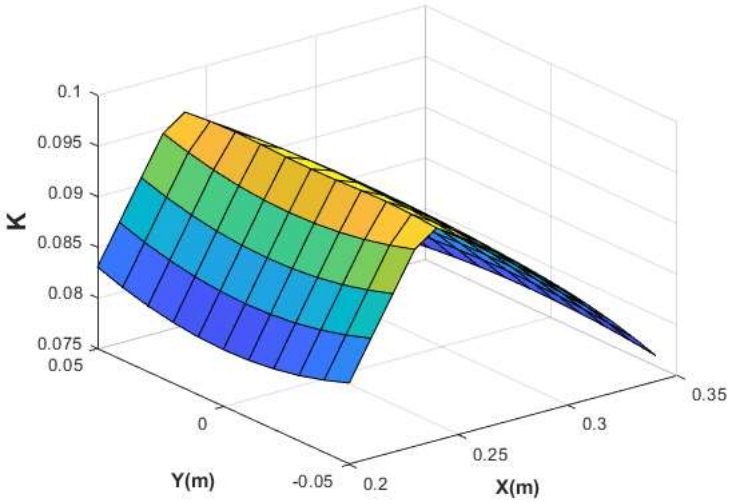
   278


L1_max =

    0.2400
```

```
L2_max =

    0.2400
```



Functions

```
% IK function
function q = ik(l1, l2, x)
 c1 = (l1^2 + x^2 - l2^2)/(2*l1*x);
 a = (l1^2 - l2^2 + x^2) / (2*x);
 h = sqrt(l1^2 - a^2);
 s1 = h/l1;
 theta1 = atan2(s1, c1);
 ca = (x-a)/l2;
 sa = h/l2;
 a = atan2(sa, ca);
 theta2 = -(theta1+a);
 q = [theta1 theta2];
end

% w function
function w = w_func(L1, L2, x, Jdiff)
    syms l1 l2 theta1 theta2

    alpha = [0, 0];
    a = [l1, l2];
    d = [0, 0];

    L(1) = Link('revolute', 'alpha', alpha(1), 'a', a(1), 'd', d(1), 'standard');
    L(2) = Link('revolute', 'alpha', alpha(2), 'a', a(2), 'd', d(2), 'standard');

    RR_robot = SerialLink(L, 'name', 'RR_robot');
    q_sym = [theta1 theta2];

    T01 = RR_robot.A(1, q_sym);
    T12 = RR_robot.A(2, q_sym);
    T02 = simplify(T01*T12);

    [R01, P01] = tr2rt(T01); R10 = transpose(R01);
    [R12, P12] = tr2rt(T12); R21 = transpose(R12);
    [R02, P02] = tr2rt(simplify(T01*T12));

    Jxyz1 = diff(P02, theta1);
    Jxyz2 = diff(P02, theta2);
    Jxyz = [Jxyz1 Jxyz2];

    roll = 0;
    pitch = 0;
    yaw = theta1 + theta2;
    Orn = [roll; pitch; yaw];
    JOrn1 = diff(Orn, theta1);
    JOrn2 = diff(Orn, theta2);
    JOrn = [JOrn1 JOrn2];
    Jdiff = [Jxyz; JOrn];

    theta = ik(L1, L2, x);
    q1 = theta(1);
```

```
    q2 = theta(2);

    config = subs(Jdiff, [l1,l2,theta1,theta2], [L1, L2, q1, q2]);
    Jconfig = config(1:2, 1:2); % reduced Jacobian
    Jconfig_T = transpose(Jconfig);

    w = sqrt(det(Jconfig*Jconfig_T));
end

function [theta] = inverseKinematicsScara3(X, Y, a1, a2)
    c2 = (X^2 + Y^2 - a1^2 - a2^2)/(2*a1*a2);
    s2 = (1 - c2^2)^(0.5);

    t2s1 = atan2(s2, c2);
    t2s2 = atan2(-s2, c2);

    if(t2s1 >= 0)
        theta2 = t2s1;
    else
        theta2 = t2s2;
    end

    beta = atan2(X, Y);
    psi = acos((X^2 + Y^2 + a1^2 - a2^2)/(2*a1*(X^2 + Y^2)^(0.5)));
    theta1 = -(beta + psi - pi/2);
    theta = [theta1; theta2];
end
```

```
pos =

     3


pos =

     7


pos =

     3
```

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