Rahul_Goyal_main Usage and Description

ME 326 Winter 2018 - Laboratory Assignment #5b

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Date Created: February 27, 2018

Date Modified: March 06, 2018

Description: This script simulates the motion of a slider-crank. Afterwards, it compares the collar force, the magnitude of each pin force, and the input torque to the angular position of link OA and the input power to time. Additionally, it animates the slider-crank by using the simulation data.

Required Files:

- Simulator.slx - This file uses Simulink to double integrate part of a MATLAB Function Block which describes the accelerations and forces of the simulation (only the accelerations are integrated). It outputs the positions as xout, the velocities as vout, the accelerations as aout, the forces as Fout, and the times as tout with inputs of the MATLAB function, initial conditions, and final condition.
- link_solver.m - This file contains a function that represents the accelerations and forces of the simulation. It returns x with an input of u.

Called Functions

clear all; clc;

Set Values

The following is used to easily change the initial and final angular positions of link OA.

```
t2_0 = deg2rad(0);                % Angular position initial of link OA (rad)
theta2_stop = t2_0-4*pi;          % Angular psoition final of link OA (rad)
```

Given Values

The following assigns values given by the problem statement to variables.

```
tdot_2 = -3;                      % Angular velocity of link OA (rad/s)
l_ab = 350/1000;                  % Length of link AB (m)
r_1 = 240/1000;                   % Length of vector R1 (m)
r_2 = 80/1000;                    % Length of vector R2 (m)
```

Initial Conditions

The following sets the initial conditions of the slider-crank. See the attached file for hand calculations.

```
% Position Initial Conditions
% Length initial of vector R2 (m) [Pythagorean Theorem]
r3_0 = hypot(r_1+r_2*cos(t2_0), r_2*sin(t2_0));
% Angular position initial of link OA (rad) [Law of Sines]
t3_0 = asin(sin(pi-t2_0)/r3_0 * r_2);
```

```
% COM[x] initial of link OA (m)
x2_0 = r_1 + r_2/2*cos(t2_0);
% COM[y] initial of link OA (m)
y2_0 = r_2/2*sin(t2_0);
% COM[x] initial of link AB (m)
x3_0 = r_1 + r_2*cos(t2_0) - l_ab/2*cos(t3_0);
% COM[y] initial of link AB (m)
y3_0 = r_2*sin(t2_0) - l_ab/2*sin(t3_0);

% Position Initial Conditions Matrix
x_0 = [r3_0, t3_0, x2_0, y2_0, x3_0, y3_0];

% Velocity Initial Conditions
A = [cos(t3_0), -r3_0*sin(t3_0);
     sin(t3_0), r3_0*cos(t3_0)];
b = [-r_2*tdot_2*sin(t2_0);
     r_2*tdot_2*cos(t2_0)];
x = A \ b;
% Velocity initial of vector R3 (m/s)
rdot3_0 = x(1);
% Angular velocity initial of link AB (rad/s)
tdot3_0 = x(2);
% Velocity_G[x] initial of link OA (m/s)
xdot2_0 = -tdot_2 * r_2/2*sin(t2_0);
% Velocity_G[y] initial of link OA (m/s)
ydot2_0 = tdot_2 * r_2/2*cos(t2_0);
% Velocity_G[x] initial of link AB (m/s)
xdot3_0 = -tdot_2*r_2*sin(t2_0) + tdot3_0*l_ab/2*sin(t3_0);
% Velocity_G[x] initial of link AB (m/s)
ydot3_0 = tdot_2*r_2*cos(t2_0) - tdot3_0*l_ab/2*cos(t3_0);

% Velocity Initial Conditions Matrix
v_0 = [rdot3_0, tdot3_0, xdot2_0, ydot2_0, xdot3_0, ydot3_0];
```

Simulate the Slider-Crank Using Simulink

The following calls the Simulink file Simulator.slx, which outputs the positions as xout, the velocities as vout, the accelerations as aout, the forces as Fout, and the times as tout with with link_solver.m as the input for the MATLAB Fuction, tdot_2, t2_0, v_0, and x_0 as the inputs for the initial conditions, and theta2_stop as the input for the final conditions.

```
sim('Simulator.slx');
```

Plotting Data Setup

The following sets up easy access to data for plotting.

```
t_2s = t2_0 + tdot_2*tout;      % Angular positions of link OA (rad)

FO_x = Fout(:, 1);              % Force[x] in pin O (N)
FO_y = Fout(:, 2);              % Force[y] in pin O (N)
FA_x = Fout(:, 3);              % Force[x] in pin A (N)
FA_y = Fout(:, 4);              % Force[y] in pin A (N)
F_C = Fout(:, 5);               % Force in pin C (N)
T = Fout(:, 6);                 % Input torque (Nm)
```

Collar Force vs. Crank Angle

The following plots the collar force as a function of crank angle.

By visual observation, the graph has periodic relative maximums at about -75° and -225°, periodic relative minimums at about -150° and -300°, and periodic zeroes at about 0°, -100°, -175°, and -250°. Converting these angles to positive values, the graph has periodic relative maximums at about 285° and 135°, periodic relative minimums at about 210° and 60°, and periodic zeroes at about 0°, 260°, 185°, and 110°.

The maximums and minimums signify maximum and minimum peaks, respectively, in the collar force; the zeroes signify zeroes in the magnitude of the collar force. Watching an animation of the slider-crank, the collar force peaks seem to occur when the velocity of link AB with respect to the collar is changing most noticeably and the collar force zeroes seem to occur when the velocity of link AB with respect to the collar flips directions. This behavior is as expected because acceleration is the derivative of velocity, and net force is directly and linearly related to acceleration. The collar exerts a force on link AB, and so it is reasonable that this force behaves similarly to the expected net force on link AB. However, because the collar force and the net force are not the same, analysis of the collar force reveals some smaller relative peaks as well. These are likely a result of the fact that the center of mass of link AB crosses the collar.

```
plot(rad2deg(t_2s), F_C, 'LineWidth', 2);
title('Collar Force vs. Crank Angle');
xlabel({'Crank Angle (°)'
        ''
        % Figure label
        '\bfFigure 1: \rmCollar Force vs. Crank Angle'});
ylabel('Collar Force (N)');
```

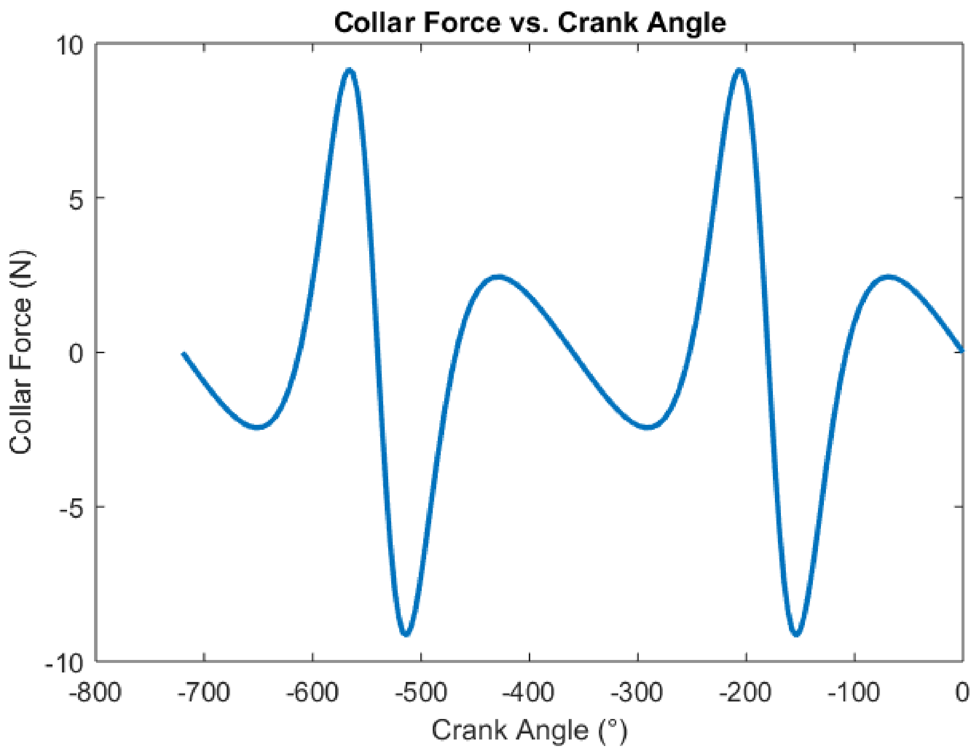

Figure 1: Collar Force vs. Crank Angle

Magnitude of Each Pin Force vs. Crank Angle

The following plots the magnitude of each pin force as a function of crank angle.

The graphs of the magnitudes of each pin force resemble each other. By visual observation, both graphs have periodic relative maximums at about 0° and -175° and periodic relative minimums at about -100° and -250°. Converting these angles to positive values, the graphs have a periodic relative maximum at about 0° and 185° and periodic relative minimums at about 260° and 110°.

The maximums and minimums signify peaks in the magnitude of the force in pin O and pin A. Unlike the collar force, neither pin force is ever zero. Watching an animatmion of the slider-crank, the magnitude of the forces increase as the magnitude of the angular velocity of link AB increases, and vice versa. This behavior is as expected because angular acceleration is the derivative of angular velocity, and net torque is directly and linearly related to angular acceleration. Both pins exert a moment on link AB (whether directly or indirectly), and so it is reasonable that this moment behaves similarly as the expected net torque on link AB.

```
F_O = hypot(FO_x, FO_y);        % Magnitude of force of pin O (N)
F_A = hypot(FA_x, FA_y);        % Magnitude of force of pin A (N)

% Plot
plot(rad2deg(t_2s), F_O, rad2deg(t_2s), F_A, 'LineWidth', 2);
title('Magnitude of Each Pin Force vs. Crank Angle');
xlabel({'Crank Angle (°)'
        ''
        % Figure label
        '\bfFigure 2: \rmMagnitude of Each Pin Force vs. Crank Angle'});
ylabel('Pin Force (N)');
legend('|Fo|', '|Fa|');
```

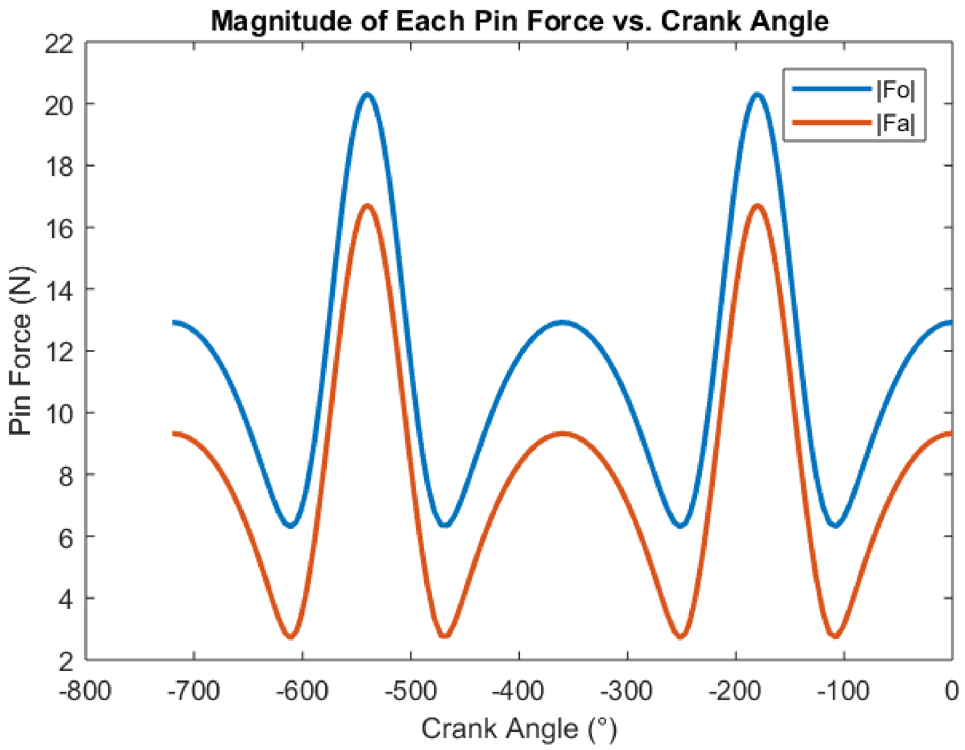

Figure 2: Magnitude of Each Pin Force vs. Crank Angle

Input Torque vs. Crank Angle

The following plots the input torque as a function of crank angle.

By visual observation, the graph has a periodic relative maximums at about -150° and -300°, periodic relative minimums at about -75° and -225°, and periodic zeroes at about 0°, -100°, -175°, and -250°. Converting these angles to positive values, the graph has periodic relative maximums at about 210° and 60°, periodic relative minimums at about 285° and 135°, and periodic zeroes at about 0°, 260°, 185°, and 110°.

The maximums and minimums signify maximum and minimum peaks, respectively, in the input torque. Comparing the maximums and minimums of the input torque to the maximums and minimums of the collar force, it's seen that the input torque increases as the collar force decreases, and vice versa.

Interestingly, the input torque behaves almost like a negative derivative of the magnitude of each pin force, but this is likely just a coincidence.

```
plot(rad2deg(t_2s), T, 'LineWidth', 2);
title('Input Torque vs. Crank Angle');
xlabel({'Crank Angle (°)'
        ''
        % Figure label
        '\bfFigure 3: \rmInput Torque vs. Crank Angle'});
ylabel('Input Torque (Nm)');
```

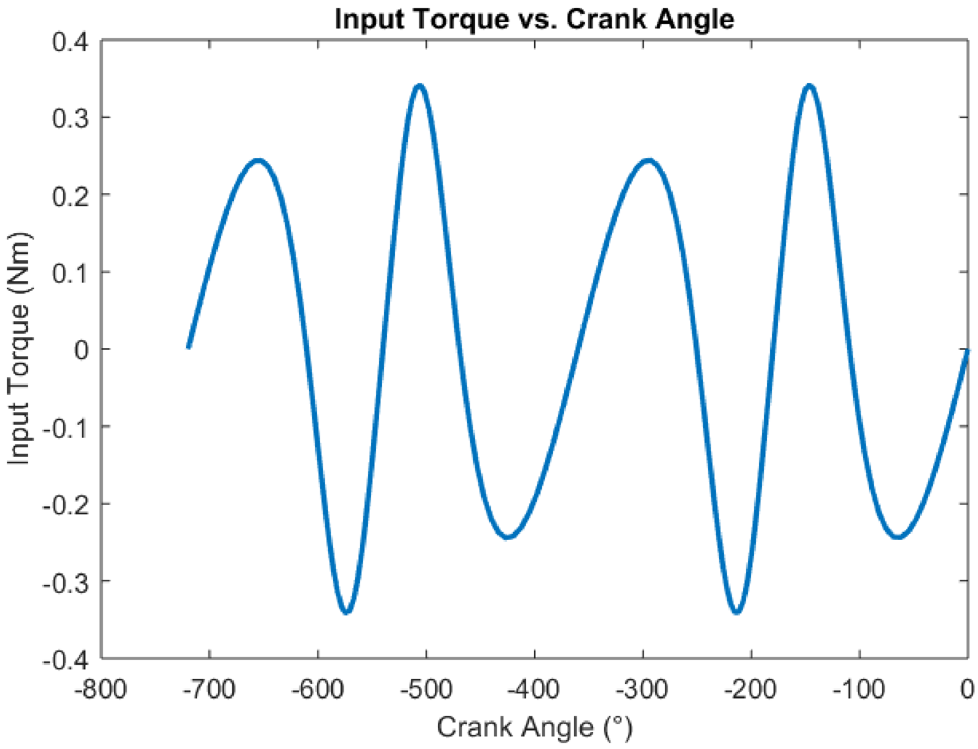

Figure 3: Input Torque vs. Crank Angle

Input Power vs. Time

The following plots the input power as a function of time.

The input power can be defined by the input torque times the angular velocity. The area under the curve represents energy because energy is equivalent to the integral of power with respect to time.

The graph of the input power resembles the graph of the input torque, however this is only because the angular velocity of link OA is constant. By visual observation, the areas under the curve sum to zero. Therefore, energy is conserved over a cycle.

```
P = T*tdot_2;                   % Input power (W)

% Plot
area(tout, P);
title('Input Power vs. Time');
```

```
xlabel({'Time (s)'
        ''
        % Figure label
        '\bfFigure 4: \rmInput Power vs. Time'});
ylabel('Input Power (W)');
```

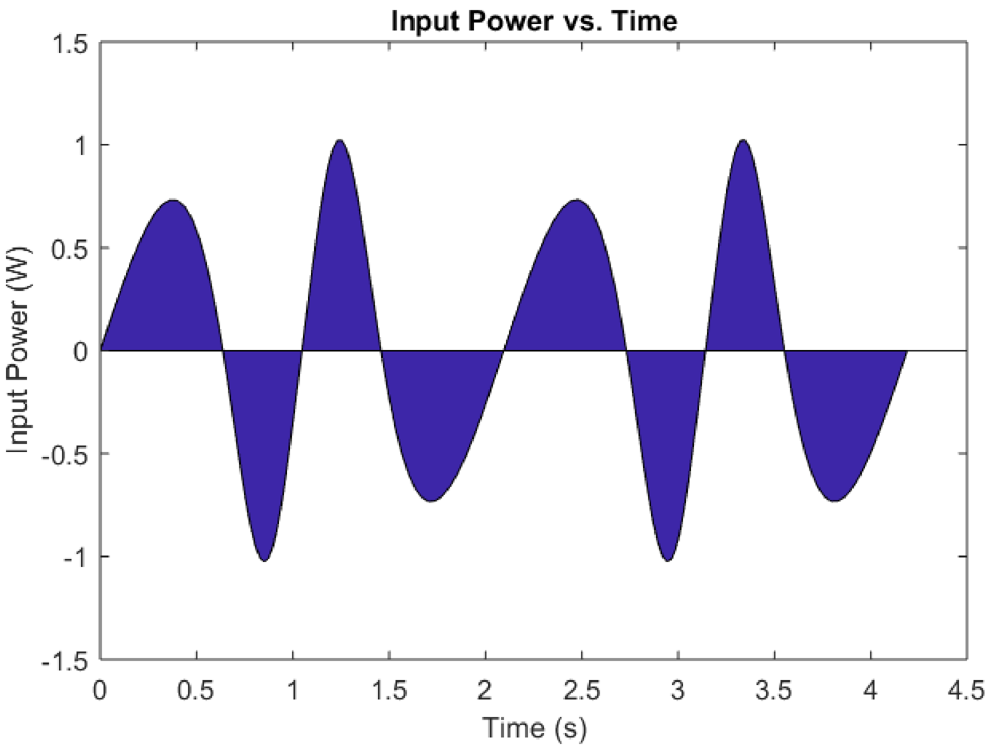

Figure 4: Input Power vs. Time

Simulation Animation

The following animates the slider-crank by using the simulation data.

```
% Cartesian Coordinates of Vector R1
r1_x = [0, r_1];
r1_y = [0, 0];
% Cartesian Coordinates of the COM of Vector R1
x_1 = (r1_x(end)-r1_y(1))/2;
y_1 = (r1_y(end)-r1_y(1))/2;

% Easy access to...
r_3 = xout(:, 1);               % Lengths of vector R3 (m)
t_3 = xout(:, 2);               % Angular positions of link AB (rad)
x_2 = xout(:, 3);               % COMs[x] of link OA (m)
y_2 = xout(:, 4);               % COMs[y] of link OA (m)
x_3 = xout(:, 5);               % COMs[x] of link AB (m)
y_3 = xout(:, 6);               % COMs[y] of link AB (m)

% Cartesian Coordinates of Point A
a_x = r1_x(end)+r_2*cos(t2_0+tdot_2*tout);
a_y = r1_y(end)+r_2*sin(t2_0+tdot_2*tout);
% Cartesian Coordinates of Point B
b_x = a_x - l_ab*cos(t_3);
b_y = a_y - l_ab*sin(t_3);
```

```
for t = 1:length(tout)

    t_2 = t2_0 + tdot_2*tout(t);    % Angular position of link OA (m)

    % Cartesian Coordinates of Vector R2
    r2_x = [r1_x(end), r1_x(end) + r_2*cos(t_2)];
    r2_y = [r1_y(end), r1_y(end) + r_2*sin(t_2)];
    % Cartesian Coordinates of Link AB
    lab_x = [r2_x(end), r2_x(end) - l_ab*cos(t_3(t))];
    lab_y = [r2_y(end), r2_y(end) - l_ab*sin(t_3(t))];

    % Plot the links, COMs, COM paths
    subplot(2, 1, 1);
    plot(r1_x, r1_y, ...            % Vector R1
         r2_x, r2_y, ...            % Vector R2
         lab_x, lab_y, ...          % Link AB
         x_2(1:t), y_2(1:t), ...    % Path of link OA COM
         x_3(1:t), y_3(1:t), ...    % Path of link AB COM
         a_x(1:t), a_y(1:t), ...    % Path of point A
         b_x(1:t), b_y(1:t), ...    % Path of point B
         'LineWidth', 2);           % Line Properties
    % COM of Vector R1
    viscircles([x_1, y_1], 0.0025, 'Color', 'k');
    % COM of Link OA
    viscircles([x_2(t), y_2(t)], 0.0025, 'Color', 'k');
    % COM of Link AB
    viscircles([x_3(t), y_3(t)], 0.0025, 'Color', 'k');
    % Keep the frame consistent
    axis equal;
    axis([-0.2, 0.8, -0.1, 0.1]);

    % Magnitude of force of pin O (N)
    F_O = hypot(Fout(t, 1), Fout(t, 2));
    % Magnitude of force of pin A (N)
    F_A = hypot(Fout(t, 3), Fout(t, 4));
    % Collar force (N)
    F_C = Fout(t, 5);

    % Plot the real-time forces
    subplot(2, 1, 2);
    bar([F_O, F_A, F_C]);
    % Keep the frame consistent
    ylim([-25, 25]);

    % Calculate the time step and pause accordingly
    if t ~= length(tout)            % Prevent index error
        % Calculate the time step (s)
        t_step = tout(t+1) - tout(t);
        pause(t_step);              % Assume negligible processing time
    end

end

% Plot labeling (last frame)
subplot(2, 1, 1);
title('Simulation Animation');
xlabel('X Position (m)');
ylabel('Y Position (m)');
legend('Vector R1', 'Vector R2', 'Link AB', ...
       'Path of Link OA COM', 'Path of Link AB COM', ...
       'Path of Point A', 'Path of Point B');
```

```
subplot(2, 1, 2);
xlabel({'Pin O                            Pin A                            Collar'
        ''
        % Figure label
        '\bfFigure 5: \rmSimulation Animation'});
ylabel('Force (N)');
legend('Pin O', 'Pin C', 'Collar');
```

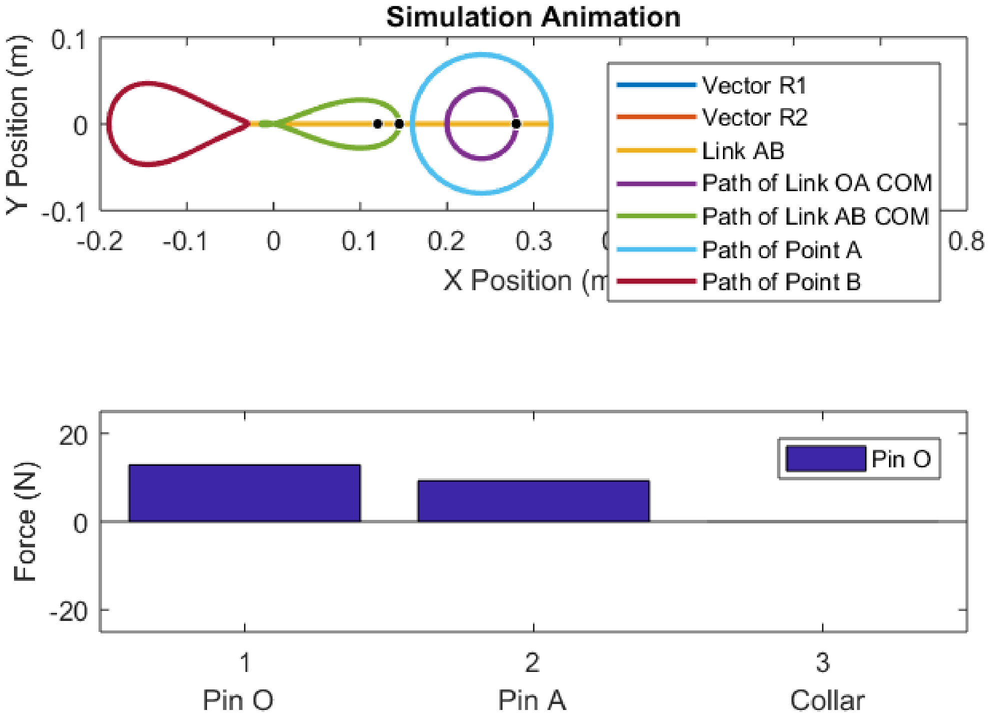

Figure 5: Simulation Animation

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Contents

Called Functions

Given Values

The following assigns values given by the problem statement to variables.

```
l_ab = 350/1000;                % Length of link AB (m)
r_1 = 240/1000;                 % Length of vector R1 (m)
r_2 = 80/1000;                  % Length of vector R2 (m)
m_2 = 10;                       % Mass of link OA (kg)
m_3 = 15;                       % Mass of link AB (kg)
```

Easy Access

The following sets up easy access to variables.

```
t_2 = u(1);                     % Angular position of link OA (rad)
tdot_2 = u(2);                  % Angular velocity of link OA (rad/s)
r_3 = u(3);                     % Length of vector R3 (m)
t_3 = u(4);                     % Angular position of link AB (rad)
rdot_3 = u(9);                  % Velocity of vector R3 (m/s)
tdot_3 = u(10);                 % Angular velocity of link AB (rad/s)
```

```
Not enough input arguments.

Error in link_solver (line 19)
t_2 = u(1);                     % Angular position of link OA (rad)
```

Solved Values

The following assigns values derived and/or solved from the given values to variables. See the attached file for hand calculations.

```
I_3 = 1/12*m_3*l_ab^2;          % Moment of inertia of link AB (kg*m^2)

A = [cos(t_3), -r_3*sin(t_3), 0, 0, 0, 0, 0, 0, 0, 0, 0, 0;
     sin(t_3), r_3*cos(t_3), 0, 0, 0, 0, 0, 0, 0, 0, 0, 0;
     0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0;
     0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0;
     -cos(t_3), (r_3-l_ab/2)*sin(t_3), 0, 0, 1, 0, 0, 0, 0, 0, 0, 0;
     -sin(t_3), -(r_3-l_ab/2)*cos(t_3), 0, 0, 0, 1, 0, 0, 0, 0, 0, 0;
     0, 0, m_2, 0, 0, 0, 1, 0, -1, 0, 0, 0;
     0, 0, 0, m_2, 0, 0, 0, 1, 0, -1, 0, 0;
     0, 0, 0, 0, 0, 0, -r_2*sin(t_2)/2, r_2*cos(t_2)/2, -r_2*sin(t_2)/2, r_2*cos(t_2)/2, 0, 1;
     0, 0, 0, 0, m_3, 0, 0, 0, 1, 0, sin(t_3), 0;
     0, 0, 0, 0, 0, m_3, 0, 0, 0, 1, -cos(t_3), 0;
     0, I_3, 0, 0, 0, 0, 0, 0, -l_ab*sin(t_3)/2, l_ab*cos(t_3)/2, r_3-l_ab/2, 0];

b = [2*rdot_3*tdot_3*sin(t_3) + r_3*tdot_3^2*cos(t_3) - r_2*tdot_2^2*cos(t_2);
     -2*rdot_3*tdot_3*cos(t_3) + r_3*tdot_3^2*sin(t_3) - r_2*tdot_2^2*sin(t_2);
     -1/2*r_2*tdot_2^2*cos(t_2);
     -1/2*r_2*tdot_2^2*sin(t_2);
     -2*rdot_3*tdot_3*sin(t_3) - r_3*tdot_3^2*cos(t_3) + l_ab/2*tdot_3^2*cos(t_3);
     2*rdot_3*tdot_3*cos(t_3) - r_3*tdot_3^2*sin(t_3) + l_ab/2*tdot_3^2*sin(t_3);
     0;
     0;
     0;
     0;
     0;
     0];
```

Solve for x

Solve for x using mldivide.

```
x = A \ b;
```

```
end
```

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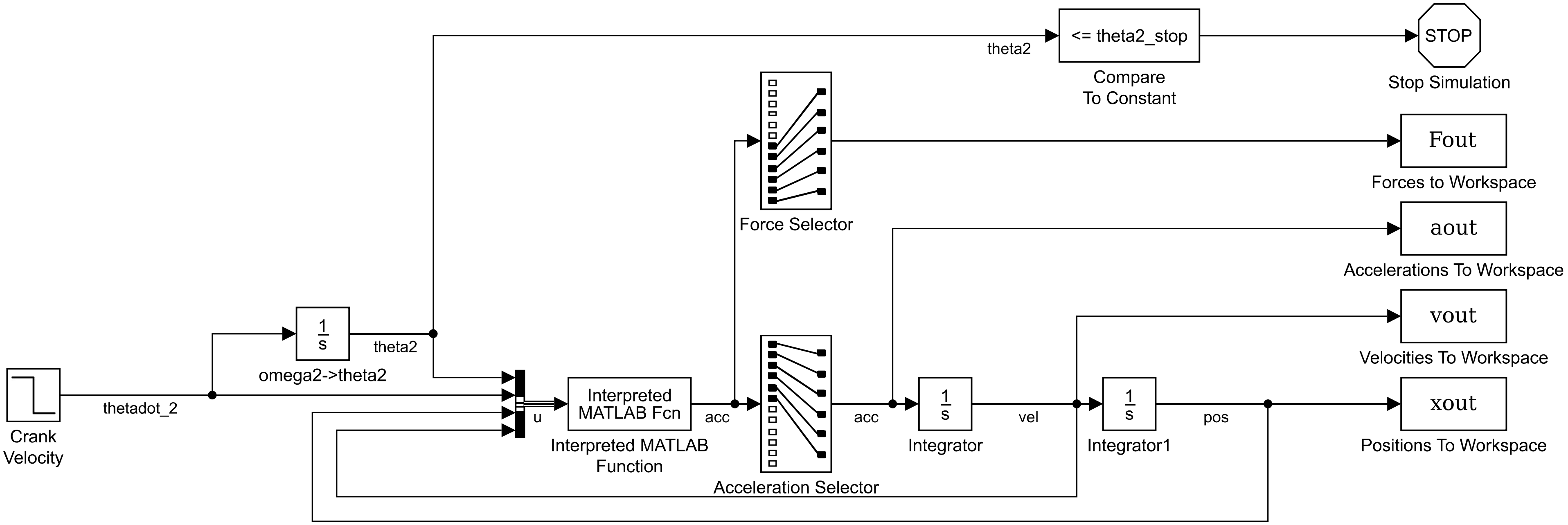

theta2
<= theta2_stop
Compare
To Constant
STOP
Stop Simulation
Fout
Forces to Workspace
Force Selector
aout
Accelerations To Workspace
vout
Velocities To Workspace
1
s
theta2
omega2->theta2
Crank
Velocity
thetadot_2
u
Interpreted
MATLAB Fcn
Interpreted MATLAB
Function
acc
Acceleration Selector
acc
1
s
Integrator
vel
1
s
Integrator1
pos
xout
Positions To Workspace

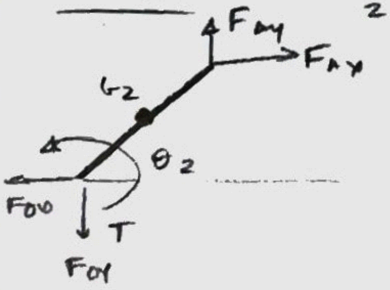
Lab 5b Hand Calculations

RAHUL GOYAL

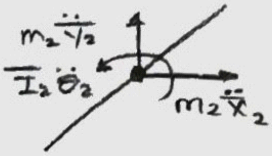
Refer to Lab 5a hand calculations first

LINK OA

FBD

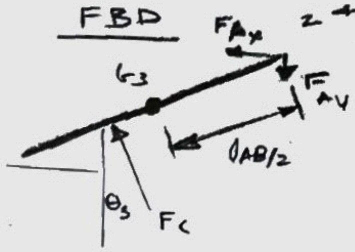


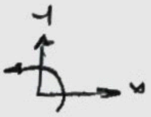
KD



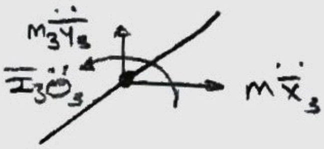
LINK AB

FBD





KD



$(\bar{I} = \frac{1}{12}ML^2)$

$$m_2\ddot{\bar{X}}_2 = F_{AX} - F_{OX}$$

$$m_2\ddot{\bar{Y}}_2 = F_{AY} - F_{OY}$$

$$\bar{I}_2\dot{\theta} = \frac{R2}{2}\left(-F_{OX} + F_{OY} - F_{AX} + F_{AY}\right) + T$$

$$m_3\ddot{\bar{X}}_3 = -F_{AX} - F_C\cos\theta_3$$

$$m_3\ddot{\bar{Y}}_3 = -F_{AY} + F_C\sin\theta_3$$

$$\bar{I}_3\ddot{\theta}_3 = \left(R_2 - \frac{l_{AB}}{2}\right)(F_C) + \frac{l_{AB}}{2}\left(F_{AX} - F_{AY}\right)$$