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Feedback Control of Legged Robots - Homework #7

Shawn Marshall-Spitzbart UC Berkeley

```
clear all; close all; clc; % starting with a clean slate

addpath('C:\Users\shawn\OneDrive\Documents\Berkeley\ME292B\HW07\gen')
```

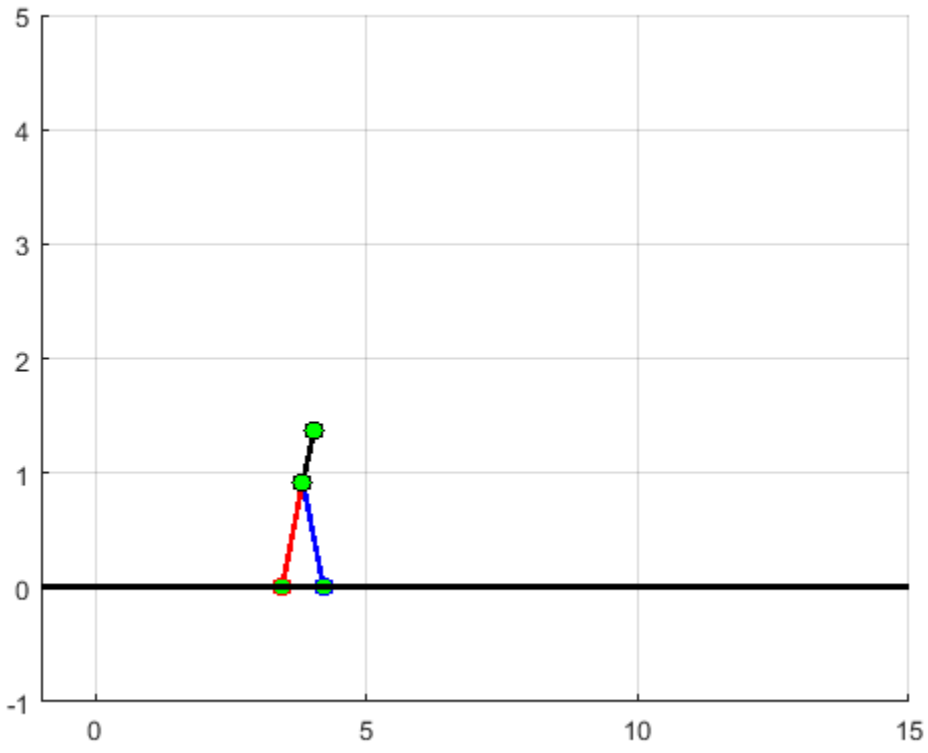
Problem 1

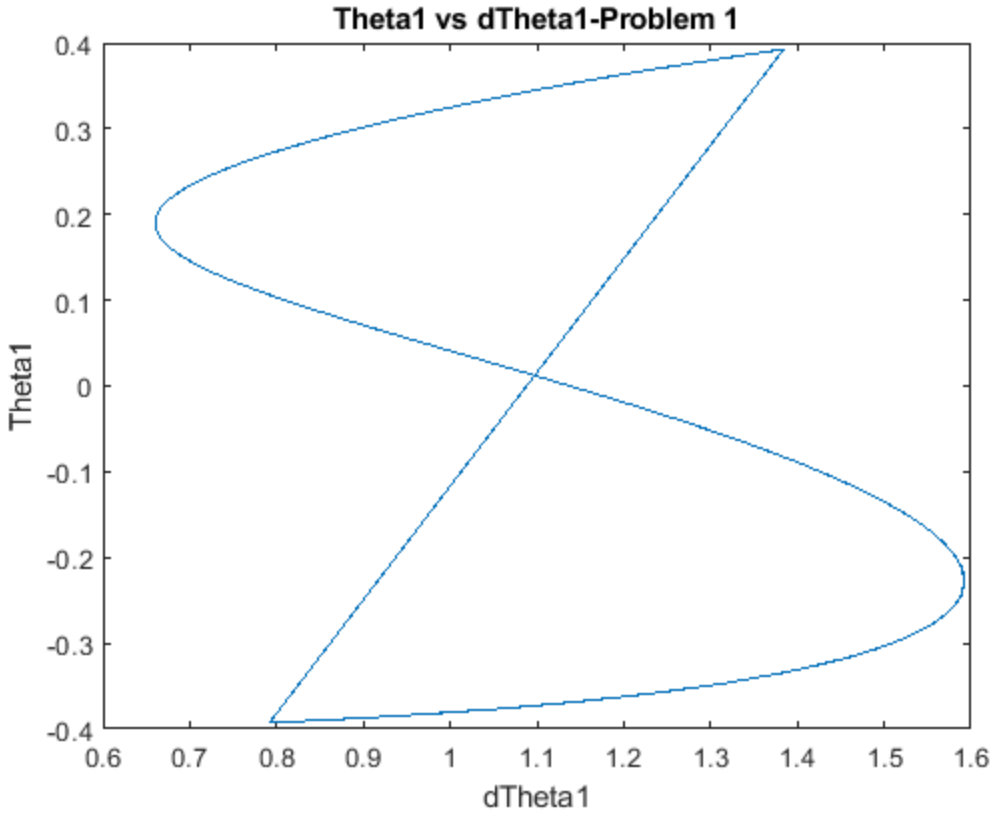
```
% Initial seed for optimization
alpha0 = pi/6; alpha1 = 0; alpha2 = 0; alpha3 = 0;
beta0 = 0; beta1 = 0; beta2 = 0; beta3 = 0;
x0 = [-0.3827;
    0.9239;
    2.2253;
    3.0107;
    0.5236;
    0.8653;
    0.3584;
    -1.0957;
    -2.3078;
    2.0323];
x_optim0 = [x0(1:10); alpha0; alpha1; alpha2; alpha3; ...
    beta0; beta1; beta2; beta3];

% Only linear constraint is to start 'x' position of hip at 0
Aineq = []; Bineq = [];
Aeq = [1 zeros(1,17)]; Beq = [0];
LB = [];
UB = [];

options = optimset('MaxFunEvals',20000,'MaxIter',20000);

% Set Desired Velocity
param.vd = 0.7;

[x_optim,obj_optim,feas_flag] =
 fmincon(@walk_obj,x_optim0,Aineq,Bineq,Aeq,Beq,LB,UB,@walk_cons,options,param);
```

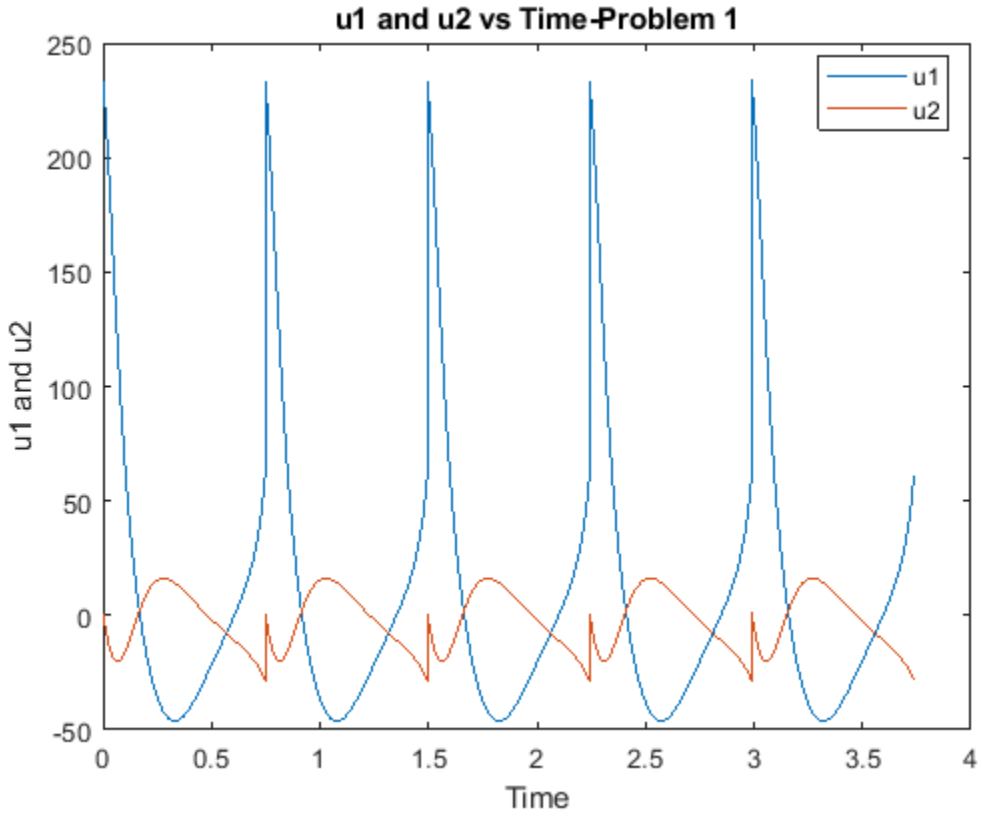
```
% Display constraints
[cineq_Problem1,ceq_Problem1] = walk_cons(x_optim,param)
```

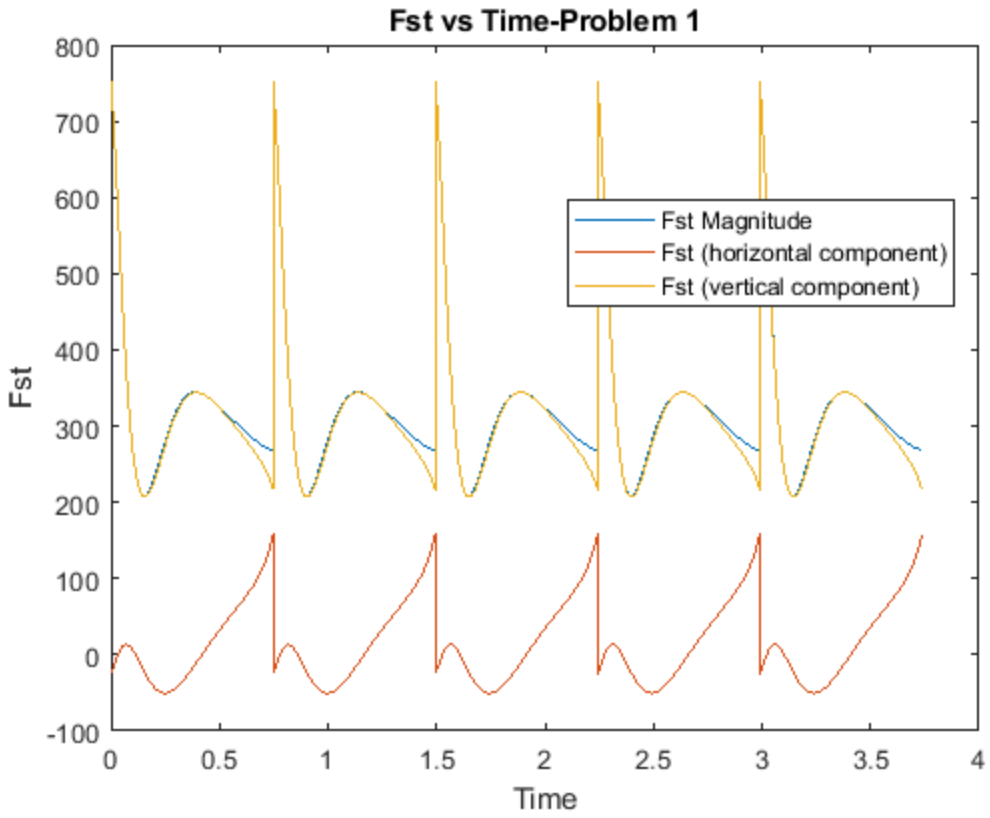
Simulate and Animate system

```
% Simulate Function for 5 steps now (alternative simulation function
 used)
[t_sim, x_sim] = sim_walk_alt(x_optim, param);

% Animate
animateThreeLink(t_sim, x_sim)

% Plots
plotting(t_sim,x_sim,x_optim,'-Problem 1');
```




Theta1 vs dTheta1-Problem 1
Theta1
dTheta1
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6


u1 and u2 vs Time-Problem 1
u1 and u2
Time
u1
u2
250
200
150
100
50
0
-50
0
0.5
1
1.5
2
2.5
3
3.5
4

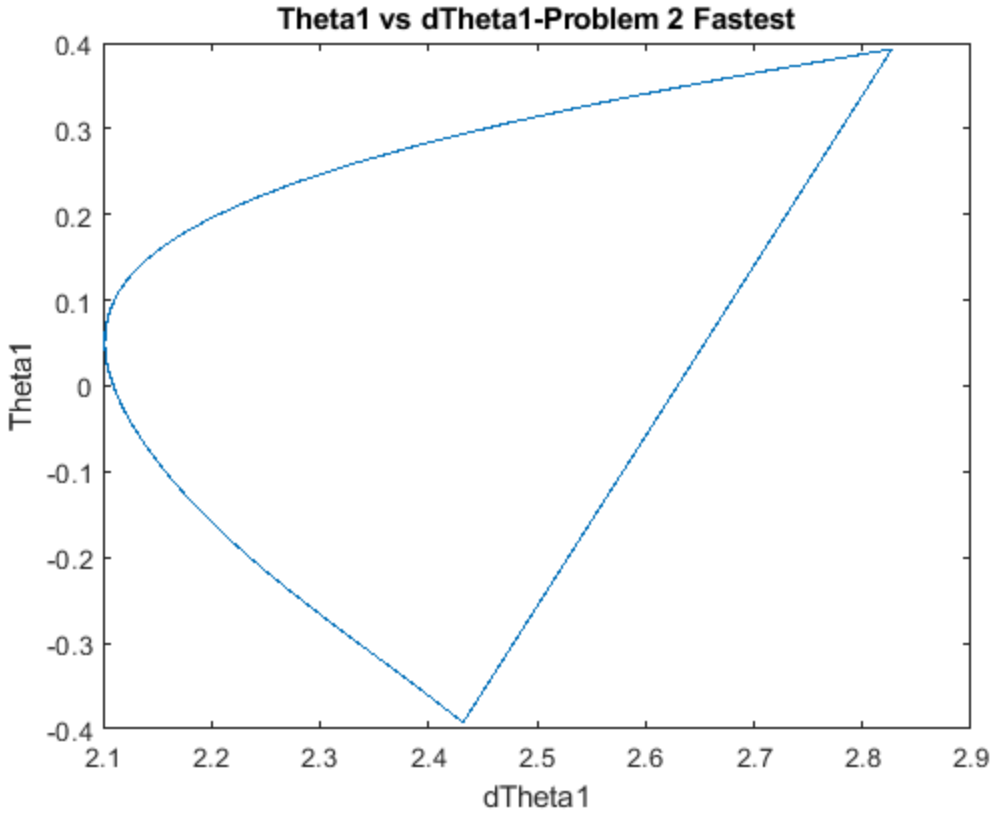


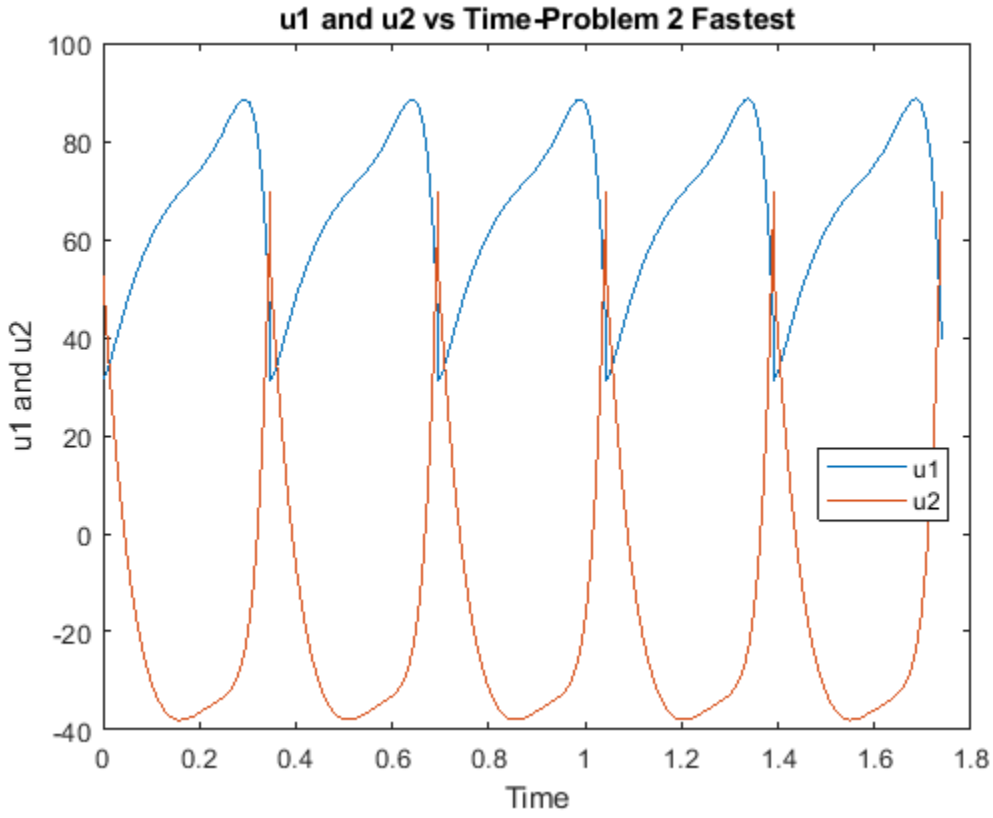
Problem 2

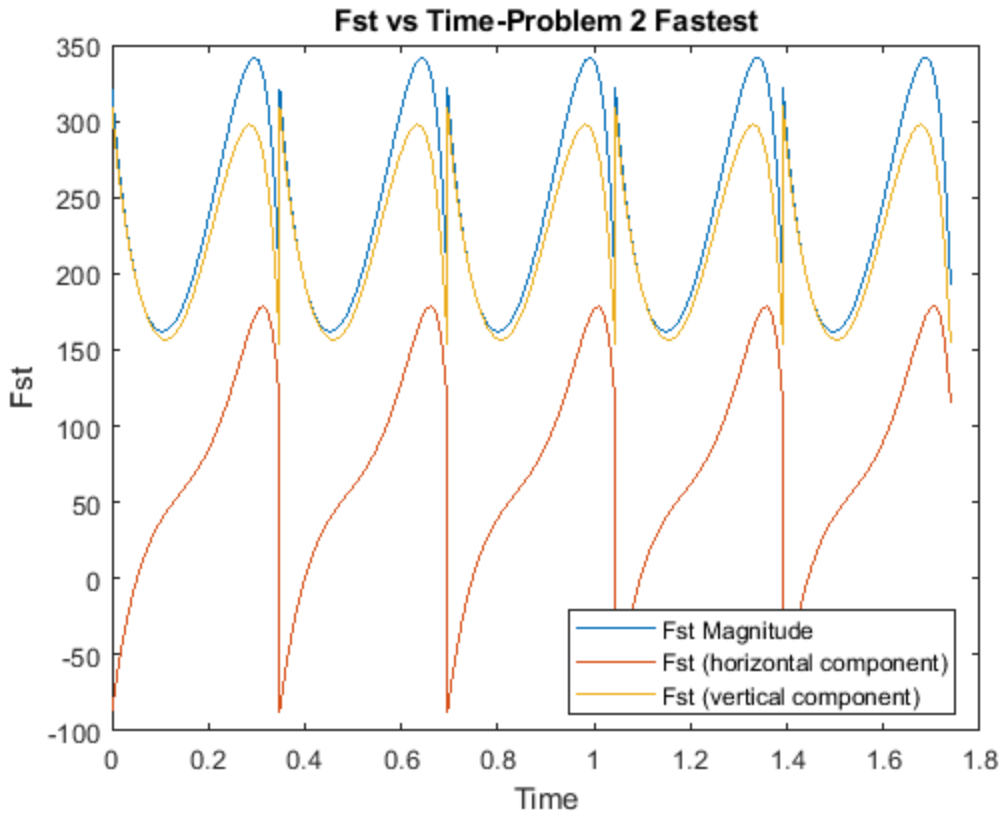
```
% Report the fastest feasible periodic walking gait, and the
% slowest feasible periodic walking gait. Then plot the same
% information as above.

% Set Fastest feasible periodic walking gait from trial and error
param.vd = 2.2;

[x_optim,obj_optim,feas_flag] =
 fmincon(@walk_obj,x_optim0,Aineq,Bineq,Aeq,Beq,LB,UB,@walk_cons,options,param);

% Print Constraints
[cineq_Problem2_fastest,ceqProblem2_fastest] =
 walk_cons(x_optim,param)

% Simulate Function for 5 steps now (alternative simulation function
 used)
[t_sim, x_sim] = sim_walk_alt(x_optim, param);

% Plots
plotting(t_sim,x_sim,x_optim,'-Problem 2 Fastest');

Warning: Failure at t=7.063197e-02.  Unable to meet integration
 tolerances
```

```
without reducing the step size below the smallest value allowed
 (2.220446e-16)
at time t.
Warning: Failure at t=7.063197e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (2.220446e-16)
at time t.
Warning: Failure at t=8.338691e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (2.220446e-16)
at time t.
Warning: Failure at t=8.338691e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (2.220446e-16)
at time t.
Warning: Failure at t=2.529777e-01.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (8.881784e-16)
at time t.
Warning: Failure at t=2.529777e-01.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (8.881784e-16)
at time t.
Warning: Failure at t=7.884202e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (2.220446e-16)
at time t.
Warning: Failure at t=7.884202e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (2.220446e-16)
at time t.
Warning: Failure at t=4.759984e-01.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (8.881784e-16)
at time t.
Warning: Failure at t=4.759984e-01.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (8.881784e-16)
at time t.
Warning: Failure at t=4.937718e-01.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (8.881784e-16)
at time t.
```

```
Warning: Failure at t=4.937718e-01.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (8.881784e-16)
at time t.
Warning: Failure at t=7.919579e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (2.220446e-16)
at time t.
Warning: Failure at t=7.919579e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (2.220446e-16)
at time t.
Warning: Failure at t=4.752888e-01.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (8.881784e-16)
at time t.
Warning: Failure at t=4.752888e-01.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (8.881784e-16)
at time t.

Local minimum possible. Constraints satisfied.

fmincon stopped because the size of the current step is less than
the value of the step size tolerance and constraints are
satisfied to within the value of the constraint tolerance.


cineq_Problem2_fastest =

 -153.8210
   -0.0057
   -0.0000


ceqProblem2_fastest =

   1.0e-10 *

   -0.0001
    0.0469
    0.0043
   -0.0043
    0.2443
   -0.0110
    0.0716
    0.2704
    0.1499
```


Theta1 vs dTheta1-Problem 2 Fastest
Theta1
dTheta1
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9


u1 and u2 vs Time-Problem 2 Fastest
u1 and u2
Time
u1
u2
100
80
60
40
20
0
-20
-40
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8




```
% Set slowest feasible periodic walking gait from trial and error
param.vd = 0.54;

[x_optim,obj_optim,feas_flag] =
 fmincon(@walk_obj,x_optim0,Aineq,Bineq,Aeq,Beq,LB,UB,@walk_cons,options,param);

% Print Contraints
[cineq_Problem2_slowest,ceq_Problem2_slowest] =
 walk_cons(x_optim,param)

% Simulate Function for 5 steps now (alternative simulation function
 used)
[t_sim, x_sim] = sim_walk_alt(x_optim, param);

% Plots
plotting(t_sim,x_sim,x_optim,'-Problem 2 Slowest');

Warning: Failure at t=1.294162e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (2.775558e-17)
at time t.
Warning: Failure at t=1.294162e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (2.775558e-17)
```

```
at time t.
Warning: Failure at t=1.118828e-03.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (3.469447e-18)
at time t.
Warning: Failure at t=1.118828e-03.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (3.469447e-18)
at time t.
Warning: Failure at t=2.888965e-03.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (6.938894e-18)
at time t.
Warning: Failure at t=2.888965e-03.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (6.938894e-18)
at time t.
Warning: Failure at t=2.119025e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (4.336809e-19)
at time t.
Warning: Failure at t=2.119025e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (4.336809e-19)
at time t.
Warning: Failure at t=2.321654e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (4.336809e-19)
at time t.
Warning: Failure at t=2.321654e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (4.336809e-19)
at time t.
Warning: Failure at t=1.975789e-03.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (6.938894e-18)
at time t.
Warning: Failure at t=1.975789e-03.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (6.938894e-18)
at time t.
Warning: Failure at t=4.258173e-03.  Unable to meet integration
 tolerances
```

```
without reducing the step size below the smallest value allowed
 (1.387779e-17)
at time t.
Warning: Failure at t=4.258173e-03.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (1.387779e-17)
at time t.
Warning: Failure at t=5.419050e-03.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (1.387779e-17)
at time t.
Warning: Failure at t=5.419050e-03.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (1.387779e-17)
at time t.
Warning: Failure at t=1.360974e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (4.336809e-19)
at time t.
Warning: Failure at t=1.360974e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (4.336809e-19)
at time t.
Warning: Failure at t=9.074088e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (1.734723e-18)
at time t.
Warning: Failure at t=9.074088e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (1.734723e-18)
at time t.
Warning: Failure at t=1.203014e-05.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (2.710505e-20)
at time t.
Warning: Failure at t=1.203014e-05.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (2.710505e-20)
at time t.
Warning: Failure at t=2.900429e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (8.673617e-19)
at time t.
```

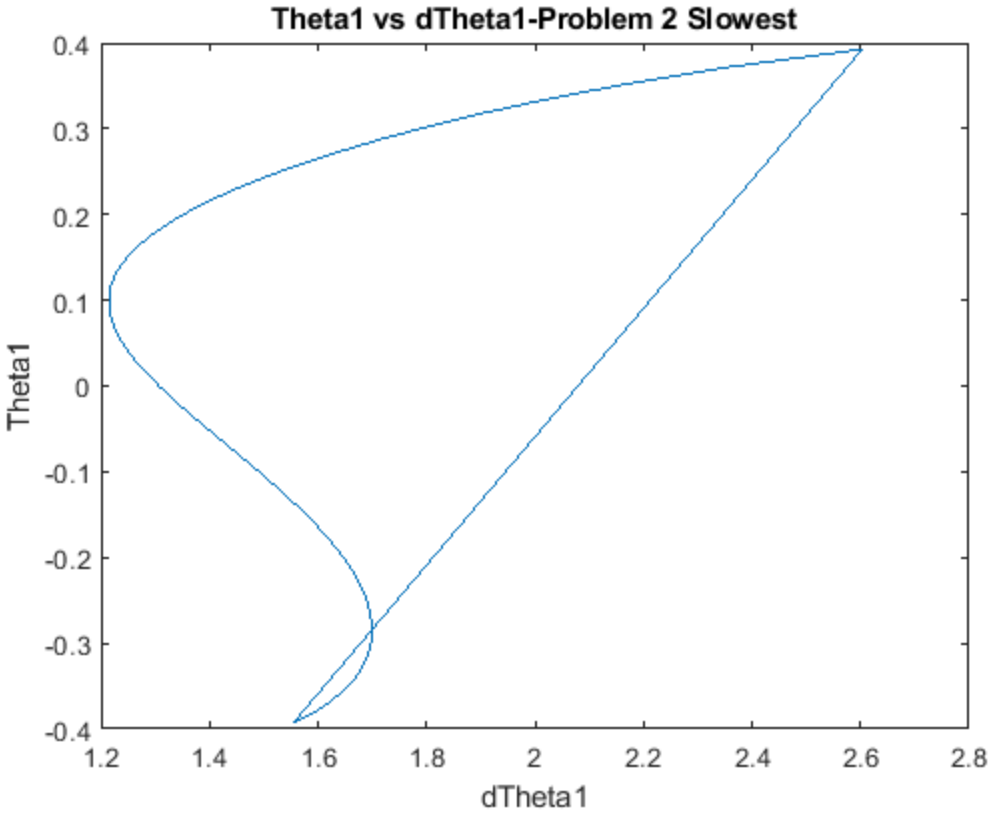
```
Warning: Failure at t=2.900429e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (8.673617e-19)
at time t.
Warning: Failure at t=6.031907e-05.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (1.084202e-19)
at time t.
Warning: Failure at t=6.031907e-05.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (1.084202e-19)
at time t.
Warning: Failure at t=2.103725e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (4.336809e-19)
at time t.
Warning: Failure at t=2.103725e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (4.336809e-19)
at time t.
Warning: Failure at t=3.035907e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (8.673617e-19)
at time t.
Warning: Failure at t=3.035907e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (8.673617e-19)
at time t.
Warning: Failure at t=5.213424e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (1.734723e-18)
at time t.
Warning: Failure at t=5.213424e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (1.734723e-18)
at time t.
Warning: Failure at t=1.173382e-05.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (2.710505e-20)
at time t.
Warning: Failure at t=1.173382e-05.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (2.710505e-20)
```

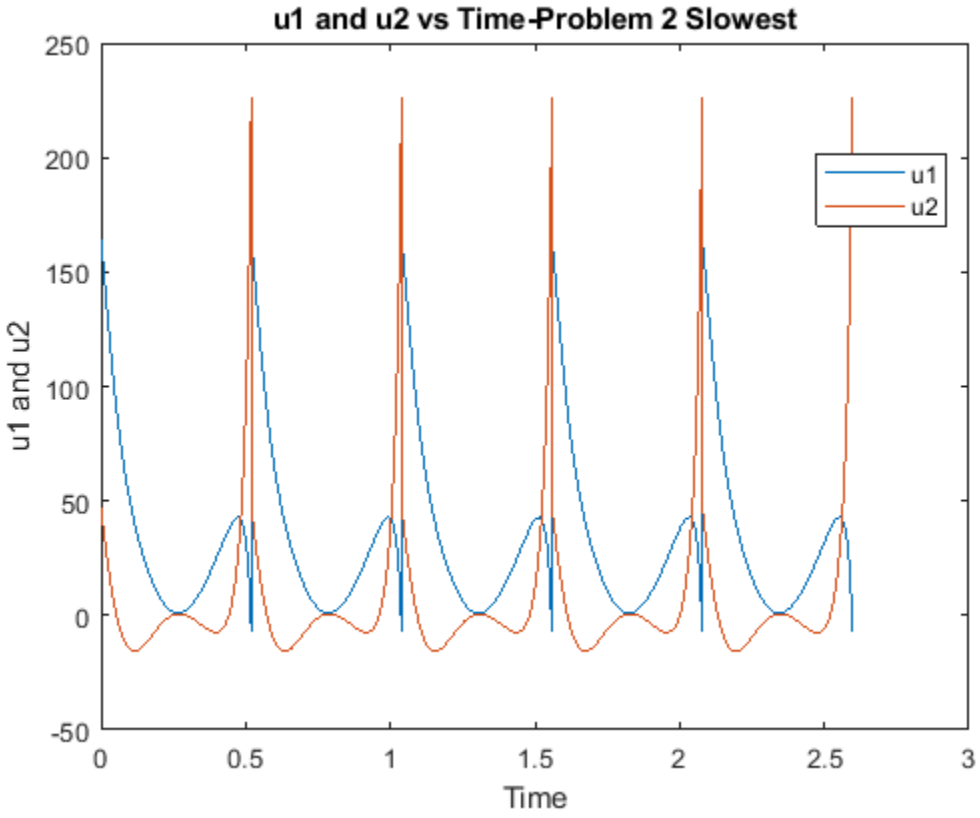
```
at time t.
Warning: Failure at t=1.698157e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (4.336809e-19)
at time t.
Warning: Failure at t=1.698157e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (4.336809e-19)
at time t.
Warning: Failure at t=1.449238e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (4.336809e-19)
at time t.
Warning: Failure at t=1.449238e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (4.336809e-19)
at time t.
Warning: Failure at t=1.365159e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (4.336809e-19)
at time t.
Warning: Failure at t=1.365159e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (4.336809e-19)
at time t.
Warning: Failure at t=4.309107e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (8.673617e-19)
at time t.
Warning: Failure at t=4.309107e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (8.673617e-19)
at time t.
Warning: Failure at t=3.741717e-03.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (6.938894e-18)
at time t.
Warning: Failure at t=3.741717e-03.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (6.938894e-18)
at time t.
Warning: Failure at t=6.904368e-03.  Unable to meet integration
 tolerances
```

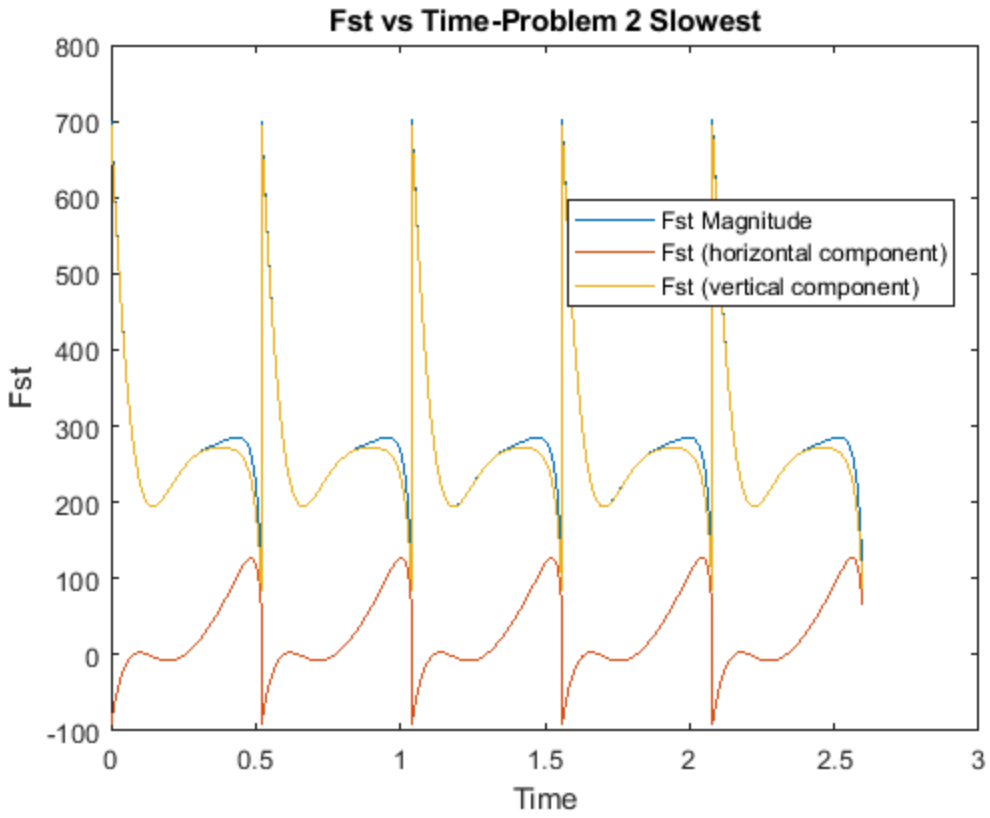
```
without reducing the step size below the smallest value allowed
 (1.387779e-17)
at time t.
Warning: Failure at t=6.904368e-03.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (1.387779e-17)
at time t.
Warning: Failure at t=8.583663e-05.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (2.168404e-19)
at time t.
Warning: Failure at t=8.583663e-05.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (2.168404e-19)
at time t.
Warning: Failure at t=1.609279e-03.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (3.469447e-18)
at time t.
Warning: Failure at t=1.609279e-03.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (3.469447e-18)
at time t.
Warning: Failure at t=2.954434e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (8.673617e-19)
at time t.
Warning: Failure at t=2.954434e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (8.673617e-19)
at time t.
Warning: Failure at t=1.007102e-03.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (3.469447e-18)
at time t.
Warning: Failure at t=1.007102e-03.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (3.469447e-18)
at time t.
Warning: Failure at t=3.806938e-03.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (6.938894e-18)
at time t.
```

```
Warning: Failure at t=3.806938e-03.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (6.938894e-18)
at time t.
Warning: Failure at t=3.995534e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (8.673617e-19)
at time t.
Warning: Failure at t=3.995534e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (8.673617e-19)
at time t.
Warning: Failure at t=2.771326e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (8.673617e-19)
at time t.
Warning: Failure at t=2.771326e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (8.673617e-19)
at time t.
Warning: Failure at t=1.524000e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (4.336809e-19)
at time t.
Warning: Failure at t=1.524000e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (4.336809e-19)
at time t.
Warning: Failure at t=6.525272e-05.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (2.168404e-19)
at time t.
Warning: Failure at t=6.525272e-05.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (2.168404e-19)
at time t.
Warning: Failure at t=2.938245e-03.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (6.938894e-18)
at time t.
Warning: Failure at t=2.938245e-03.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (6.938894e-18)
```

```
at time t.
Warning: Failure at t=3.138389e-03.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (6.938894e-18)
at time t.
Warning: Failure at t=3.138389e-03.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (6.938894e-18)
at time t.
Warning: Failure at t=1.350732e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (4.336809e-19)
at time t.
Warning: Failure at t=1.350732e-04.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (4.336809e-19)
at time t.

Local minimum possible. Constraints satisfied.

fmincon stopped because the size of the current step is less than
the value of the step size tolerance and constraints are
satisfied to within the value of the constraint tolerance.


cineq_Problem2_slowest =

  -85.1270
   -0.0002
   -0.9331


ceq_Problem2_slowest =

   1.0e-11 *

    0.0003
   -0.0047
    0.0010
   -0.0007
   -0.0044
    0.0074
   -0.1272
   -0.1134
    0.1261
```


Theta1 vs dTheta1-Problem 2 Slowest
Theta1
dTheta1
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8


u1 and u2 vs Time-Problem 2 Slowest
u1 and u2
Time
u1
u2
250
200
150
100
50
0
-50
0
0.5
1
1.5
2
2.5
3



Placeholder for MATLAB publishing

```
placeholder = 1
```

```
placeholder =

     1
```

Functions

```
function obj_sum = walk_obj(x,param)

    % Simulate walk
    [t_vec, x_vec] = sim_walk(x, param) ;

    alpha = x(11:14)';
    beta = x(15:18)';

    u = @(s, alpha, beta) LgLfy_gen(s, alpha, beta)^-1*(-Lf2y_gen(s,
 alpha, ...
    beta) + v_gen(s, alpha, beta));

    % cumulative cost
    x_TI = x_vec(end,1);
```

```
    % Implement the integral cost function
    obj_sum = 0;
    for i = 1:length(t_vec)-1
    obj_sum = obj_sum + (1 / x_TI ) * norm( u(x_vec(i,:)', alpha,...
        beta) ) * (t_vec(i+1) - t_vec(i));
    end

end

function [cineq,ceq] = walk_cons(x,param)

    % unraveling the input variable
    x0 = x(1:10);
    alpha = x(11:14)';
    beta = x(15:18)';

    u = @(s, alpha, beta) LgLfy_gen(s, alpha, beta)^-1*(-Lf2y_gen(s,
 alpha, ...
        beta) + v_gen(s, alpha, beta));

    % Simulate 1 step to produce (non-decision variable) paramters
 that will
    % feed into nonlinear constraints
    [t_vec, x_vec] = sim_walk(x, param);

    u_vec = zeros(size(x_vec, 1), 2);
    for row = 1:size(x_vec, 1)
        u_vec(row,1:2) = u(x_vec(row,:)', alpha, beta);
    end

    for row = 1:size(x_vec, 1)
        Fst(row,:) = Fst_gen(x_vec(row,:)', u_vec(row,:)');
    end

    % inequality constraints (nonlinear)
    cineq = [];

    % constraint (a) - Unilateral ground constraints
    cineq = [cineq; max(-Fst(:, 2))];

    % constraint (b) - Friction cone constraints
    mu_s = 0.75;
    cineq = [cineq;  max( abs(Fst(:, 1)./Fst(:, 2))) - mu_s ];

    % constraint (c) - Desired Average Speed Constraints
    x_TI = x_vec(end,1);
    TI = t_vec(end);
    cineq = [cineq; -x_TI / TI + param.vd];

    % equality constraints
    ceq = [];

    % constraint (d) - Periodicity constraints
```

```
    R = [1 0 0 0 0;
    0 1 0 0 0;
    0 0 0 1 0;
    0 0 1 0 0;
    0 0 0 0 1];
    ceq = [ceq; x0(2:5,1) - R(2:end,2:end) * x_vec(end,2:5)']; % Dont
 include 'x' since robot moves forward after step
    ceq = [ceq; x0(6:10,1) - R * dqPlus_gen(x_vec(end,:)')];

end

function [t_ode, x_ode] = sim_walk(x, param)

% unraveling the input variable
q0 = x(1:10);
alpha = x(11:14)';
beta = x(15:18)';

% Define u and ds
u = @(s, alpha, beta) LgLfy_gen(s, alpha, beta)^-1*(-Lf2y_gen(s,
 alpha, ...
    beta) + v_gen(s, alpha, beta));

% Define state function to integrate
ds = @(t,s,alpha,beta) f_gen(s) + g_gen(s) * u(s, alpha, beta);

% Define time range to simulate the system
tspan = [0 10] ;

% Define the event functions (stop integration when impact happens)
options = odeset('Events', @three_link_event);

% Simulate the system for each step
[t_ode,x_ode] = ode45(@(t,s) ds(t,s,alpha,beta),tspan,q0,options);

end
function [value,isterminal,direction] = three_link_event(t,x)

value = x(3) + x(5) - pi - pi/8; % detect when phi - 2*theta == 0
 (approx)
isterminal = 1 ; % stop integration when value == 0
direction = 1 ; % detect zero when function is increasing

end

function [t_vec, x_vec] = sim_walk_alt(x, param)

% unraveling the input variable
q0 = x(1:10);
alpha = x(11:14)';
beta = x(15:18)';

% Define u and ds
```

```
u = @(s, alpha, beta) LgLfy_gen(s, alpha, beta)^-1*(-Lf2y_gen(s,
 alpha, ...
    beta) + v_gen(s, alpha, beta));

% Define state function to integrate
ds = @(t,s,alpha,beta) f_gen(s) + g_gen(s) * u(s, alpha, beta);

% Initialize vectors
t_vec = []; x_vec = [];

t0 = 0 ; % Initial Time

% Impact map
R = [1 0 0 0 0;
0 1 0 0 0;
0 0 0 1 0;
0 0 1 0 0;
0 0 0 0 1];

    % Loop for 5 steps
    for i = 1:5

    % Define time range to simulate the system
    tspan = [0 10] ;

    % Define the event functions (stop integration when impact
 happens)
    options = odeset('Events', @three_link_event);

    % Simulate the system for each step
    [t_ode,x_ode] = ode45(@(t,s)
 ds(t,s,alpha,beta),t0+tspan,q0,options);

    % Save simulation data
    t_vec = [t_vec; t_ode] ;
    x_vec = [x_vec; x_ode] ;

    % Initialize xo and t for next step
    q0(1:5,1) = R * x_ode(end,1:5)';
    q0(6:10,1) = R * dqPlus_gen(x_ode(end,:)');
    t0 = t_vec(end);

    end

end

function plotting(t_sim,x_sim,x_optim,string)

% Theta1 vs dTheta1

% Transformation matrix:
T = [1 0 0 0 0;
     0 1 0 0 0;
     0 0 1 0 1;
```

```
     0 0 0 1 1;
     0 0 0 0 1];
d = [0;
     0;
     -pi;
     -pi;
     0];

% First convert data to theta coordinates
q_tild = zeros(size(x_sim, 1), 5);
dq_tild = zeros(size(x_sim, 1), 5);

for row = 1:size(x_sim, 1)
    q_tild(row, 1:5) = T * x_sim(row,1:5)' + d;
    dq_tild(row, 1:5) = T * x_sim(row,6:10)' + zeros(5,1);
end

% Plot
figure()
plot(dq_tild(:, 3) , q_tild(:, 3))
title(strcat('Theta1 vs dTheta1',' ',string))
xlabel('dTheta1')
ylabel('Theta1')

% u1 and u2 vs time
u = @(s, alpha, beta) LgLfy_gen(s, alpha, beta)^-1*(-Lf2y_gen(s,
 alpha, ...
beta) + v_gen(s, alpha, beta));

uplot = zeros(size(x_sim, 1), 2);
for row = 1:size(x_sim, 1)
    uplot(row,1:2) = u(x_sim(row,1:10)', x_optim(11:14)',
 x_optim(15:18)');
end

u1plot = uplot(:,1);
u2plot = uplot(:,2);

% Plot
figure()
plot(t_sim(:,1), u1plot(:,1))
hold on
plot(t_sim(:,1), u2plot(:,1))
legend('u1', 'u2', 'Location', 'Best')
title(strcat('u1 and u2 vs Time',' ',string))
xlabel('Time')
ylabel('u1 and u2')

% Fst vs time
Fst_plot = zeros(size(x_sim, 1), 2);
for row = 1:size(x_sim, 1)
    Fst_plot(row,1:2) = Fst_gen(x_sim(row,:)', uplot(row,:)');
end
```

```
Fst_plot_tot = sqrt(Fst_plot(:,1).^2 + Fst_plot(:,2).^2);

% Plot
figure()
plot(t_sim(:,1), Fst_plot_tot)
hold on
plot(t_sim(:,1), Fst_plot(:,1))
plot(t_sim(:,1), Fst_plot(:,2))
legend('Fst Magnitude', 'Fst (horizontal component)', 'Fst (vertical
 component)','Location', 'Best')
title(strcat('Fst vs Time',' ',string))
xlabel('Time')
ylabel('Fst')

end
```

```
Warning: Failure at t=2.736691e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (5.551115e-17)
at time t.
Warning: Failure at t=2.736691e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (5.551115e-17)
at time t.
Warning: Failure at t=2.225603e-01.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (4.440892e-16)
at time t.
Warning: Failure at t=2.225603e-01.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (4.440892e-16)
at time t.
Warning: Failure at t=1.879082e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (5.551115e-17)
at time t.
Warning: Failure at t=1.879082e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (5.551115e-17)
at time t.
Warning: Failure at t=3.090794e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (5.551115e-17)
at time t.
Warning: Failure at t=3.090794e-02.  Unable to meet integration
 tolerances
```

```
without reducing the step size below the smallest value allowed
 (5.551115e-17)
at time t.
Warning: Failure at t=3.106456e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (5.551115e-17)
at time t.
Warning: Failure at t=3.106456e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (5.551115e-17)
at time t.
Warning: Failure at t=2.450535e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (5.551115e-17)
at time t.
Warning: Failure at t=2.450535e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (5.551115e-17)
at time t.
Warning: Failure at t=2.451792e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (5.551115e-17)
at time t.
Warning: Failure at t=2.451792e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (5.551115e-17)
at time t.
Warning: Failure at t=2.555331e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (5.551115e-17)
at time t.
Warning: Failure at t=2.555331e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (5.551115e-17)
at time t.
Warning: Failure at t=2.554846e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (5.551115e-17)
at time t.
Warning: Failure at t=2.554846e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (5.551115e-17)
at time t.
```

```
Warning: Failure at t=2.658737e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (5.551115e-17)
at time t.
Warning: Failure at t=2.658737e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (5.551115e-17)
at time t.
Warning: Failure at t=2.734129e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (5.551115e-17)
at time t.
Warning: Failure at t=2.734129e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (5.551115e-17)
at time t.
Warning: Failure at t=1.877566e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (5.551115e-17)
at time t.
Warning: Failure at t=1.877566e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (5.551115e-17)
at time t.
Warning: Failure at t=1.417554e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (2.775558e-17)
at time t.
Warning: Failure at t=1.417554e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (2.775558e-17)
at time t.
Warning: Failure at t=3.354220e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (1.110223e-16)
at time t.
Warning: Failure at t=3.354220e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (1.110223e-16)
at time t.
Warning: Failure at t=4.290773e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (1.110223e-16)
```

```
at time t.
Warning: Failure at t=4.290773e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (1.110223e-16)
at time t.
Warning: Failure at t=7.552169e-01.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (1.776357e-15)
at time t.
Warning: Failure at t=7.552169e-01.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (1.776357e-15)
at time t.
Warning: Failure at t=8.540176e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (2.220446e-16)
at time t.
Warning: Failure at t=8.540176e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (2.220446e-16)
at time t.
Warning: Failure at t=1.576184e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (5.551115e-17)
at time t.
Warning: Failure at t=1.576184e-02.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (5.551115e-17)
at time t.
Warning: Failure at t=1.993549e-01.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (4.440892e-16)
at time t.
Warning: Failure at t=1.993549e-01.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (4.440892e-16)
at time t.
Warning: Failure at t=1.187588e+00.  Unable to meet integration
 tolerances
without reducing the step size below the smallest value allowed
 (3.552714e-15)
at time t.
Warning: Failure at t=1.187588e+00.  Unable to meet integration
 tolerances
```

```
without reducing the step size below the smallest value allowed
 (3.552714e-15)
at time t.

Local minimum possible. Constraints satisfied.

fmincon stopped because the size of the current step is less than
the value of the step size tolerance and constraints are
satisfied to within the value of the constraint tolerance.


cineq_Problem1 =

 -207.0917
   -0.0182
   -0.3240


ceq_Problem1 =

   1.0e-10 *

    0.0027
    0.0166
   -0.0014
   -0.0073
    0.0083
   -0.0046
    0.0818
    0.1292
   -0.0758
```

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