## ECE381V HW1 - Mingyo Seo (EID: ms84662)

## Question 1

Let  $i_k$  be the slew rate at time  $t_k$ . Then, the equations of linear time-invariant system is given as,

$$egin{aligned} x_{k+1} &= A_k + x_k + B_k u_k \ u_{k+1} &= u_i + \Delta t i_k \end{aligned}$$

Let define new variables as

 $\$  \bar{x}\_k = \begin{cases} \left[ x\_k, u\_k \wedge ight]^{\cdot} & \text{for } k \ ar{u}\_k = [0, i\_k]^\top.

Then, the above equations are formulated as,

$$\bar{x}_{k+1} = A_k \bar{x}_k + B_k \bar{u}_k,$$

where

$$ar{A}_k = egin{bmatrix} A_k & B_k \ O & I \end{bmatrix}$$
 ,  $ar{B}_k = \Delta t egin{bmatrix} O & O \ O & I \end{bmatrix}$  .

From the above formulation, we can apply a quadratic cost with respect to  $\bar{x}_k$  and  $\bar{u}_k$ . To regulate  $i_k$ ,  $u_k$  and  $x_k$  to the zero point, the quadratic cost can be given as,

 $c(\bar{x}_k, \bar{x}_k, \bar{x}_k) = \frac{1\over x}_k^{\infty} Q_k \bar{x}_k + \frac{1\over x}_k^{\infty} Q_k + \frac$ 

By plugging these results into the LQR formulation of an LTI system, the optimal sequence of  $\{\bar{u}_k\}_{k=1}^N$  is given as,

$$ar{u}_k^* = L_k ar{x}_k$$
 for  $k \leq N-1$ ,

where

$$egin{aligned} L_k &= - \Big( R_k + ar{B}_k^ op K_{k+1} ar{B}_k \Big)^{-1} \left( ar{B}_k^ op K_{k+1} ar{B}_k 
ight) ext{ for } k \leq N-1, \ K_k &= \left\{ egin{aligned} Q_k + L_k^ op R_k L_k + \left( ar{A}_k + ar{B}_k L_k 
ight)^ op K_{k+1} \left( ar{A}_k + ar{B}_k L_k 
ight) & ext{ for } k \leq N-1 \ P_N & ext{ for } k = N \end{aligned} 
ight.. \end{aligned}$$

 $\bar{u}_k^*$  can be computed backward from k=N-1 to k=1.

Then, the optimal control sequence  $u_k^st$  can be computed forward from k=1 to k=N-1, by the equation

$$\bar{x}_{k+1} = \bar{A}_k \bar{x}_k + \bar{B}_k \bar{u}_k.$$

## Question 2

Define a new variable, as

 $\$  \\ \text{for } \k Then, we can re-write the formulations of the given dynamics and the quadratic cost with respect  $\bar{x}_k$ , as

$$egin{aligned} ar{x}_{k+1} &= ar{A}_k ar{x}_k, \ c(ar{x}_k) &= rac{1}{2} ar{x}_k^ op ar{Q}_k ar{x}_k + ar{q}_k^ op ar{x}_k + h_k, \end{aligned}$$

where

$$ar{A}_k = egin{bmatrix} A_k & B_k \ O & O \end{bmatrix}$$
 ,  $ar{Q}_k = egin{bmatrix} Q_k & H \ H^ op & R_k \end{bmatrix}$  ,  $ar{q}_k = egin{bmatrix} q_k \ r_k \end{bmatrix}$  .

Let  $J_k$  be the cost-to-go at k-th step. Then,  $J_{N-1}$  is given as,

$$J_{N-1} = rac{1}{2}ar{x}_{N-1}^ op ar{Q}_{N-1}ar{x}_{N-1} + ar{q}_{N-1}^ op + h_{N-1} + J_N$$

By using the equation  $ar{x}_{k+1} = ar{A}_k ar{x}_k$  we can get

$$egin{aligned} J_{N-1} &= rac{1}{2}ar{x}_{N-1}^ op \left[ar{Q}_{N-1}A_N^ op ar{Q}_N
ight]ar{x}_{N-1} + \left[ar{q}_{N-1}^ op + 2d_{N-1}^ op ar{Q}_NA_{N-1} + ar{q}_NA_{N-1}
ight]ar{x}_{N-1} + h_{N-1} + h_$$

where

$$egin{aligned} V_N &= ar{Q}_{N-1} A_N^ op ar{Q}_N, \ v_N &= ig[ar{q}_{N-1}^ op + 2 d_{N-1}^ op ar{Q}_N A_{N-1} + ar{q}_N A_{N-1}ig]^ op, \ w_N &= h_{N-1} + h_N - ar{q}_N d_{N-1} + d_{N-1}^ op d_{N-1}. \end{aligned}$$

Likewise, by computing backward from k=N-1,  $J_k$  is given as,

$$egin{aligned} J_k &= rac{1}{2}ar{x}_k^ opar{Q}_kar{x}_k + ar{q}_k^ op + h_k + J_{k+1} \ &= rac{1}{2}ar{x}_k^ op ig[ar{Q}_kA_{k+1}^ op ar{Q}_{k+1}ig]\,ar{x}_k + ig[ar{q}_k^ op + 2d_k^ op ar{Q}_{k+1}A_k + ar{q}_{k+1}A_kig]\,ar{x}_k + h_k + h_{k+1} - ar{q}_{k+1}d_k + d_k^ op d_k \ &= rac{1}{2}ar{x}_k^ op V_kar{x}_k + v_k^ op ar{x}_k + w_k \end{aligned}$$

where

$$egin{aligned} V_k &= ar{Q}_k A_N^ op ar{Q}_{k+1}, \ v_k &= ig[ar{q}_k^ op + 2d_k^ op ar{Q}_{k+1} A_k + ar{q}_{k+1} A_kig]^ op, \ w_k &= h_k + h_{k+1} - ar{q}_{k+1} d_k + d_k^ op d_k. \end{aligned}$$

Thus, for all  $k \leq N$ , the above cost-to-go can be written as,

$$c(ar{x}_k) = rac{1}{2} (ar{x}_k - ar{b}_k)^ op V_k (ar{x}_k - ar{b}_k) + h_k.$$

whore

$$ar{b}_k = 2ig(V_k + V_k^ opig)^{-1}v^ op$$
 ,

which is minimized at  $ar{x}_k = -ar{b}_k$ .

From the above results, the optimal sequence of  $\{ar{x}_k\}_{k=1}^N$  can be computed backward from k=N, as

$$egin{aligned} ar{x}_k^* &= -2ig(V_k + V_k^ opig)^{-1}v^ op. \ V_k &= ar{Q}_k A_N^ op ar{Q}_{k+1}, \ v_k &= ig[ar{q}_k^ op + 2d_k^ op ar{Q}_{k+1} A_k + ar{q}_{k+1} A_kig]^ op, \ w_k &= h_k + h_{k+1} - ar{q}_{k+1} d_k + d_k^ op d_k. \end{aligned}$$

Then, the optimal control sequence  $u_k^*$  can be found at  $\{\bar{x}_k^*\}_{k=1}^{N-1}$ 

## Question 3

The differential equation of the dynamics are given as

$$\begin{bmatrix} F \\ 0 \end{bmatrix} = \begin{bmatrix} M_t & -ml\cos\theta \\ -ml\cos\theta & J_t \end{bmatrix} \begin{bmatrix} \ddot{q} \\ \ddot{\theta} \end{bmatrix} + \begin{bmatrix} c & 0 \\ 0 & \gamma \end{bmatrix} \begin{bmatrix} \dot{q} \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} ml\theta^2\sin\theta \\ -mgl\sin\theta \end{bmatrix}.$$

We can linearlize the equation as,

$$\begin{bmatrix} F \\ 0 \end{bmatrix} \approx \begin{bmatrix} M_t & -ml\cos\theta \\ -ml\cos\theta & J_t \end{bmatrix} \begin{bmatrix} \ddot{q} \\ \ddot{\theta} \end{bmatrix} + \begin{bmatrix} c & 0 \\ 0 & \gamma \end{bmatrix} \begin{bmatrix} \dot{q} \\ \dot{\theta} \end{bmatrix} + \dot{\theta} \begin{bmatrix} ml\left(2\theta\sin\theta + \theta^2\cos\theta\right) \\ -mgl\cos\theta \end{bmatrix}$$
(6)
$$= C\left(q,\theta\right) \begin{bmatrix} \ddot{q} \\ \ddot{\theta} \end{bmatrix} + D\left(\theta\right) \begin{bmatrix} \dot{q} \\ \dot{\theta} \end{bmatrix}$$
(7)

where

$$C\left(q, heta
ight) = egin{bmatrix} M_t & -ml\cos heta \ -ml\cos heta \end{bmatrix} , D\left( heta
ight) = egin{bmatrix} c & ml\left(2 heta\sin heta + heta^2\cos heta
ight) \ 0 & \gamma - mgl\cos heta \end{bmatrix} .$$

Define the states of the discrete-time system at  $t_k$  as  $x_t = \left[q(t_k), \theta(t_k), \dot{q}(t_k), \dot{\theta}(t_k)\right]^{\top}$  and the control inputs  $u_k = \left[F_k, 0, 0, 0\right]^{\top}$ .

Then, by using the linearlized equation derived above, the dynamics of  $\boldsymbol{x}_t$  is linearlzed as,

$$x_{k+1} pprox A_k x_k + B_k u_k$$

where

$$A_k = egin{bmatrix} I & \delta t I \ O & -\Delta t C^{-1}(q_k, heta) D( heta_k) \end{bmatrix}$$
 ,  $B_k = egin{bmatrix} O & O \ \Delta t C_k^{-1} & O \end{bmatrix}$  .

Here, I and O are the unit, and zero matrices, respectively, and  $\Delta t$  is the time step.

We can also apply the below quadratic cost. Here  $Q_k$ ,  $R_k$  and  $P_N$  are positive semi-definite.

 $c(x_k, u_k) = \left( x_k + 1 \right) = \left( x_k + 1 \right)$ With the above formulations, we can contorl the cart-pole system. The code are presented below.

```
N = 100

MAT_R = 0.1*np.eye(4)

MAT_Q = np.eye(4)

MAT_Q[:2, :2] = 100*np.eye(2)
```

In this simulation, we set up a consistent time step  $\Delta t=0.1 {
m sec}$ , and used a finite time horizon N=100 (in simulation time,  $10 {
m sec}$ ). For the quadratic cost, we used positive definite diagonal matrices.

```
In [19]: # Descrete LQR
def solve_dlqr(A,B,Q,R):

    X = np.array(sp.linalg.solve_discrete_are(A, B, Q, R))
    K = np.linalg.inv(B.T@X@B+R) @ (B.T@X@A)
    eig_vals, eig_vecs = np.linalg.eig(A-B@K)

    return K, X, eig_vals
```

In solve\_dlqr function, we solve the LQR of the discrete-time system of

```
egin{aligned} x_{k+1} &= Ax_k + Bu_k, \ Cost &= \sum_{k=1}^{N-1} \left( x_k^{	op} Q x_k + u_k^{	op} R u_k 
ight) + x_N^{	op} Q x_N. \ A,\,B,\,Q,\,R \ 	ext{are given as the inputs of the function.} \end{aligned}
```

```
In [28]: # Define the cart-pole dyanmics
         class CartPole(object):
             def init (self, parameters):
                 self. dt = parameters['Time step']
                 self. c = parameters['Viscousity']
                 self._r = parameters['Damping']
                 self. l = parameters['Pole length']
                 self. m = parameters['Pendulum mass']
                 self. g = parameters['Gravity']
                 self. M t = parameters['Cart mass'] + parameters['Pendulum mass']
                 self._J_t = parameters['Cart inertia'] + (self._m * self._l**2)
             def reset(self, init state):
                 # state = [Cart pos, Pendulum ang, Cart vel, Pendulum angvl]
                 self. state = np.array(init state)
             def get mat C(self, state):
                 theta = state[1]
                 mat_C = np.array([[self._M_t, - self._m * self._l * np.cos(theta)],
                                    [- self._m * self._l * np.cos(theta), self._J_t]])
                 return mat C
             def get mat D(self, state):
```

```
theta = state[1]
    mat_D = np.array([[self._c, self._m * self._l * (2 * theta * np.sin(theta) + (t
                      [0, self._r - self._m * self._g * np.cos(theta)]])
    return mat D
def linearize(self, state):
    mat C = self. get mat C(state)
    mat D = self. get mat D(state)
    mat inv C = np.linalg.inv(mat C)
    mat A = np.zeros((4, 4))
    mat A[:2, :2] = np.eye(2)
    mat_A[:2, 2:] = self_dt * np.eye(2)
    mat_A[2:, 2:] = self._dt * mat_inv_C @ mat_D
    mat B = np.zeros((4, 4))
    mat B[:2, 2:] = self. dt * mat inv C
    return mat A, mat B
def step(self, u):
    mat C = self. get mat C(self. state)
    mat inv C = np.linalg.inv(mat C)
    dq = self. state[2]
    dtheta = self. state[3]
    theta = self. state[1]
    vec_nonlin = - self._m * self._l * np.sin(theta) * np.array([theta**2, - self._
    vec_lin = - np.array([self._c * dq, self._r * dtheta])
    vec ctrl = np.array(u[2:])
    self._state[:2] += self._dt * self._state[2:]
    self. state[2:] += self. dt * mat inv C @ (vec ctrl + vec lin + vec nonlin)
    return np.copy(self. state)
@property
def state(self):
    return np.copy(self. state)
```

In CartPole, we define the cart-pole system. Every simulation, reset initiate the system with the given initial states. For computing iLQR, linearize computes the linearized dynamic matrices. For evaluation, step computes the forward dynamics.

```
In [56]: target_state = np.array([0,0.5,0,0.0])
env = CartPole(DYNAMIC_PARAMETERS)
env.reset(init_state)
A, B = env.linearize(target_state)
K,_,_ = solve_dlqr(A,B,MAT_Q,MAT_R)
print("K", K)
```

```
print("A", A)
print("B", B)
init state = np.array([0, 10./180.*np.pi, 0., 0.])
U = cp.Variable((N, 4))
X = cp.Variable((N+1,4))
control = np.zeros((N, 4))
states = np.zeros((N+1,4))
for atempt in range(100):
    const = []
    const.append( X[0,:] == np.zeros((4)))
    env.reset(init state)
    states[0,:] = env.state
    for i in range(N):
        A, B = env.linearize(env.state)
        env.step(control[i])
        states[i+1,:] = env.state
        const.append( X[i+1,:] == A @ X[i,:] + B @ U[i,:] )
    X p = X + states
    U p = U + control
    cost = 100*cp.sum((X p[:,0] - target state[0])**2) + \
           100*cp.sum((X p[:,1] - target state[1])**2) + \
           1*cp.sum((X_p[:,2] - target_state[2])**2) + \
           1*cp.sum((X p[:,3] - target state[3])**2) + \
             0.1* cp.sum((U p[:,2])
    prob = cp.Problem(cp.Minimize(cost), const)
    prob.solve()
    print(atempt)
    for a,b in zip(U.value+control, X.value+states):
        print("angle", b[1], "vel", b[1], "act", a[2])
    control += U.value
```

```
K [[ 0.00000000e+00 0.00000000e+00 0.00000000e+00 0.00000000e+00]
 [ 0.00000000e+00 0.0000000e+00 0.00000000e+00 0.00000000e+00]
 [ 3.12264267e+01 -1.54249067e-01 1.56145841e+00 5.31834070e-01]
 [-1.54249067e-01 3.14241633e+01 -7.64682592e-03 2.19783423e+00]]
A [[1.00000000e+00 0.00000000e+00 5.00000000e-02 0.00000000e+00]
 [0.00000000e+00 1.00000000e+00 0.00000000e+00 5.00000000e-02]
 [0.00000000e+00 0.00000000e+00 7.98507138e-05 2.58927506e-01]
 [0.000000000e+00 \ 0.00000000e+00 \ 3.11447084e-05 \ 2.92111986e-01]]
B [[0.
                          0.00079851 0.00031145]
 [0.
            0.
                        0.00031145 0.00039925]
 [0.
            0.
                        0.
                                   0.
                                             ]
[0.
            0.
                        0.
                                   0.
                                             ]]
angle 0.17453292468499115 vel 0.17453292468499115 act -5.829039422084705
angle 0.3604030658856764 vel 0.3604030658856764 act -5.740445395933394
angle 0.3646983113004555 vel 0.3646983113004555 act -5.65154106559572
angle 0.36870290012573353 vel 0.36870290012573353 act -5.562443443601401
angle 0.3722439926450606 vel 0.3722439926450606 act -5.473350148390723
angle 0.3751778610433935 vel 0.3751778610433935 act -5.38452418392933
angle 0.37740018224381056 vel 0.37740018224381056 act -5.296274450761857
angle 0.3788541212386233 vel 0.3788541212386233 act -5.208933582431083
angle 0.37953500435741666 vel 0.37953500435741666 act -5.122834424467315
angle 0.3794907208240517 vel 0.3794907208240517 act -5.038286218901435
angle 0.3788184789174676 vel 0.3788184789174676 act -4.955552034485579
angle 0.3776597143291267 vel 0.3776597143291267 act -4.874829968054945
angle 0.37618938906550475 vel 0.37618938906550475 act -4.79623792280449
angle 0.3746049022478797 vel 0.3746049022478797 act -4.719804445831617
angle 0.37311158958061996 vel 0.37311158958061996 act -4.6454653847777365
angle 0.37190738605611257 vel 0.37190738605611257 act -4.57306670081976
angle 0.3711703293674813 vel 0.3711703293674813 act -4.502374903263605
angle 0.37104291400991446 vel 0.37104291400991446 act -4.433091609384823
angle 0.3716234587628824 vel 0.3716234587628824 act -4.364873968132962
angle 0.37295724571046873 vel 0.37295724571046873 act -4.297357232670627
angle 0.37503456079267006 vel 0.37503456079267006 act -4.230179643878591
angle 0.3777902119774554 vel 0.3777902119774554 act -4.163006137575587
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angle 0.3887880879526001 vel 0.3887880879526001 act -3.9590033194776537
angle 0.39276458269100717 vel 0.39276458269100717 act -3.8897320391878947
angle 0.39656662440260776 vel 0.39656662440260776 act -3.8198315130871388
angle 0.4000090314508007 vel 0.4000090314508007 act -3.7494439236803228
angle 0.4029338376013303 vel 0.4029338376013303 act -3.6787940178886975
angle 0.4052205956648739 vel 0.4052205956648739 act -3.6081741632805837
angle 0.40679358913466657 vel 0.40679358913466657 act -3.537924293303992
angle 0.4076266265591841 vel 0.4076266265591841 act -3.468408525643293
angle 0.4077431724696559 vel 0.4077431724696559 act -3.399989191159889
angle 0.40721305178069034 vel 0.40721305178069034 act -3.33299995499916
angle 0.40614718470433414 vel 0.40614718470433414 act -3.2677205454466898
angle 0.40468948819609285 vel 0.40468948819609285 act -3.204354760947998
angle 0.4030066602787452 vel 0.4030066602787452 act -3.143013387780885
angle 0.40127825648728843 vel 0.40127825648728843 act -3.0837044895400476
angle 0.39968491794000116 vel 0.39968491794000116 act -3.0263313425060563
angle 0.39839643095044397 vel 0.39839643095044397 act -2.970698339752156
angle 0.3975619698939141 vel 0.3975619698939141 act -2.916525542973735
angle 0.3972992985751173 vel 0.3972992985751173 act -2.863469395170207
angle 0.39768720489414716 vel 0.39768720489414716 act -2.8111487129007973
angle 0.3987594146425893 vel 0.3987594146425893 act -2.7591731105606527
angle 0.4005014724426812 vel 0.4005014724426812 act -2.7071713888982685
angle 0.4028514294442844 vel 0.4028514294442844 act -2.654817797481824
angle 0.40570330717273345 vel 0.40570330717273345 act -2.601853677355404
angle 0.4089133406411683 vel 0.4089133406411683 act -2.548102616655366
angle 0.4123105288601387 vel 0.4123105288601387 act -2.4934791856323217
```

```
angle 0.41570821663755103 vel 0.41570821663755103 act -2.437990344984219
angle 0.41891737712608035 vel 0.41891737712608035 act -2.381730243520892
angle 0.4217594641229499 vel 0.4217594641229499 act -2.324868876686655
angle 0.42407955631327354 vel 0.42407955631327354 act -2.2676365119039263
angle 0.4257572564617546 vel 0.4257572564617546 act -2.2103048795224134
angle 0.4267151278244511 vel 0.4267151278244511 act -2.1531664847529006
angle 0.42692477606752144 vel 0.42692477606752144 act -2.0965137400837754
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angle 0.42147153921898284 vel 0.42147153921898284 act -1.879543344565329
angle 0.4192120135020778 vel 0.4192120135020778 act -1.8284344691625638
angle 0.416964336808442 vel 0.416964336808442 act -1.7786301860879687
angle 0.4149262761629203 vel 0.4149262761629203 act -1.7300319870884977
angle 0.4132777330070129 vel 0.4132777330070129 act -1.6824793736176888
angle 0.41216636908710647 vel 0.41216636908710647 act -1.6357622728468266
angle 0.4116947445848569 vel 0.4116947445848569 act -1.5896361524637586
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angle 0.41433329759135995 vel 0.41433329759135995 act -1.452200774237932
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angle 0.4213684608122159 vel 0.4213684608122159 act -1.3115021784176313
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angle 0.4264780626992494 vel 0.4264780626992494 act -1.2142484493790449
angle 0.42867536037811105 vel 0.42867536037811105 act -1.1646207420130485
angle 0.43047472181353175 vel 0.43047472181353175 act -1.1144910494298672
angle 0.4318057871540627 vel 0.4318057871540627 act -1.0640537151559026
angle 0.43264253669614805 vel 0.43264253669614805 act -1.013545885934474
angle 0.4330026351995899 vel 0.4330026351995899 act -0.963231696755355
angle 0.43294195267085567 vel 0.43294195267085567 act -0.9133830266907946
angle 0.4325457019807656 vel 0.4325457019807656 act -0.8642581928617079
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angle 0.4311686184059568 vel 0.4311686184059568 act -0.7690191183364476
angle 0.4304045365811294 vel 0.4304045365811294 act -0.723172049989472
angle 0.42971874758941897 vel 0.42971874758941897 act -0.678557427394765
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