Due at 1700, Fri. 11/16 in bcourses .

Note: up to 2 students may turn in a single writeup. Reading Nise 5, 12.

1. (20 pts) Cayley-Hamilton (handout)

Given

$$A = \begin{bmatrix} -19 & 2 \\ 1 & -20 \end{bmatrix}. \tag{1}$$

By Cayley-Hamilton, $e^{At} = \alpha_0(t)I + \alpha_1(t)A$. Find $\alpha_0(t)I + \alpha_1(t)A$. Show that this e^{At} agrees with $e^{At} = \mathcal{L}^{-1}[sI - A]^{-1}$.

2. (35 pts) Output, State, and Observer Feedback (Separation principle handout)

Given the following system

$$\dot{\mathbf{x}} = A\mathbf{x} + Bu = \begin{bmatrix} 0 & 1 \\ -42 & -13 \end{bmatrix} \mathbf{x} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u(t), \quad y = [6\ 0]\ \mathbf{x}, \qquad \mathbf{x}(0) = \begin{bmatrix} -1 \\ -2 \end{bmatrix}$$

[5pts] a) Design an output feedback controller $u = r - ky$ such that the system has a damping factor of $\zeta = 0.5$. Determine ω_n. Plot the step response $y(t)$ using Matlab.

[5pts] b) Design a state feedback controller $u = r - [k_1\ \ k_2]\mathbf{x}$ such that the closed loop system has $\zeta = 0.5$ and ω_n which is twice the ω_n found in part a. Plot the step response $y(t)$ using Matlab.

[6pts] c) Design a critically damped observer $\dot{\hat{\mathbf{x}}} = A\hat{\mathbf{x}} + Bu + L(y - \hat{y})$ with both observer poles at $s = -20$.

[8pts] d) Write the state space equations for the controller with $u = r - K\hat{\mathbf{x}}$, such that ζ and ω_n are the same as in part b. (This should have 4 state variables, either $\mathbf{x}, \hat{\mathbf{x}}$ or $\mathbf{x}, \mathbf{e}$.) From the separation principle, what are the eigenvalues of the combined system with observer and feedback control? Plot the step response $y(t)$ of the controller using the observer using Matlab.

[6pts] e) Use Matlab to plot the states $\mathbf{x}(t)$ and $\hat{\mathbf{x}}(t)$ for $t > 0$ for the closed loop system of part d for a step input $r(t)$. (Suggestion, use `sys = ss(Ac,Bc,Cc,Dc)` and `[Y,T,X] = lsim(sys,r,t,x0)`, where `Ac, Bc, Cc, Dc` are the matrices for the system with observer).

[5pts] f) Compare the output responses $y(t)$ to the step input from part b) and d). What differences are there? (quantify).

3. (35 pts) Linear Quadratic Regulator (handout)

Consider two cars travelling in a straight line. The dynamics of car 1 are $\dot{x_2} = \ddot{x_1} = 4u_1$, and car 2 has a plant model $\dot{x_4} = \ddot{x_3} = 3u_2$ where u_1 and u_2 are the car's thrust due to engine and braking. (x_1 is a point 0.5 m behind car 1, and x_3 is the front bumper of car 2.) The outputs of the system are $y_1 = x_1$ and $y_2 = x_3 - x_1$. Note that if $y_2 > 0$ then car 2 has intruded on the safety zone of car 1.

Initial conditions are car 1 at -250 m, 30 m/sec, and car 2 at -260 m, 40 m/sec.

[4pts] a) Write the system equations in state space form.

[6pts] b) Use the LQR output method (Matlab function `lqry(sys,Q,R)`, with `Q=diag([1,1])` and `R=diag([1,1])` to find an optimal K for the state feedback control $\mathbf{u} = -K_b\mathbf{x}$. Plot $\mathbf{x}(t)$ and $\mathbf{u}(t)$ for the given initial condition (Matlab `initial`) and state feedback with gain K_b. How long does it take car 1 to get to within 1 m of the origin? What is car 1 velocity at 10 sec? Are there any problems with the system performance?

[12pts] c) Find new cost functions Q and R which maintains $y_2 < 0.2$ meter to prevent a collision, minimizes overshoot, and has both cars moving at less than 0.5 m/sec in 10 seconds. Also, max velocity should be less than $100m \cdot s^{-1}$ (which is approximately 200 mph). Plot $\mathbf{x}(t)$ and $\mathbf{u}(t)$ for the given initial condition (Matlab `initial`) and state feedback with new gain K_c.

[4pts] d) Find the solution to the Riccati equation P using Matlab function `care(A,B,Q,R)` and estimate the cost $J = (x^T P x)(0)$ for each of b) and c).

[4pts] e) Briefly compare the tradeoffs between control effort and time response between the two cases.