University of Maryland at College Park
Dept. of Aerospace Engineering

ENAE 432: Aerospace Control Systems

Final Examination: Design Project

Part I

This project is not a homework, but rather the **approved, formal equivalent of a final examination in ENAE 432**. This is the first of two parts of the project, aimed to get you started thinking about the dynamics of the system and the requirements for your design. More detailed specifications for the final write-up will be contained in the second part of the project, which will follow in about one week.

As this is an examination, **no collaboration of any form is permitted. You must only work individually, and may not discuss your work with anyone else – whether in the class or not**. This means current and former TAs, current and former students, tutors, internet chat groups or message lists, etc are *unauthorized* sources of information for this project. Similarly, you may not reference any materials beyond those explicitly distributed to you in this semester's class or those available in the suggested texts listed in the syllabus. Any materials beyond this approved set, including any past year course materials or materials downloaded from the internet, are *unauthorized and prohibited* sources of information for this project.

Any evidence of collaboration, discussion, or use of unauthorized sources, for any aspect of this project will be immediately forwarded for judicial review with the attendent potential consequences. Note as well that "apathy or acquiescence in the presence of academic dishonesty is not a neutral act" (quoting from the UMD code of academic integrity). To witness academic dishonesty and remain silent is to be complicit and culpable in that dishonesty. I remind you again that this project is your *final examination* – while you will be working on it outside of class, it is in no way similar to a homework that you are free to discuss with others. You are in every way subject to the same rules governing an in-class examination, save that you may use computers and course materials to assist your effort.

The *only* permissible source of discussions about this project is with me personally, and the contents of those discussions may not be shared with others. However, **as this is a final exam**, I will answer only factual questions about the theory discussed in the class, clarifying questions about the subject or general objectives of the project, and practical details about using any provided project code. In particular, I will not give specific guidance on the details of your modeling, data interpretation, controller design, controller implementation, controller performance, etc. These are entirely up to you, and indeed are the primary basis for your final grade on the project.

Lock on target!

A "coronagraph" is a new type of space telescope for detecting exoplanets. It is actually a rather simple technique, using a tiny occlusion disk at the exact center of the field of view. The disk serves to mask the light from the star being observed, allowing the much fainter light possibly reflected from planets circling that star to be detected.

To be successful, such a design must be able to very accurately position the occlusion disk over the observed star, and maintain the occlusion while searching for the faint light from orbiting planets. This accurate pointing is complicated by both the inherently flexible dynamics of a large space telescope, as well as the internal and external disturbance sources which act to perturb the pointing angle.

Your job will be to design a controller to vary the speed of a reaction wheel which reorients the telescope so that a selected target star is brought under the occlusion disk as rapidly as possible, and then ensures that the telescope maintains this pointing as accurately as possible during the observing period.

System Model

We will use a two-element, lumped-mass model to approximate the flexible pointing dynamics of the telescope:

$$\begin{aligned}
I_1\dot{\omega}_1 &= \tau_m + d + K_s(\theta_2 - \theta_1) + B_s(\omega_2 - \omega_1) \\
I_2\dot{\omega}_2 &= K_s(\theta_1 - \theta_2) + B_s(\omega_1 - \omega_2) \\
\dot{\theta}_1 &= \omega_1 \\
\dot{\theta}_2 &= \omega_2 \\
\tau_m &= K_m u \\
y &= 60\left(\frac{180}{\pi}\right)\theta_1 + n
\end{aligned}$$

where I_1, I_2 are inertias, K_s, B_s are structural stiffness and damping constants, and τ_m are the applied reaction wheel torques. The output y is the pointing angle, in arcminutes, and the measurements of this angle contain some noise, n. Disturbances d act as additional torques rotating the vehicle. Finally, K_m is a gain inherent in the drive electronics of the reaction wheel system.

The above is a generic differential equation model for a rotational system with a single structural mode. Specific models depend on the numerical values of the inertias, structural stiffness and damping, and electronics gain. For the project, the following approximate values are known: $I_{tot} = I_1 + I_2 \approx 1000$ and $I_2/I_1 \approx 1/3$. B_s and K_s are such that transient oscillations due to the structural mode have approximately $0.3 - 0.6\%$ damping (i.e. $\zeta \approx 0.003 - 0.006$) and a natural frequency of between 4.5-7.5 rad/sec. Finally K_m is in the range 0.3-3.0.

There is still a wide range of possible models within these approximate values. Each student in the class has a unique model whose parameters are in the indicated ranges. However, the only way to determine the physical characteristics of your own specific vehicle is through careful analysis of representative flight test data as described below.

Simulated Flight Test

Flight test data is available for your vehicle through the `testdata` file provided with this project. The `testdata` function will show you the angular velocity $\dot{y}(t)$ (arcmin/sec) that results from an approximately impulsive input $u(t)$ to the wheel electronics. In particular $u(t) \approx 0.1\delta(t)$ for this test.

The general use of the `testdata` function is

```
[w,t]=testdata(uid);
```

where `uid` must be *the last four digits of your UID (university ID) number.* The outputs will be the time history of $\dot{y}(t)$ at the times specified in the array `t`. Note that there will be a representative amount of measurement noise contained in this data.

Important: You *must* use for your design the model corresponding to your UID number. Each vehicle has unique dynamics, and part of your grade on this project will be determined by running the controller you design for your specific model and examining the results. Using someone else's data (and/or control strategy) will almost certainly produce poor performance or instability in your vehicle, resulting in a very low grade for the project (in addition to being a violation of the honor policy for this exam). If for any reason you cannot generate the data for your model, tell me as soon as possible so that I can resolve the situation quickly.

Controller Design Problem

Your controller must use the available (and noisy) angle measurements $y(t)$ to compute an input $u(t)$ which will steer the telescope to point at the desired star, and maintain this pointing so that the occlusion disk completely covers the star after the initial reorientation. In so doing, it must reject the effects of both the sensor noise, as well as the disturbances which will have both constant and oscillating components. Finally, the wheel is capable of providing no more than ± 0.2 N-m of torque, so that $|\tau_m(t)| \leq 0.2$ must be ensured, or else saturation will occur.

Each observing period is two minutes in length, and part of your final score will be determined by the percentage of this time that the star is completely beneath the occlusion disk. When your controller is activated, the target star will be initially offset by up to ± 3 arcminutes from the center of the field of view, with a small rate of change due to residual angular velocity in the vehicle before the controller is engaged. The location of the target star in the field of view will be also be input as a constant y_d to your controller.

In additional to the usual control design metrics, your controller will need to satisfy two specialized additional requirements: 1.) there must be a single, unique magnitude crossover frequency; and 2.) the Nichols plot for your open-loop transfer function must never enter a box extending from -6dB to +6dB, and $-210°$ to $-150°$. (This latter is roughly equivalent to a comparable exclusion disk around -1 on the Nyquist plot, but a bit easier to visualize).

Design Project: First steps

1. Find generically the transfer function $G(s)$ which relates $Y(s)$ to $U(s)$ symbolically in terms of the physical parameters I_1, K_s, etc. Your answer for $G(s)$ should be a ratio of polynomials.
2. Use the `testdata` function to identify as specifically as possible the numerical form of your $G(s)$. Note that this data will not allow you to identify all parameters uniquely, but it will give you sufficient information to approximately identify the most significant features of your $G(s)$. Use the nominal parameter values as needed where the test data does not allow determination of unique values.
3. Generate a Bode plot for your $G(s)$. Based on this, start to think about how you will need to design your controller to satisfy the above requirements. Plan for relatively limited capabilities in the (space-rated) computer system and electronics which will implement your controller. Loop rates of 10Hz or less, and probably closer to 5Hz, are typical for these missions.