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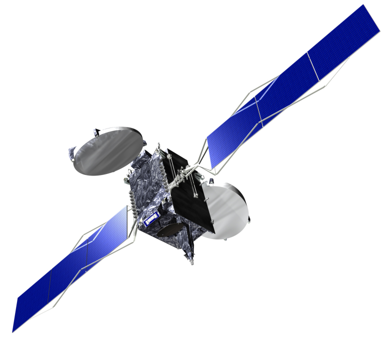
Date: March 21, 2013

To: ME 5506 Students

From: Dr. Steve Southward

Subject: **Midterm Project**



The US Space Surveillance Network (SSN) has monitored more than 24,000 space objects orbiting the earth since 1957. Approximately 3000 of these objects today are satellites. I have just received a notice from the SSN that the satellite known only as #8675309 was recently struck by space debris, causing damage to some of the on-board electronics. Fortunately, the communications uplink to the Telemetry, Tracking, & Control (TT&C) subsystem appears to be working properly, and the power regulation and storage subsystems do not appear to have been damaged.

Much like the example photo above shows, the most common satellite power system is a combination of solar cells and rechargeable batteries. The solar cells are mounted on flexible panels that extend from the main body. These flexible panels are controlled by position control systems in order to maintain their orientation facing the sun. Initial attempts to communicate with these position control systems have failed, leading to the general consensus that they sustained damage from the debris impact.

Stabilization and attitude control are also necessary to ensure that each satellite maintains the proper attitude. Satellites are subjected to a number of forces in space such as particles streaming from the Sun, meteorites, atmospheric drag, gravity from the Moon, gravity gradients, and other perturbations. These forces cause satellites to wobble, spin, drift, or move in other undesirable ways. The attitude control thrusters can be used to maintain proper orientation of the solar panels with the sun, as well as actively damp out unwanted vibrations of the flexible structure.

Your ultimate objective is to design an output feedback control system that can regulate (i.e. drive to zero) three sensor readings (outputs) using two attitude control thrusters (inputs) that are available and functioning properly. As you recall from your previous state-space applied controls course, before you can design an output feedback controller, you will first need a dynamic state-space model of the open-loop plant. Normally, you would develop a physics-based model using the equations of motion, but unfortunately, there is no information available regarding the design of the #8675309 satellite. The first phase of this task (Midterm Project) will be to develop an empirical discrete-time dynamic state-space model of the satellite. The second phase of this task (Final Project) will be to develop and evaluate an output feedback controller.

Although you don't have any physical information about the satellite design, you do have some information that has either been determined or assumed by the engineers at Satellite Recovery Corporation after probing the TT&C system. You can only consider the open-loop plant as a "black box" system that has two inputs and three outputs; however, you must assume that the following are facts:

Control Inputs: u_1 and u_2

- Each control signal drives an attitude control thruster that provides bi-directional dynamic forces to the satellite
- The physical locations of the two control forces are unknown, but each flexible panel appears to contain one of the attitude control thrusters
- Each control signal is capable of generating forces from DC to about 10 Hz
- All control signals are sampled at a fixed rate of 20 Hz
- Control input signals may not exceed a value of $|u_i| \le 10$
- Control signals with values larger than this limit will be clipped
- Control signals must not saturate the DAC's for more than four samples
- The physical units on the control signals are unknown
- You can upload a matrix of control input data to the satellite using **`satellite_uplink.p`** (see below for more detail)

Sensor Responses: y_1, y_2, and y_3

- Each sensor measures a bi-directional response of the satellite frame
- The physical locations and type of the sensors are unknown, but it is believed that each flexible panel contains at least one of the sensors
- Each sensor signal already has appropriate anti-aliasing built into the signal conditioning so there is no need for you to provide this
- All sensor signals are sampled at a fixed rate of 20 Hz
- Sensor signals may not exceed a value of $|y_i| \le 2$
- Sensor signals with values larger than this limit will be clipped
- Sensor signals must not saturate the ADC's for more than four samples
- The physical units on the sensor response signals are unknown
- You can retrieve a matrix of sensor response data from the satellite using **`satellite_uplink.p`** (see below for more detail)
- Each sensor signal is corrupted with stationary random noise n_1, n_2, and n_3

In order to estimate the open-loop dynamics of this MIMO plant, you will need to probe the satellite with an appropriate excitation and upload the signals to the satellite. After generating excitation signals for inputs u_1 and u_2, you must store the data in a $2 \times N$ matrix, where each control input signal is on a separate row:

$$u = \begin{bmatrix} u_{11} & \cdots & u_{1k} & \cdots & u_{1N} \\ u_{21} & \cdots & u_{2k} & \cdots & u_{2N} \end{bmatrix}$$

To upload these excitations to the satellite, you simply pass the control input matrix into the Matlab p-file: **`satellite_uplink.p`**. The exact call structure is given by:

```
y = satellite_uplink(u);
```

where **`y`** is a $3 \times N$ matrix of sensor responses due to the control inputs. If you only want to excite one control input at a time, you still need to upload two rows in the **`u`** matrix, so you will have to define one of the rows with all zeros.

Midterm Project: System ID Task

To complete this task, you will need to identify the dynamics for each of the six input-output paths in the open-loop MIMO satellite system. From the class notes, you know that you will need to make a number of decisions, and your first attempt may not be what is needed. You should take a trial-and-error approach and document your results.

Task 1a. [6 pts] Provide a detailed description of the final excitation you chose for system identification, i.e. type, duration, amplitude, spectral content? Provide a written explanation justifying why you chose this particular excitation.

Task 1b. [10 pts] Demonstrate that your final excitation signal does not saturate the control inputs. On a single figure, create a 2x2 grid of subplots. In two of the subplots, plot the complete time domain signal for each of the excitations. In the other two subplots, plot the properly scaled spectrum for each of the excitations. (1 Figure)

Task 1c. [8 pts] Estimate and document the SNR (dB) for each of the six paths associated with your specific excitations from Task 1a. Provide a written explanation documenting how you estimated the SNR. Note: You must attempt to maximize the SNR without saturating either the excitations or the responses!

Task 1d. [20 pts] Demonstrate that your final excitation signal does not saturate the sensor responses. On a single figure for each actuator, create a 3x2 grid of subplots. In three of the subplots, plot the complete time domain signal for each of the sensor responses as well as the noise-only response. Both curves must be visible! In the other three subplots, plot the properly scaled spectrum for each of the responses and the properly scaled spectrum of the noise responses. (2 Figures)

Task 1e. [12 pts] Estimate frequency response functions for each path in the open-loop plant. Document each FRF with a Bode diagram (generate a separate figure for each FRF). Create a 2x1 grid of subplots on each figure. The first subplot should be the phase angle (degrees) vs. log frequency, and the second subplot should be the dB magnitude vs. log frequency. Provide a written explanation documenting the method you used to obtain the frequency response estimates. (6 Figures)

Task 1f. [8 pts] Estimate and document discrete time transfer function models for each of the six paths in the open-loop plant. Provide a written explanation for the steps you took to achieve these estimates. How many poles and zeros did you choose for each model?

Task 1g. [4 pts] Compute the poles for each of the six discrete time open-loop models you estimated in Task 1f. On a single figure window, use the **`zgrid`** function in

Matlab to generate a z-domain grid, and then plot each set of poles on this plot using distinct markers for each of the six estimated path models. (1 Figure)

Task 1h. [10 pts] Analyze the plot from Task 1g by identifying and documenting "clusters" of poles, and which path models are associated with each pole cluster. Clusters indicate pole locations that are common between paths. Technically all six paths should have the exact same poles since they are all associated with the same dynamic system. This may not be the case because the estimation process is an approximation for each individual path. Some poles will not belong to any cluster and not all paths will show up in every cluster.

Task 1i. [6 pts] Using the estimated pole locations from Task 1g, compute the damping ratios and natural frequencies (Hz) of the first two flexible modes.

Task 1j. [6 pts] Construct a discrete state-space model of the open-loop plant, using the individual path models estimated previously. Provide a written explanation of the steps you took to achieve this state-space model. What is the order of your discrete time state-space model? Do not need list the final A, B, C, and D matrices, but provide a written justification for the order of your final estimated model.

Task 1k. [10 pts] Demonstrate and comment on the accuracy of your discrete state-space model estimate by computing and plotting the frequency response functions. Plot your results on the same figures you generated in Task 1e.

RULES:

- You must use the provided Word Project Report template (or an equivalently formatted TeX document) for your Midterm Project Report
- You must submit only <u>one PDF</u> document and only <u>one Matlab</u> script
- Your total submission must be less than 2 Mb
- If you need to include them in your report, equations must either be inserted with the Word equation editor, or with equivalent TeX math formatting
- Do not include Matlab code in your Midterm Project Report document
- Clearly label sections of your Matlab code with respect to the Task number
- Figures are NOT allowed to have shaded backgrounds
- Figures can not be larger than one-half of an 8.5"x11" page (2 figures/page)
- All text on all figures must be clearly readable (11 point font minimum)
- All signals and axes within a figure must be properly annotated (legend, axis labels, title, colors, and markers where appropriate)
- All frequency domain plots should show data from 0.007 Hz to 10 Hz
- If a figure contains more than one time-domain or frequency-domain plot, each set of axes must have the same y-axis limits for direct comparison
- Answer all parts of every question (don't forget parts of multi-part questions)