24-774: Special Topics in ACSI
Laboratory 1: DC Motor Control

Background: The goal of this lab is to gain basic familiarity with the Tumbbler hardware platform while beginning to code digital controllers. For many of you this will be a review. We will consider step response-based system modeling and model based controller design.

Figure 1: Tumbbler hardware. The hardware has various sensors (wheel encoders, IMU, ultrasonic) that can be used to control the 4 degree of freedom robot.

Background

For this portion of the class we will be looking only at wheel speed, so you will need to place the Tumblller in a position in which its wheels are not touching the ground. Feel free to use either wheel for your analysis.

The relationship between motor voltage and wheel angular velocity is well known and is given by

$$\frac{\omega(s)}{v(s)} = \frac{\frac{k_T}{RJ}}{s + \frac{1}{J}\left(D + \frac{k_T k_B}{R}\right)} = \frac{K}{\tau s + 1}$$

where R is the motor resistance, J the inertia, k_T and k_B are the motor torque and back EMF constants respectively, and D is the damping. We *could* look up all of these parameters in data sheets, but that is painful – it's much easier to convert things into the equivalent form on the right, where we need only find the total system gain K and the time constant τ. Both parameters are easy to compute from the measured step response.

System Modeling

Given that we know that the plant (voltage to speed) is well modeled by a first order transfer function, we need to find its fundamental parameters (gain and time constant). For such a simple model and experimental step response is effective in computing both parameters.

1. Capture data for the step response of the system. You will want to give it a voltage input (make sure it's well above the motor deadzone) and look at the motor speed. Using the

step response, compute the system gain and time constant. If it has been a while, you can review this step here. You are now ready to do model-based control.

2. Find the pulse transfer function for the system with a zero order hold and arbitrary sampling rate T. This is the model that you will use for direct digital design.
3. Create two Simulink models for your plant, one in continuous time and one in discrete time. The continuous time plant should have a time delay that approximates the effect of the zero order hold; keep the sampling period a variable that is easy to change in the Matlab workspace. Provide images of both of your models in the writeup. You can find a good review of Simulink here.

PID Control

For a first (or second) order dynamic system, if you are not using a PID controller design you are doing it wrong. Effective design of PID controllers is still a critical skill in industrial control, so we want to give you some practice applying a PID in hardware.

Controller Design

1. For a first order system you should typically use a PI controller $\left(C_{PI} = k_p + \frac{k_I}{s} = k_p \frac{s+\frac{k_I}{k_p}}{s}\right)$. Design a PI controller such that its zero (approximately) cancels the pole of the system model. You are now left with a pure integrator with time delay in the forward path. There are now two parameters that we need to consider: the overall gain of the controller k_p, and the time delay T.

   ***Discussion*:**
   a. For a time delay of 5 ms, find the maximum gain for which the system is stable (you can use Simulink to test this). What is the maximum gain for a delay of 100 ms? In both cases, where are the closed loop poles at the gain that leads to instability?
   b. Using the pulse transfer function, find the maximum sampling period T that provides stability given the maximum gain you found in part a for a 5 ms delay. Does it agree with the analysis you did above, i.e. does it return ~ 5ms?
   c. Based on your Simulink model, find a value of the gain that you are happy with (no hard requirements) for a sampling rate of 5 ms. Plot the step response of the closed loop system.
2. An alternative approach is to let Matlab design your PID controller for you. In your discrete time Simulink model add a discrete PID control block. Now you can use Simulink to optimize your design as in this link.

   Discussion:
   a. Design a controller using the optimization that gives performance you are happy with (no hard requirements here) for a sampling period of 5ms. Compare the response of your discrete time model using this controller with the response of your CT model using the controller designed in part 1. Which works better?

Hardware Integration

3. Write code that implements a controller of arbitrary order. Provide an image of your controller code in the report.
   Discussion:
   a. Using your code, implement your digital controller (part 2) and plot the step response. Recall that for a PID controller to be realizable you will have to add a pole at high frequency (see the Simulink PID block).
   b. Discretize the continuous design you performed in part 1 (no need for a high frequency pole – no derivative action). Apply this PID in your code.
   c. How do the measured step responses relate to the Simulink responses? What might be causing differences between the responses?
4. Thus far we have developed a servo speed controller. What if we want to control position as in a standard servo motor? Design a PID controller using the method of your choice to control the plant below.

$$\frac{\theta(s)}{v(s)} = \frac{K}{s(\tau s + 1)}$$

   Discussion:
   a. Implement your controller in hardware and compare the step response to that found from the Simulink model. You will almost certainly have derivative control action in this case, so be sure to add a pole to make your controller realizable.

Reporting

Compile a single PDF lab report following the guidelines below.

Your report should be organized in terms of numbered items in the lab procedure. For each numbered item in the lab procedure you must address the following items at a minimum:

1.) The details of all calculations involved in generating your results. Be sure to highlight the main results.
2.) Presentation of your results in the form of plots and tables. This should include all relevant plots and Simulink models. Do not present plots that use the black background that is the Simulink scope default.
3.) General discussion. What sense do you make of the results? What can you conclude?
4.) Answers to all the discussion questions in the lab procedure.

After completing these tasks for all numbered items in the lab procedure, complete the following sections to finish your report:

- Conclusions: What were the main results? What did you learn (if anything) by completing the lab? What suggestions do you have to make the lab better or more interesting?
- References: Compile all of your references into a single section at the end of the document. I highly recommend the use of a reference manager, e.g. Bibtex, EndNote, etc.