

General Discussion for Lab 2

For this lab, I setup the following tasks.

The Trajectory Interpolator, running in the ISR for timer 0, a 10ms CTC timer.

The PDController, running in the ISR for timer 3, a 20ms CTC timer.

A millisecond timer, accurate to within %0.03, running in the ISR for timer 1, a 100us CTC timer.

A console user interface task, running in the main loop.

General functions for setting up CTC timers are in `ktimers.[ch]` You may specify a period in msec, a timer number (0, 1, or 3), a callback function and an argument to pass to the callback function. The callback function is invoked from the ISR. In this way, you can easily setup a function to be called and not remember the specifics of how to define an ISR. There is also an option to setup timer 1 or 3 as a millisecond timer, to replace the pololou functions like `get_ms()` that use timer 2 (which is being used for the motor speed) adjustment.

The `kserial.[ch]` files specify functions that perform serial I/O, including `s_printf`, used exactly like standard `printf`, except it writes to the serial output.

The `kutils.[ch]` files contain some useful functions, including functions to return whether interrupts are currently enabled, and macros `BEGIN_ATOMIC` and `END_ATOMIC`, which ensure that interrupts are disabled between them, and that interrupts are restored to their previous state afterward.

The `kcmd.[ch]` files contain functions that poll serial input each time they are called, accumulating characters until the user hits the enter key, when they return a value indicate a command has been entered. The command line is parsed into an `argc/argv` and a pre-registered function associated with `argv[0]`, the command name, is invoked. This is easily extended to additional commands. The final list of commands I have written is

```
help or '?' {displays the following}
commands:
  L {start/stop logging Pr, Pm, and T}
  I {same as L}
  kp new_value {set/get current value of Kp}
  kd new_value {set/get current value of Kd}
  info {displays the following info}
      kp
      kd
      torque
```

```

        target-angle
        current-angle
        max-acceleration
        PDControl-period
        acceleration factor {max acceleration will be MAX_TORQUE/factor}
        torque new_value
        rotate degrees {rotate the motor}
        period {set msec period of PDControl task}
        zero {stop motor, handlers, set angle to 0}
        go
        stop
        xprog {run the canned program}
        clock period nloops numerator denominator {test the 1 ms timer by setting a
period}

```

You may notice that I removed the P, p, D, and d commands in favor of the kp/kd commands that allow setting of Kp or Kd to specific values rather than nudging them up or down. Other useful commands include

- period: for adjusting the period of the PDController
- acceleration: for adjusting the maximum allowed change in torque for each iteration of the PDController (this avoids jackrabbit starts and sudden stops)
- xprog: run the specified program (rotate 360, pause 0.5s, rotate -360, pause 0.5s, rotate 5).

I modified the logging output from what you asked. A line of log output looks like this:

```
19 Pr=2131, Pm=1954, T=1000, TC=1416, 8.00*177 + 0.00*0.0238, 1416 + 0, exceeds max
```

The first number is a line number. TC is the calculated torque, 1416 in this case. You can see that 8.00 is Kp, 177 is (Pr-Pm), 0.00 is Kd, and 0.0238 is the velocity, in degrees/ms. The $8.00 \times 177 + 0.00 \times 0.0238$ simplifies to $1416 + 0$, so you can easily see how all factors contribute. In addition, there may be additional adjustments made to the torque. In this case, "exceeds max" indicates the the value computed, 1416, exceeds the maximum allowed. In my system, torque must be in the range [-1000,1000].

Questions

1. Experiment with the speed of the motor: Run your motor at full speed. Modify your gains to achieve position control at that speed (as best you can). Slow the motor down as much as possible. Modify your gains to acheive position control. Repeat with one or two speeds in between. For each, record the approximate speed in rotations per second, record your equation (gains), and report on the behavior of the system and your ability to control the position.

My program allows dynamic setting of the period of the PDControl task. At 1 KHz, a period of 1

msec, the speed is not interesting because it is always measured as 0. You recommended checking the speed only sometimes during the task, but doing it this way means that you are setting new torque every 1 msec but using a speed that was determined in the past. I opted instead to modify the period of the PDControl task. I experimented with this period, and a 100 msec there is significant overshoot in positioning, but at 20 msec the positioning is clean, and there is a measurable velocity. So I went with 20 msec.

My torque calculation uses the formula as given, with some additional modifications

$$T = K_p(P_r - P_m) + K_d V_m$$

Modification 1: I limit the change in torque from the previous iteration.

Modification 2: If the computed torque is too small to produce movement, but the target position is not yet reached, the minimum torque is applied.

With $K_p=10$ and $K_d=-20$, a rotation of 18000 degrees ($18000/360=50$ revolutions) takes 28.8 seconds, including the slight ramp-up and ramp-down time. This is $50/28.8=1.74$ revolutions/sec. There is a slight overshoot with the gain this high.

This compares with setting the motor torque directly (ignoring the control tasks) and measuring the top speed at $100.0/54.63=1.83$ revolutions/sec.

The minimum torque that reliably produces motion is 4.5% of full on. The speed at that setting is $2/37.8=0.053$ revolutions/sec. This can be achieved by setting $K_p=K_d=0$ and relying on the modifications I stated above, that the minimum torque is applied.

Here is sample output with $K_p=20$, $K_d=-1000$, performing a rotation of 360 degrees. Note that my torque is specified in a range of $[-1000,1000]$.

1 $P_r=180$, $P_m=0$, $T=250$, $TC=3600$, $20.00*180 + -1000.00*0.0000$, $3600 + 0$, rapid acc, exceeds max

2 $P_r=180$, $P_m=0$, $T=500$, $TC=3600$, $20.00*180 + -1000.00*0.0000$, $3600 + 0$, rapid acc, exceeds max

3 $P_r=182$, $P_m=2$, $T=750$, $TC=3595$, $20.00*180 + -1000.00*0.0043$, $3600 + -4$, rapid acc, exceeds max

4 $P_r=185$, $P_m=5$, $T=1000$, $TC=3593$, $20.00*180 + -1000.00*0.0065$, $3600 + -6$, exceeds max

5 $P_r=191$, $P_m=11$, $T=1000$, $TC=3586$, $20.00*180 + -1000.00*0.0130$, $3600 + -13$, exceeds max

6 $P_r=196$, $P_m=16$, $T=1000$, $TC=3589$, $20.00*180 + -1000.00*0.0108$, $3600 + -10$, exceeds max

7 $P_r=205$, $P_m=25$, $T=1000$, $TC=3580$, $20.00*180 + -1000.00*0.0194$, $3600 + -19$, exceeds max

8 $P_r=213$, $P_m=33$, $T=1000$, $TC=3582$, $20.00*180 + -1000.00*0.0173$, $3600 + -17$, exceeds max

9 $P_r=222$, $P_m=45$, $T=1000$, $TC=3514$, $20.00*177 + -1000.00*0.0260$, $3540 + -25$, exceeds max

10 $P_r=233$, $P_m=56$, $T=1000$, $TC=3516$, $20.00*177 + -1000.00*0.0238$, $3540 + -23$, exceeds max

11 Pr=244, Pm=64, T=1000, TC=3582, $20.00 \times 180 + -1000.00 \times 0.0173$, 3600 + -17, exceeds max

12 Pr=255, Pm=78, T=1000, TC=3509, $20.00 \times 177 + -1000.00 \times 0.0303$, 3540 + -30, exceeds max

13 Pr=267, Pm=87, T=1000, TC=3580, $20.00 \times 180 + -1000.00 \times 0.0194$, 3600 + -19, exceeds max

14 Pr=278, Pm=101, T=1000, TC=3509, $20.00 \times 177 + -1000.00 \times 0.0303$, 3540 + -30, exceeds max

15 Pr=289, Pm=109, T=1000, TC=3582, $20.00 \times 180 + -1000.00 \times 0.0173$, 3600 + -17, exceeds max

16 Pr=300, Pm=123, T=1000, TC=3509, $20.00 \times 177 + -1000.00 \times 0.0303$, 3540 + -30, exceeds max

17 Pr=312, Pm=135, T=1000, TC=3514, $20.00 \times 177 + -1000.00 \times 0.0259$, 3540 + -25, exceeds max

18 Pr=323, Pm=146, T=1000, TC=3516, $20.00 \times 177 + -1000.00 \times 0.0238$, 3540 + -23, exceeds max

19 Pr=334, Pm=157, T=1000, TC=3516, $20.00 \times 177 + -1000.00 \times 0.0238$, 3540 + -23, exceeds max

20 Pr=345, Pm=168, T=1000, TC=3516, $20.00 \times 177 + -1000.00 \times 0.0238$, 3540 + -23, exceeds max

21 Pr=360, Pm=182, T=1000, TC=3529, $20.00 \times 178 + -1000.00 \times 0.0303$, 3560 + -30, exceeds max

22 Pr=360, Pm=194, T=1000, TC=3294, $20.00 \times 166 + -1000.00 \times 0.0260$, 3320 + -25, exceeds max

23 Pr=360, Pm=205, T=1000, TC=3076, $20.00 \times 155 + -1000.00 \times 0.0238$, 3100 + -23, exceeds max

24 Pr=360, Pm=216, T=1000, TC=2856, $20.00 \times 144 + -1000.00 \times 0.0238$, 2880 + -23, exceeds max

25 Pr=360, Pm=227, T=1000, TC=2636, $20.00 \times 133 + -1000.00 \times 0.0238$, 2660 + -23, exceeds max

26 Pr=360, Pm=239, T=1000, TC=2394, $20.00 \times 121 + -1000.00 \times 0.0260$, 2420 + -25, exceeds max

27 Pr=360, Pm=253, T=1000, TC=2109, $20.00 \times 107 + -1000.00 \times 0.0302$, 2140 + -30, exceeds max

28 Pr=360, Pm=264, T=1000, TC=1896, $20.00 \times 96 + -1000.00 \times 0.0238$, 1920 + -23, exceeds max

29 Pr=360, Pm=275, T=1000, TC=1676, $20.00 \times 85 + -1000.00 \times 0.0238$, 1700 + -23, exceeds max

30 Pr=360, Pm=286, T=1000, TC=1456, $20.00 \times 74 + -1000.00 \times 0.0238$, 1480 + -23, exceeds max

31 Pr=360, Pm=300, T=1000, TC=1169, $20.00 \times 60 + -1000.00 \times 0.0302$, 1200 + -30, exceeds max

32 Pr=360, Pm=312, T=934, TC=934, $20.00 \times 48 + -1000.00 \times 0.0260$, 960 + -25

33 Pr=360, Pm=323, T=716, TC=716, $20.00 \times 37 + -1000.00 \times 0.0239$, 740 + -23
 34 Pr=360, Pm=334, T=496, TC=496, $20.00 \times 26 + -1000.00 \times 0.0239$, 520 + -23
 35 Pr=360, Pm=345, T=276, TC=276, $20.00 \times 15 + -1000.00 \times 0.0239$, 300 + -23
 36 Pr=360, Pm=357, T=45, TC=33, $20.00 \times 3 + -1000.00 \times 0.0261$, 60 + -26, no movement
 37 Pr=360, Pm=362, T=-50, TC=-50, $20.00 \times -2 + -1000.00 \times 0.0109$, -40 + -10
 38 Pr=360, Pm=368, T=-173, TC=-173, $20.00 \times -8 + -1000.00 \times 0.0130$, -160 + -13
 39 Pr=360, Pm=371, T=-226, TC=-226, $20.00 \times -11 + -1000.00 \times 0.0065$, -220 + -6
 40 Pr=360, Pm=371, T=-220, TC=-220, $20.00 \times -11 + -1000.00 \times 0.0000$, -220 + 0
 41 Pr=360, Pm=368, T=-153, TC=-153, $20.00 \times -8 + -1000.00 \times -0.0065$, -160 + 6
 42 Pr=360, Pm=365, T=-93, TC=-93, $20.00 \times -5 + -1000.00 \times -0.0065$, -100 + 6
 43 Pr=360, Pm=365, T=-100, TC=-100, $20.00 \times -5 + -1000.00 \times 0.0000$, -100 + 0
 44 Pr=360, Pm=362, T=-45, TC=-33, $20.00 \times -2 + -1000.00 \times -0.0065$, -40 + 6, no movement
 45 Pr=360, Pm=362, T=-45, TC=-40, $20.00 \times -2 + -1000.00 \times 0.0000$, -40 + 0, no movement
 46 Pr=360, Pm=360, T=0, TC=0, $20.00 \times 0 + -1000.00 \times 0.0000$, 0 + 0

As you can see, Pr starts out at 180 and gradually moves to 360. That is because the trajectory interpolator gives PDCControl a max delta of 180. You can see the effect of limiting the acceleration in the first few iterations. The calculated torque (given as TC), is larger than the max, and the change from zero can be at most 1/4 of 1000, or 250. That is why the torque used, T, goes from 0, to 250, to 500, to 750, and finally to 1000. Once the torque reaches 1000, it maxes out, despite the formula producing larger calculations. As we near the target of 360, the torque drops, but you can see that it overshoots to a maximum of 371 degrees. You also see that several times the computed torque was too small to produce motion, and so the minimum (+-45) was used.

Testing various values for Kd seem to make little difference. Here are the results with Kd=-2000.

1 Pr=180, Pm=0, T=250, TC=3600, $20.00 \times 180 + -2000.00 \times 0.0000$, 3600 + 0, rapid acc, exceeds max

2 Pr=180, Pm=0, T=500, TC=3600, $20.00 \times 180 + -2000.00 \times 0.0000$, 3600 + 0, rapid acc, exceeds max

3 Pr=182, Pm=2, T=750, TC=3591, $20.00 \times 180 + -2000.00 \times 0.0043$, 3600 + -8, rapid acc, exceeds max

4 Pr=185, Pm=5, T=1000, TC=3586, $20.00 \times 180 + -2000.00 \times 0.0065$, 3600 + -13, exceeds max

5 Pr=191, Pm=11, T=1000, TC=3573, $20.00 \times 180 + -2000.00 \times 0.0130$, 3600 + -26, exceeds max

6 Pr=196, Pm=19, T=1000, TC=3505, $20.00 \times 177 + -2000.00 \times 0.0173$, 3540 + -34, exceeds max

7 Pr=208, Pm=28, T=1000, TC=3561, $20.00 \times 180 + -2000.00 \times 0.0194$, 3600 + -38, exceeds max

8 Pr=216, Pm=36, T=1000, TC=3565, $20.00 \times 180 + -2000.00 \times 0.0173$, 3600 + -34, exceeds max

9 Pr=225, Pm=47, T=1000, TC=3512, $20.00 \times 178 + -2000.00 \times 0.0238$, 3560 + -47, exceeds max

10 Pr=236, Pm=56, T=1000, TC=3561, $20.00 \times 180 + -2000.00 \times 0.0194$, 3600 + -38, exceeds max

11 Pr=247, Pm=67, T=1000, TC=3552, $20.00 \times 180 + -2000.00 \times 0.0238$, 3600 + -47, exceeds max

12 Pr=255, Pm=78, T=1000, TC=3492, $20.00 \times 177 + -2000.00 \times 0.0238$, 3540 + -47, exceeds max

13 Pr=267, Pm=90, T=1000, TC=3488, $20.00 \times 177 + -2000.00 \times 0.0260$, 3540 + -51, exceeds max

14 Pr=278, Pm=101, T=1000, TC=3492, $20.00 \times 177 + -2000.00 \times 0.0238$, 3540 + -47, exceeds max

15 Pr=289, Pm=112, T=1000, TC=3492, $20.00 \times 177 + -2000.00 \times 0.0238$, 3540 + -47, exceeds max

16 Pr=303, Pm=123, T=1000, TC=3552, $20.00 \times 180 + -2000.00 \times 0.0238$, 3600 + -47, exceeds max

17 Pr=315, Pm=135, T=1000, TC=3548, $20.00 \times 180 + -2000.00 \times 0.0259$, 3600 + -51, exceeds max

18 Pr=326, Pm=146, T=1000, TC=3552, $20.00 \times 180 + -2000.00 \times 0.0238$, 3600 + -47, exceeds max

19 Pr=337, Pm=157, T=1000, TC=3552, $20.00 \times 180 + -2000.00 \times 0.0238$, 3600 + -47, exceeds max

20 Pr=348, Pm=171, T=1000, TC=3479, $20.00 \times 177 + -2000.00 \times 0.0302$, 3540 + -60, exceeds max

21 Pr=360, Pm=182, T=1000, TC=3512, $20.00 \times 178 + -2000.00 \times 0.0238$, 3560 + -47, exceeds max

22 Pr=360, Pm=194, T=1000, TC=3268, $20.00 \times 166 + -2000.00 \times 0.0260$, 3320 + -51, exceeds max

23 Pr=360, Pm=205, T=1000, TC=3052, $20.00 \times 155 + -2000.00 \times 0.0238$, 3100 + -47, exceeds max

24 Pr=360, Pm=216, T=1000, TC=2832, $20.00 \times 144 + -2000.00 \times 0.0238$, 2880 + -47, exceeds max

max

25 Pr=360, Pm=227, T=1000, TC=2612, $20.00 \times 133 + -2000.00 \times 0.0238$, 2660 + -47, exceeds max

26 Pr=360, Pm=239, T=1000, TC=2368, $20.00 \times 121 + -2000.00 \times 0.0260$, 2420 + -51, exceeds max

27 Pr=360, Pm=250, T=1000, TC=2152, $20.00 \times 110 + -2000.00 \times 0.0238$, 2200 + -47, exceeds max

28 Pr=360, Pm=264, T=1000, TC=1859, $20.00 \times 96 + -2000.00 \times 0.0303$, 1920 + -60, exceeds max

29 Pr=360, Pm=275, T=1000, TC=1652, $20.00 \times 85 + -2000.00 \times 0.0238$, 1700 + -47, exceeds max

30 Pr=360, Pm=286, T=1000, TC=1432, $20.00 \times 74 + -2000.00 \times 0.0238$, 1480 + -47, exceeds max

31 Pr=360, Pm=300, T=1000, TC=1139, $20.00 \times 60 + -2000.00 \times 0.0302$, 1200 + -60, exceeds max

32 Pr=360, Pm=312, T=908, TC=908, $20.00 \times 48 + -2000.00 \times 0.0260$, 960 + -51

33 Pr=360, Pm=323, T=692, TC=692, $20.00 \times 37 + -2000.00 \times 0.0239$, 740 + -47

34 Pr=360, Pm=334, T=472, TC=472, $20.00 \times 26 + -2000.00 \times 0.0239$, 520 + -47

35 Pr=360, Pm=345, T=252, TC=252, $20.00 \times 15 + -2000.00 \times 0.0239$, 300 + -47

36 Pr=360, Pm=354, T=80, TC=80, $20.00 \times 6 + -2000.00 \times 0.0196$, 120 + -39

37 Pr=360, Pm=362, T=-74, TC=-74, $20.00 \times -2 + -2000.00 \times 0.0174$, -40 + -34

38 Pr=360, Pm=365, T=-113, TC=-113, $20.00 \times -5 + -2000.00 \times 0.0065$, -100 + -13

39 Pr=360, Pm=368, T=-173, TC=-173, $20.00 \times -8 + -2000.00 \times 0.0065$, -160 + -13

40 Pr=360, Pm=368, T=-160, TC=-160, $20.00 \times -8 + -2000.00 \times 0.0000$, -160 + 0

41 Pr=360, Pm=365, T=-87, TC=-87, $20.00 \times -5 + -2000.00 \times -0.0065$, -100 + 12

42 Pr=360, Pm=365, T=-100, TC=-100, $20.00 \times -5 + -2000.00 \times 0.0000$, -100 + 0

43 Pr=360, Pm=362, T=-45, TC=-27, $20.00 \times -2 + -2000.00 \times -0.0065$, -40 + 12, no movement

44 Pr=360, Pm=362, T=-45, TC=-40, $20.00 \times -2 + -2000.00 \times 0.0000$, -40 + 0, no movement

45 Pr=360, Pm=360, T=0, TC=0, $20.00 \cdot 0 + -2000.00 \cdot 0.0000$, $0 + 0$

You can see that the overshoot is slightly smaller with $K_d=-2000$, but it gets to the target sooner, with 45 lines of log output rather than 46 previously.

Experimenting with various values shows that a value of $K_p=10$ and $K_d=-1000$ produce very smooth results:

1 Pr=180, Pm=0, T=250, TC=1800, $10.00 \cdot 180 + -1000.00 \cdot 0.0000$, $1800 + 0$, rapid acc, exceeds max

2 Pr=180, Pm=0, T=500, TC=1800, $10.00 \cdot 180 + -1000.00 \cdot 0.0000$, $1800 + 0$, rapid acc, exceeds max

3 Pr=182, Pm=2, T=750, TC=1795, $10.00 \cdot 180 + -1000.00 \cdot 0.0043$, $1800 + -4$, rapid acc, exceeds max

4 Pr=185, Pm=5, T=1000, TC=1793, $10.00 \cdot 180 + -1000.00 \cdot 0.0065$, $1800 + -6$, exceeds max

5 Pr=191, Pm=11, T=1000, TC=1786, $10.00 \cdot 180 + -1000.00 \cdot 0.0130$, $1800 + -13$, exceeds max

6 Pr=196, Pm=19, T=1000, TC=1752, $10.00 \cdot 177 + -1000.00 \cdot 0.0173$, $1770 + -17$, exceeds max

7 Pr=205, Pm=28, T=1000, TC=1750, $10.00 \cdot 177 + -1000.00 \cdot 0.0195$, $1770 + -19$, exceeds max

8 Pr=213, Pm=36, T=1000, TC=1752, $10.00 \cdot 177 + -1000.00 \cdot 0.0173$, $1770 + -17$, exceeds max

9 Pr=225, Pm=45, T=1000, TC=1780, $10.00 \cdot 180 + -1000.00 \cdot 0.0194$, $1800 + -19$, exceeds max

10 Pr=236, Pm=56, T=1000, TC=1776, $10.00 \cdot 180 + -1000.00 \cdot 0.0238$, $1800 + -23$, exceeds max

11 Pr=244, Pm=67, T=1000, TC=1746, $10.00 \cdot 177 + -1000.00 \cdot 0.0238$, $1770 + -23$, exceeds max

12 Pr=255, Pm=78, T=1000, TC=1746, $10.00 \cdot 177 + -1000.00 \cdot 0.0238$, $1770 + -23$, exceeds max

13 Pr=267, Pm=90, T=1000, TC=1744, $10.00 \cdot 177 + -1000.00 \cdot 0.0259$, $1770 + -25$, exceeds max

14 Pr=281, Pm=101, T=1000, TC=1776, $10.00 \cdot 180 + -1000.00 \cdot 0.0238$, $1800 + -23$, exceeds max

15 Pr=292, Pm=115, T=1000, TC=1739, $10.00 \cdot 177 + -1000.00 \cdot 0.0303$, $1770 + -30$, exceeds max

16 Pr=303, Pm=126, T=1000, TC=1746, $10.00 \cdot 177 + -1000.00 \cdot 0.0238$, $1770 + -23$, exceeds max

17 Pr=315, Pm=137, T=1000, TC=1756, $10.00 \cdot 178 + -1000.00 \cdot 0.0238$, $1780 + -23$, exceeds max

18 Pr=329, Pm=149, T=1000, TC=1774, $10.00 \cdot 180 + -1000.00 \cdot 0.0260$, $1800 + -25$, exceeds max

19 Pr=340, Pm=160, T=1000, TC=1776, $10.00 \cdot 180 + -1000.00 \cdot 0.0238$, $1800 + -23$, exceeds max

20 Pr=351, Pm=171, T=1000, TC=1776, $10.00 \cdot 180 + -1000.00 \cdot 0.0238$, $1800 + -23$, exceeds max

21 Pr=360, Pm=182, T=1000, TC=1756, $10.00 \times 178 + -1000.00 \times 0.0238$, 1780 + -23, exceeds max
 22 Pr=360, Pm=196, T=1000, TC=1609, $10.00 \times 164 + -1000.00 \times 0.0303$, 1640 + -30, exceeds max
 23 Pr=360, Pm=208, T=1000, TC=1494, $10.00 \times 152 + -1000.00 \times 0.0259$, 1520 + -25, exceeds max
 24 Pr=360, Pm=219, T=1000, TC=1386, $10.00 \times 141 + -1000.00 \times 0.0238$, 1410 + -23, exceeds max
 25 Pr=360, Pm=230, T=1000, TC=1276, $10.00 \times 130 + -1000.00 \times 0.0238$, 1300 + -23, exceeds max
 26 Pr=360, Pm=244, T=1000, TC=1129, $10.00 \times 116 + -1000.00 \times 0.0302$, 1160 + -30, exceeds max
 27 Pr=360, Pm=255, T=1000, TC=1026, $10.00 \times 105 + -1000.00 \times 0.0238$, 1050 + -23, exceeds max
 28 Pr=360, Pm=267, T=904, TC=904, $10.00 \times 93 + -1000.00 \times 0.0260$, 930 + -25
 29 Pr=360, Pm=278, T=796, TC=796, $10.00 \times 82 + -1000.00 \times 0.0239$, 820 + -23
 30 Pr=360, Pm=289, T=686, TC=686, $10.00 \times 71 + -1000.00 \times 0.0239$, 710 + -23
 31 Pr=360, Pm=300, T=576, TC=576, $10.00 \times 60 + -1000.00 \times 0.0239$, 600 + -23
 32 Pr=360, Pm=312, T=453, TC=453, $10.00 \times 48 + -1000.00 \times 0.0261$, 480 + -26
 33 Pr=360, Pm=323, T=346, TC=346, $10.00 \times 37 + -1000.00 \times 0.0239$, 370 + -23
 34 Pr=360, Pm=331, T=272, TC=272, $10.00 \times 29 + -1000.00 \times 0.0174$, 290 + -17
 35 Pr=360, Pm=340, T=180, TC=180, $10.00 \times 20 + -1000.00 \times 0.0196$, 200 + -19
 36 Pr=360, Pm=345, T=139, TC=139, $10.00 \times 15 + -1000.00 \times 0.0109$, 150 + -10
 37 Pr=360, Pm=351, T=76, TC=76, $10.00 \times 9 + -1000.00 \times 0.0130$, 90 + -13
 38 Pr=360, Pm=354, T=53, TC=53, $10.00 \times 6 + -1000.00 \times 0.0065$, 60 + -6
 39 Pr=360, Pm=357, T=45, TC=23, $10.00 \times 3 + -1000.00 \times 0.0065$, 30 + -6, no movement
 40 Pr=360, Pm=360, T=0, TC=0, $10.00 \times 0 + -1000.00 \times 0.0000$, 0 + 0

You can see that there is no overshoot, and there are only 40 lines of log output.

2. Change the step size to something very large (more than 2π), and try a reference position of $4\pi + \text{current_position}$. How does system behavior differ from your tuned step size? Try tuning your controller for that very large step size. What happens if you then set the reference position to be very close to the current position (within a few degrees)?

The controller requires no special tuning for different step sizes. Here is sample output for a rotation of 720 degrees.

1 Pr=180, Pm=0, T=250, TC=1800, $10.00 \times 180 + -1000.00 \times 0.0000$, 1800 + 0, rapid acc, exceeds max
 2 Pr=180, Pm=0, T=500, TC=1800, $10.00 \times 180 + -1000.00 \times 0.0000$, 1800 + 0, rapid acc, exceeds max
 3 Pr=182, Pm=2, T=750, TC=1795, $10.00 \times 180 + -1000.00 \times 0.0043$, 1800 + -4, rapid acc, exceeds max

4 Pr=185, Pm=5, T=1000, TC=1793, $10.00 \times 180 + -1000.00 \times 0.0065$, 1800 + -6, exceeds max
 5 Pr=191, Pm=11, T=1000, TC=1786, $10.00 \times 180 + -1000.00 \times 0.0130$, 1800 + -13, exceeds max
 6 Pr=196, Pm=19, T=1000, TC=1752, $10.00 \times 177 + -1000.00 \times 0.0173$, 1770 + -17, exceeds max
 7 Pr=208, Pm=28, T=1000, TC=1780, $10.00 \times 180 + -1000.00 \times 0.0195$, 1800 + -19, exceeds max
 8 Pr=216, Pm=36, T=1000, TC=1782, $10.00 \times 180 + -1000.00 \times 0.0173$, 1800 + -17, exceeds max
 9 Pr=225, Pm=47, T=1000, TC=1756, $10.00 \times 178 + -1000.00 \times 0.0238$, 1780 + -23, exceeds max
 10 Pr=236, Pm=56, T=1000, TC=1780, $10.00 \times 180 + -1000.00 \times 0.0194$, 1800 + -19, exceeds
 max
 11 Pr=247, Pm=67, T=1000, TC=1776, $10.00 \times 180 + -1000.00 \times 0.0238$, 1800 + -23, exceeds
 max
 12 Pr=258, Pm=78, T=1000, TC=1776, $10.00 \times 180 + -1000.00 \times 0.0238$, 1800 + -23, exceeds
 max
 13 Pr=270, Pm=92, T=1000, TC=1749, $10.00 \times 178 + -1000.00 \times 0.0302$, 1780 + -30, exceeds
 max
 14 Pr=281, Pm=104, T=1000, TC=1744, $10.00 \times 177 + -1000.00 \times 0.0260$, 1770 + -25, exceeds
 max
 15 Pr=292, Pm=115, T=1000, TC=1746, $10.00 \times 177 + -1000.00 \times 0.0238$, 1770 + -23, exceeds
 max
 16 Pr=303, Pm=126, T=1000, TC=1746, $10.00 \times 177 + -1000.00 \times 0.0238$, 1770 + -23, exceeds
 max
 17 Pr=317, Pm=137, T=1000, TC=1776, $10.00 \times 180 + -1000.00 \times 0.0238$, 1800 + -23, exceeds
 max
 18 Pr=329, Pm=149, T=1000, TC=1774, $10.00 \times 180 + -1000.00 \times 0.0260$, 1800 + -25, exceeds
 max
 19 Pr=340, Pm=160, T=1000, TC=1776, $10.00 \times 180 + -1000.00 \times 0.0238$, 1800 + -23, exceeds
 max
 20 Pr=351, Pm=174, T=1000, TC=1739, $10.00 \times 177 + -1000.00 \times 0.0302$, 1770 + -30, exceeds
 max
 21 Pr=362, Pm=185, T=1000, TC=1746, $10.00 \times 177 + -1000.00 \times 0.0238$, 1770 + -23, exceeds
 max
 22 Pr=374, Pm=196, T=1000, TC=1756, $10.00 \times 178 + -1000.00 \times 0.0238$, 1780 + -23, exceeds
 max
 23 Pr=385, Pm=208, T=1000, TC=1744, $10.00 \times 177 + -1000.00 \times 0.0259$, 1770 + -25, exceeds
 max
 24 Pr=399, Pm=222, T=1000, TC=1739, $10.00 \times 177 + -1000.00 \times 0.0303$, 1770 + -30, exceeds
 max
 25 Pr=410, Pm=233, T=1000, TC=1746, $10.00 \times 177 + -1000.00 \times 0.0238$, 1770 + -23, exceeds
 max
 26 Pr=421, Pm=244, T=1000, TC=1746, $10.00 \times 177 + -1000.00 \times 0.0238$, 1770 + -23, exceeds
 max
 27 Pr=435, Pm=255, T=1000, TC=1776, $10.00 \times 180 + -1000.00 \times 0.0238$, 1800 + -23, exceeds
 max
 28 Pr=447, Pm=267, T=1000, TC=1774, $10.00 \times 180 + -1000.00 \times 0.0260$, 1800 + -25, exceeds

max

29 Pr=458, Pm=278, T=1000, TC=1776, $10.00 \times 180 + -1000.00 \times 0.0238$, $1800 + -23$, exceeds

max

30 Pr=469, Pm=289, T=1000, TC=1776, $10.00 \times 180 + -1000.00 \times 0.0238$, $1800 + -23$, exceeds

max

31 Pr=480, Pm=303, T=1000, TC=1739, $10.00 \times 177 + -1000.00 \times 0.0303$, $1770 + -30$, exceeds

max

32 Pr=492, Pm=315, T=1000, TC=1744, $10.00 \times 177 + -1000.00 \times 0.0260$, $1770 + -25$, exceeds

max

33 Pr=506, Pm=329, T=1000, TC=1739, $10.00 \times 177 + -1000.00 \times 0.0303$, $1770 + -30$, exceeds

max

34 Pr=517, Pm=340, T=1000, TC=1746, $10.00 \times 177 + -1000.00 \times 0.0238$, $1770 + -23$, exceeds

max

35 Pr=528, Pm=351, T=1000, TC=1746, $10.00 \times 177 + -1000.00 \times 0.0238$, $1770 + -23$, exceeds

max

36 Pr=542, Pm=365, T=1000, TC=1739, $10.00 \times 177 + -1000.00 \times 0.0303$, $1770 + -30$, exceeds

max

37 Pr=554, Pm=376, T=1000, TC=1756, $10.00 \times 178 + -1000.00 \times 0.0238$, $1780 + -23$, exceeds

max

38 Pr=565, Pm=388, T=1000, TC=1744, $10.00 \times 177 + -1000.00 \times 0.0260$, $1770 + -25$, exceeds

max

39 Pr=579, Pm=399, T=1000, TC=1776, $10.00 \times 180 + -1000.00 \times 0.0238$, $1800 + -23$, exceeds

max

40 Pr=590, Pm=413, T=1000, TC=1739, $10.00 \times 177 + -1000.00 \times 0.0303$, $1770 + -30$, exceeds

max

41 Pr=601, Pm=424, T=1000, TC=1746, $10.00 \times 177 + -1000.00 \times 0.0238$, $1770 + -23$, exceeds

max

42 Pr=615, Pm=438, T=1000, TC=1739, $10.00 \times 177 + -1000.00 \times 0.0303$, $1770 + -30$, exceeds

max

43 Pr=627, Pm=450, T=1000, TC=1744, $10.00 \times 177 + -1000.00 \times 0.0260$, $1770 + -25$, exceeds

max

44 Pr=641, Pm=464, T=1000, TC=1739, $10.00 \times 177 + -1000.00 \times 0.0302$, $1770 + -30$, exceeds

max

45 Pr=652, Pm=475, T=1000, TC=1746, $10.00 \times 177 + -1000.00 \times 0.0238$, $1770 + -23$, exceeds

max

46 Pr=663, Pm=486, T=1000, TC=1746, $10.00 \times 177 + -1000.00 \times 0.0238$, $1770 + -23$, exceeds

max

47 Pr=677, Pm=500, T=1000, TC=1739, $10.00 \times 177 + -1000.00 \times 0.0302$, $1770 + -30$, exceeds

max

48 Pr=689, Pm=511, T=1000, TC=1756, $10.00 \times 178 + -1000.00 \times 0.0238$, $1780 + -23$, exceeds

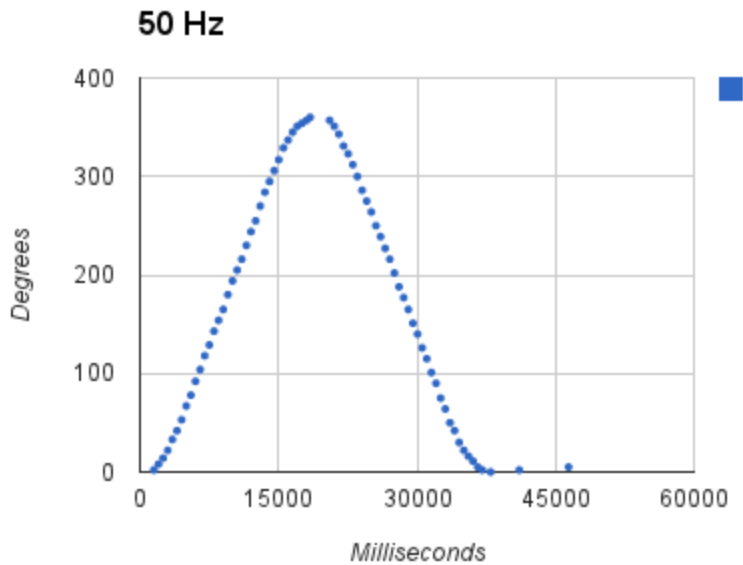
max

49 Pr=700, Pm=523, T=1000, TC=1744, $10.00 \times 177 + -1000.00 \times 0.0260$, $1770 + -25$, exceeds

max

50 Pr=711, Pm=534, T=1000, TC=1746, $10.00 \times 177 + -1000.00 \times 0.0238$, 1770 + -23, exceeds max
 51 Pr=720, Pm=548, T=1000, TC=1689, $10.00 \times 172 + -1000.00 \times 0.0302$, 1720 + -30, exceeds max
 52 Pr=720, Pm=559, T=1000, TC=1586, $10.00 \times 161 + -1000.00 \times 0.0238$, 1610 + -23, exceeds max
 53 Pr=720, Pm=570, T=1000, TC=1476, $10.00 \times 150 + -1000.00 \times 0.0238$, 1500 + -23, exceeds max
 54 Pr=720, Pm=582, T=1000, TC=1354, $10.00 \times 138 + -1000.00 \times 0.0259$, 1380 + -25, exceeds max
 55 Pr=720, Pm=596, T=1000, TC=1209, $10.00 \times 124 + -1000.00 \times 0.0303$, 1240 + -30, exceeds max
 56 Pr=720, Pm=607, T=1000, TC=1106, $10.00 \times 113 + -1000.00 \times 0.0238$, 1130 + -23, exceeds max
 57 Pr=720, Pm=621, T=959, TC=959, $10.00 \times 99 + -1000.00 \times 0.0303$, 990 + -30
 58 Pr=720, Pm=632, T=856, TC=856, $10.00 \times 88 + -1000.00 \times 0.0239$, 880 + -23
 59 Pr=720, Pm=644, T=733, TC=733, $10.00 \times 76 + -1000.00 \times 0.0261$, 760 + -26
 60 Pr=720, Pm=655, T=626, TC=626, $10.00 \times 65 + -1000.00 \times 0.0239$, 650 + -23
 61 Pr=720, Pm=666, T=516, TC=516, $10.00 \times 54 + -1000.00 \times 0.0239$, 540 + -23
 62 Pr=720, Pm=677, T=406, TC=406, $10.00 \times 43 + -1000.00 \times 0.0239$, 430 + -23
 63 Pr=720, Pm=689, T=283, TC=283, $10.00 \times 31 + -1000.00 \times 0.0261$, 310 + -26
 64 Pr=720, Pm=694, T=249, TC=249, $10.00 \times 26 + -1000.00 \times 0.0109$, 260 + -10
 65 Pr=720, Pm=703, T=150, TC=150, $10.00 \times 17 + -1000.00 \times 0.0196$, 170 + -19
 66 Pr=720, Pm=708, T=109, TC=109, $10.00 \times 12 + -1000.00 \times 0.0109$, 120 + -10
 67 Pr=720, Pm=714, T=46, TC=46, $10.00 \times 6 + -1000.00 \times 0.0130$, 60 + -13
 68 Pr=720, Pm=717, T=45, TC=23, $10.00 \times 3 + -1000.00 \times 0.0065$, 30 + -6, no movement
 69 Pr=720, Pm=717, T=45, TC=30, $10.00 \times 3 + -1000.00 \times 0.0000$, 30 + 0, no movement
 70 Pr=720, Pm=720, T=0, TC=0, $10.00 \times 0 + -1000.00 \times 0.0000$, 0 + 0

3. Using your optimally tuned values for the PD controller running at 1kHz, graph Pm, Pr and T while executing the trajectory: rotate the motor forward 360 degrees, hold for .5 seconds, then rotate backwards for 360 degrees, hold for .5 seconds, rotate forwards for 5 degrees. Be sure to graph the entire trajectory.



4. Run your PD controller at 50Hz and 5Hz while graphing the same variables. Discuss the results.

50 Hz was my default operating mode, graphed in question 3 above.

In the graph below, you see that it overshoots quite a bit. At 5 Hz, the PDController's measurements are too far behind what is actually happening, so it is always correcting too late.

