Problem 1 (12 points) For What Is Mechatronics Good?

Problem Statement:

High-precision high-speed motors, such as in disk drives, typically use ball bearings on the motor shaft to keep the motor shaft precisely centered, and to reduce friction. As with all mechanical components, the balls and tracks in the bearing are not perfect. In a disk drive, wobble of the motor shaft can make head tracking difficult, reducing data storage density.

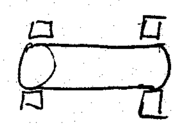
A magnetic bearing approach has been proposed to reduce shaft wobble and eliminate motor friction. The magnetic bearing can be thought of as a set of electromagnets which, without contact with the shaft, can apply forces to translate the shaft while it rotates, keeping it centered. Active control is required to keep the bearing centered.

[2 pts.] a) Briefly explain how you would implement a mechatronic approach to the precision motor bearing problem.

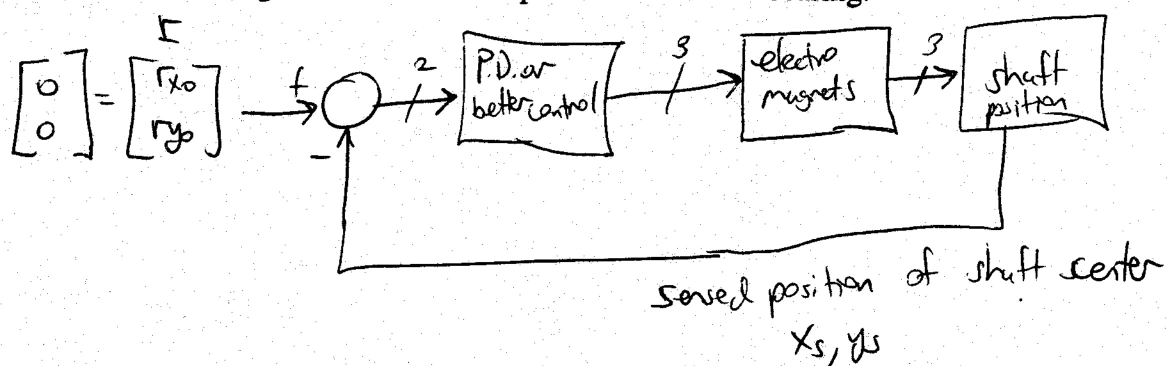
use precise sensing and control to reject disturbances
Since there is no contact, static friction and mechanical wobble are eliminated.

[3 pts.] b) List required sensors and actuators, and estimate the required resolution and sampling rate. (Assume motor turns at 1,000 revolutions per second, motor shaft is 5mm diameter, and maximum allowable wobble is 0.5μm.)

5 if shaft height matters.
Sensors: shaft position optical/magnetic at least 2 at each end, could also use tracks
actuators: 2 to control shaft position at each end of bearing
could make self centering ⇒ 4 dof
resolution: probably 10x or 50nm to allow smooth control
Sample rate: min 10 samples/revolution, better would be 50KHz.



[3 pts.] c) Draw a block diagram of a closed-loop controller for the bearing.



[2 pts.] **d) Discuss software requirements for the active magnetic bearing, including self-test and self-check.**

1. sensor check → all sensor values sensible & change with actuation
2. actuator check → all actuators change sensor values appropriately.
3. Stabilize bearing before starting motor rotation to avoid wear.
4. tight control loop at 50 KHz, minimal user interface except error indication. Must be real time, perhaps use DSP chip for fast calculations.
5. observer to indicate out of bound parameter, state, or control values to signal error.

[2 pts.] **e) List advantages and disadvantages of the mechatronic approach to this problem.**

Advantages: 1) tolerance limited by sensor/algorithm/actuator, not mechanical fabrication technology

2) no dry friction, should have long lifetime

3) diagnostics & monitoring of any disk problems

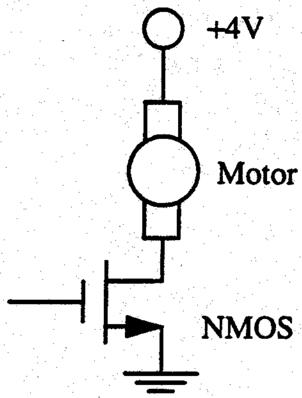
Disadvantages: 1) cost of sensor/cpu/actuator

2) extra power consumption

3) possible stability problems with dynamic loading of disk..

Problem 2 (8 points)

Consider the NMOS motor drive shown below:



$\frac{4V}{.05\Omega} = 80$ amps

$\frac{2V}{.05\Omega} = 40$ amps

Figure 1

Typical Electrical Characteristics

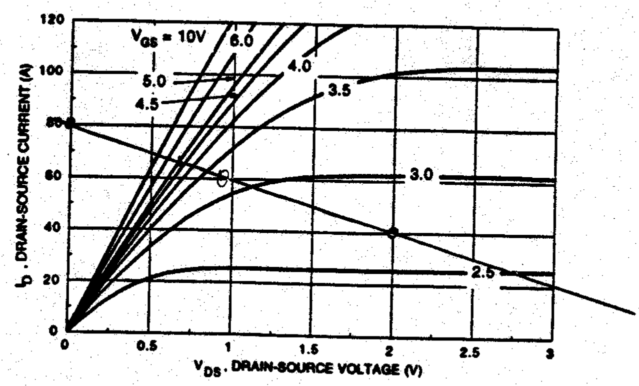


Figure 2: On-region Characteristics

The motor resistance is 0.05 ohm. Recall $P = I^2R, P = VI$. Assume the motor is stalled.

[4 pts.] a) Given that the NMOS transistor is able to dissipate 50 Watts, estimate the minimum V_{GS} required to prevent NMOS failure.

$I = 80 - 20V$, $P = IV = V(80 - 20V)$; $20V^2 - 80V + 50 = 0$

$V^2 - 4V + 5/2 = 0$

$V = \frac{4 \pm \sqrt{16-10}}{2} = 2 \pm \frac{\sqrt{6}}{2} \approx 0.8V \Rightarrow V_{GS} \gtrsim 3.3V$.

[4 pts.] b) What is the efficiency $\left(\frac{P_{motor}}{P_{motor} + P_{transistor}}\right)$ of the circuit when $V_{GS} = 5V$?

$P_{trans} = (65 \text{ amps})(0.7V) = 45$ watts

$P_{motor} = (65 \text{ amps}) \cdot (3.3V) = \sout{280 \text{ watts}}$ 215

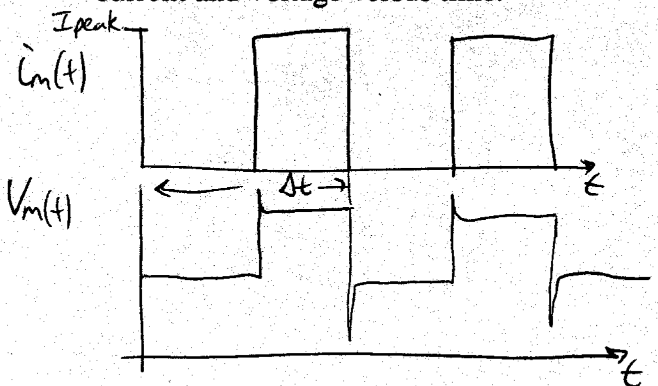
$\frac{280}{280+45} = \frac{280}{325} \approx \frac{7}{8} \approx 87\%$

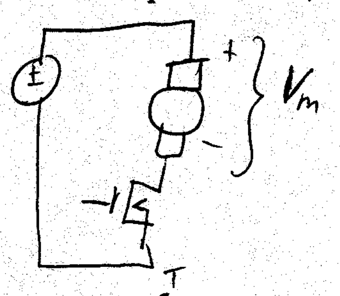
$\frac{215}{215+45} = \frac{215}{260} = \frac{43}{52} \approx 83\%$.

$52 \overline{)43.0} = .83$

Problem 3 (6 points) — PWM (Pulse Width Modulation)

[2 pts.] **a)** Explain how PWM can be used to drive a DC motor at 50% of peak current, using sketches of motor current and voltage versus time.





for 50% duty cycle, Δt small

$$\frac{\int_0^T i_m(t)\,dt}{T} = \frac{I_{peak}}{2}$$

[2 pts.] **b)** Why is PWM used instead of driving a power transistor and motor in a linear fashion?

power dissipation in transistor is minimized (V_{DS} is minimized $\Rightarrow$ minimum power), hence efficiency is maximized.

[2 pts.] **c)** In EECS 192, we generated PWM signals in hardware in the Xilinx FPGA. PWM could also be generated in software, toggling a bit on a simple digital output port.

Briefly explain the advantages and disadvantages of executing PWM code in the top level (foreground) as opposed to a background (interrupt-driven) process.

1) advantage, none really:
don't have to communicate with interrupt driven process

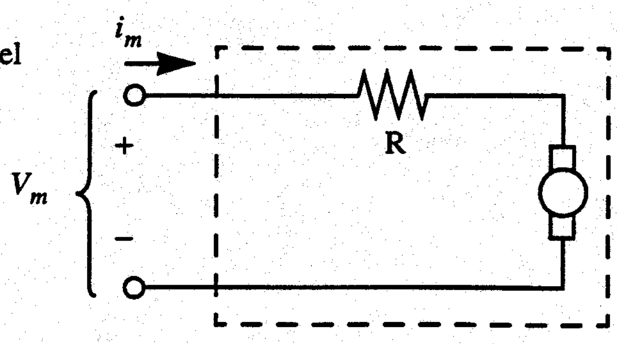
Disadvantage:
1) timing will not be as precise. Changes in code can change frequency and duty cycle of PWM.

Problem 4 (8 points)

For this problem, consider a DC permanent magnet motor (as used in your car). The car is on a carpet and moves in a straight line with no slip between the wheels and the carpet. The car is initially moving at a speed of 2 meters per second.

You can assume a motor model as shown below. The qualitative shape of the curves is more important than magnitudes.

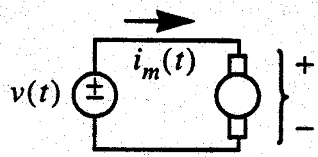
motor model

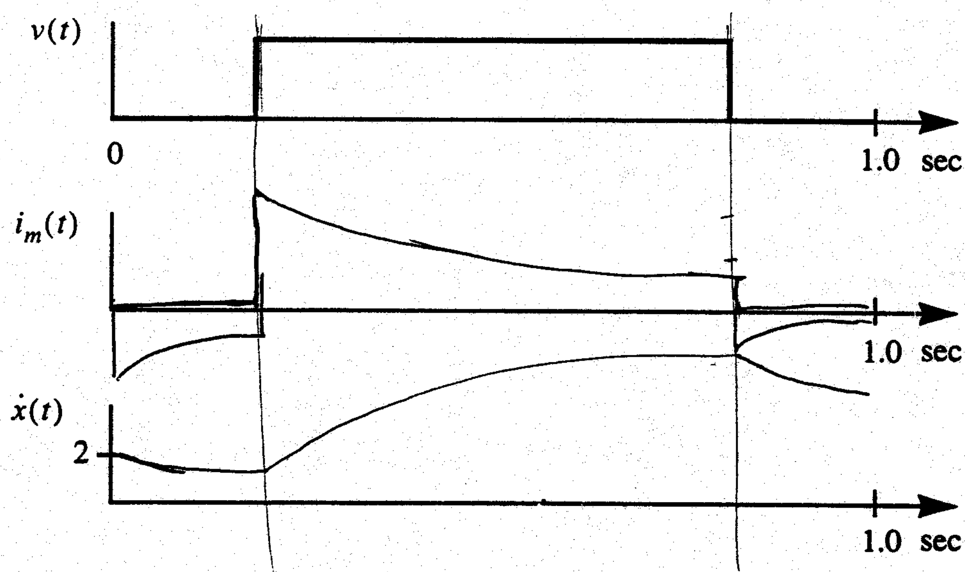


assume peak accel: 5m/s²

ΔV in 0.1 sec = 0.5m/sec

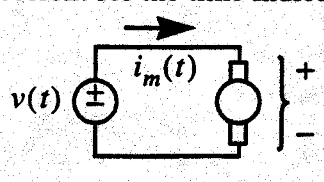
[4 pts.] **a)** Consider the motor driven from a voltage source with voltage $v(t)$, as shown. Sketch car velocity $\dot{x}(t)$ and motor terminal current for the time indicated.

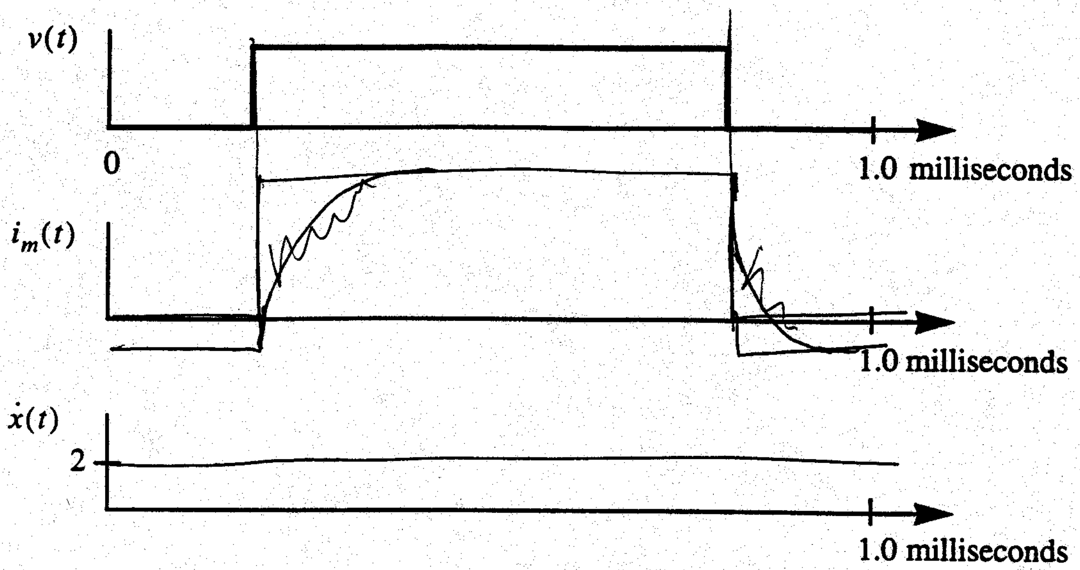




[4 pts.] **b) Consider the motor driven from a voltage source with voltage $v(t)$, as shown. Sketch car velocity $\dot{x}(t)$ and motor terminal current for the time indicated.**

(1.0ms) (5m/s²) = .005m/s





no inductor

$$V = iR + L\frac{di}{dt}$$

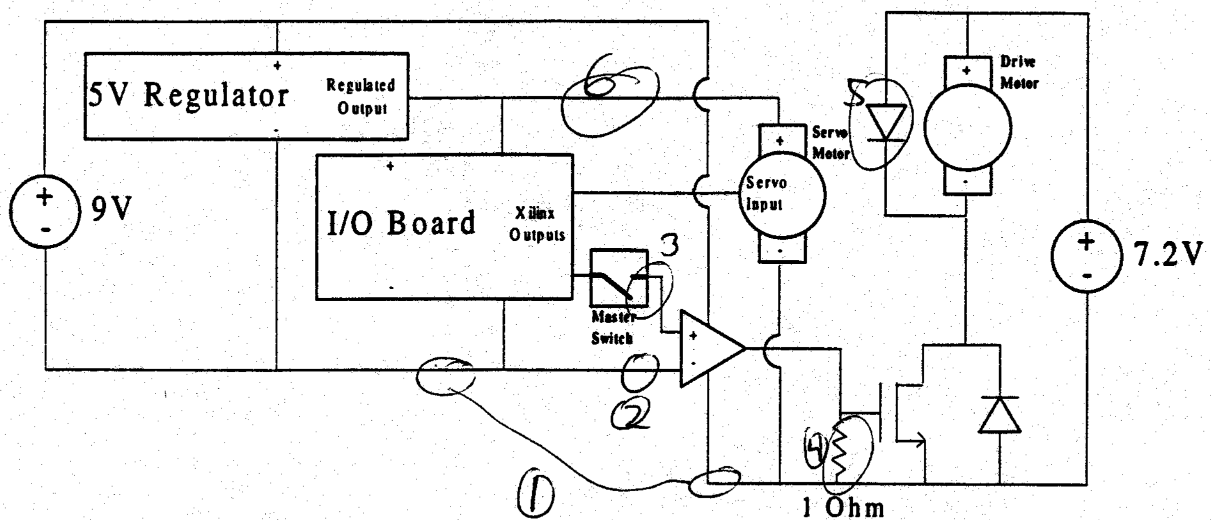
$$V(s) = I(s)(R + Ls)$$

$$\frac{I(s)}{V(s)} = \frac{1}{R+sL} = \frac{1/L}{s+R/L} =$$

$$i(t) = \frac{1}{L}e^{-tR/L}$$

Problem 5 (8 points)

During the up-coming spring semester, Professor Fearing requests that the students lay out a complete schematic for their project proposal. Shown below is one of the many schematics that Fearing receives. As he is sure to notice, there are several problems with this schematic. Help Prof. Fearing grade this schematic by circling the areas that are poorly designed and by labeling each of these areas with a different number. Below the schematic, write the numbers that correspond to the problems that you have found, followed by an explanation telling the student why that part of the circuit is flawed and what should be done to fix it. (Hint: None of the components are ideal; they are the same types of parts that we used in the lab. Assume that the operational amplifier can drive 100 mA at its output.)



(1) no common ground between 9v and 7.2v

(2) Comparator V− should be at ~0.5v (max logic 0)

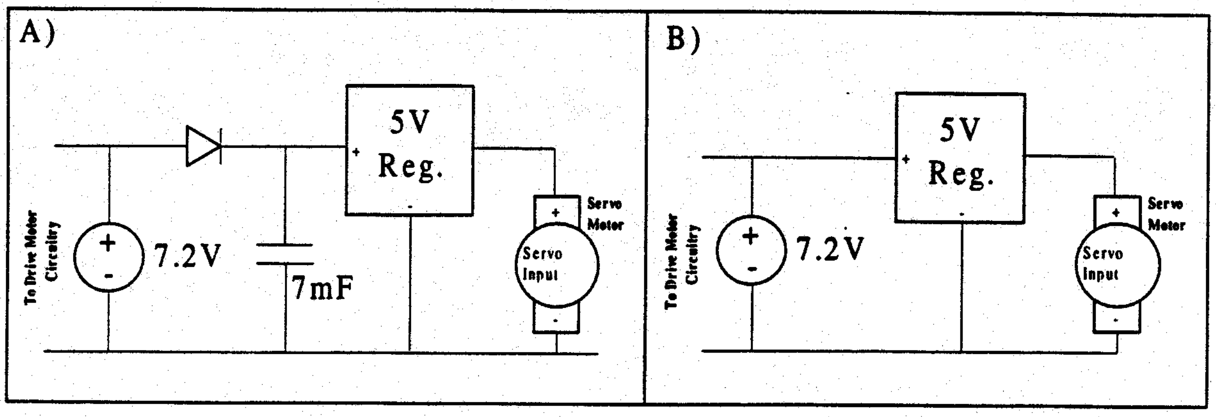
(3) Input floats when switch opened → gate might be at intermediate value, frying MOSFET

(4) 1 ohm pull down exceeds op amp current drive capability

(5) diode is backwards

(6) Servo motor current draw can pull Xilinx board below 5v, causing reset.

Problem 6 (6 points)



[4 pts.] **a)** Both schematics A and B show two different ways of connecting a servo to a 7.2V power supply, which also powers a drive motor. Explain why schematic A is a better way of regulating a servo's 5V supply than schematic B. You can assume that the regulator does not need any extra capacitors to keep its output from fluctuating under normal conditions (in which the + terminal is either 5V or above). (Hint: Be sure to explain the function of each component that was added to circuit A.)

When the ~~drive~~ drive motor is off, the capacitor is charged up to ≈ 7.2V – 0.3V diode drop. When the drive motor is on, pulling the 7.2V battery below 7.2V, the diode prevents discharge of the capacitor. With 100 Hz PWM (10ms), the capacitor could supply

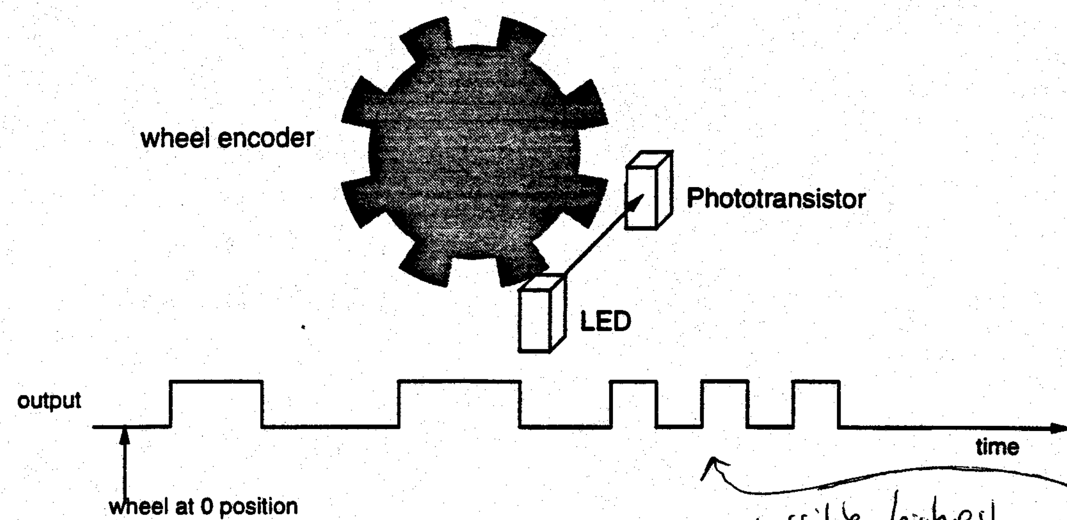
$i = C\frac{dV}{dt}$ $(7\times10^{-3}F)\cdot\frac{2V}{10ms} = 1.4$ amps during time drive motor is on.

[2 pts.] **b)** A student measures a voltage of 8.3 V across his 9V battery, which is powering his I/O board. When he plugs the battery into his I/O board, however, the Xilinx chip keeps on resetting during its initialization. He then measures the regulator's output voltage with the hand-held multimeter from the EE 192 laboratory and gets a value of 4.8 V. The student concludes from this that one of the chips on his board is bad because he knows that his I/O board will run off of a 4.8V supply. Is the student correct in making this assumption? If so, why do you think he is? If not, what else could be happening?

No Multimeter only measures average voltage, not worst case. A power glitch, say to 4V for a few us could be causing a reset.

Problem 7 (8 points)

Consider the single-channel incremental encoder and its output shown in the figure below.



possible highest

[2 pts.] **a) If the wheel initially starts at 0, is it possible to estimate the final wheel position? Why or why not?**

No. Can't tell direction of wheel from single encoder signal.

[2 pts.] **b) Is it possible to estimate the maximum velocity from this data? Why or why not?**

No. Don't know Δx, can't estimate $\frac{\Delta x}{\Delta t}$.

However, can determine maximum possible velocity $|V_{max}| = \max\left|\frac{\Delta x}{\Delta t}\right|$

[4 pts.] **c) Assuming the car always goes forward, list two methods of estimating velocity from the incremental encoder signal. Explain advantages and disadvantages of each method.**

Method #1: measure duration of high period with fast counter $= \Delta t$, $v = \frac{1}{\Delta t}$

Advantages— 1) good at slow speed

Disadvantages— 1) need to do division to get velocity

2) does not indicate car stopped

3) hard to measure velocity at ~~low speed~~ near zero speed

4) low resolution at high speed

Method #2: Count rising/falling edges $= \Delta x$, $v = \frac{\Delta x}{T}$

Advantages—

1) good at high speed

2) simple computation

Disadvantages—

1) very poor resolution at low speed.

Problem 8 (3 points)

Defective sensors are a big problem in EE 192 (and also in real life). Suggest 3 possible ways of recognizing in software that a magnetic sensor has failed (observations):

a) ~~output~~ sensor outside of permissible range

b) excessive variance (noise)

c) sensor value uncorrelated with other sensors

d) sensor values stuck, not changing

Problem 9 (3 points)

Explain how limited magnetic sensor resolution may affect EECS 192 car performance.

1) Steering becomes coarse
2) hard to estimate lateral velocity (needed for PD) hence less stable
3) poor tracking could lead to confusion on crossings.

Problem 10 (3 points)

In the EECS 192 car, what factors limit magnetic sensor resolution? Suggest a software method of improving sensor resolution.

limiting factors
1) distance from current source
2) op amp noise
3) power supply noise
4) coupling from motors/computer.
5) A/D resolution

Software method
1) filtering to trade off temporal resolution with spatial resolution (averaging, FIR, IIR etc). digital filter
2) ~~differential~~ inputs in software - subtract off noise
3) models of sensor/car/road positions to do prediction and filtering

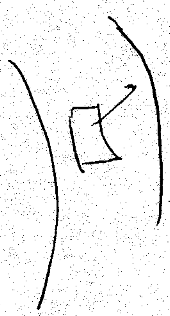
Problem 11 (6 points)

Due to control instability, cars can get lost off the track.

[3 pts.] **a) Suggest two software strategies for detecting the car getting lost:**

1) sensor signale disappearing

2) Sensor signal appearing on wrong (unexpected side)
(know track is to left ...)



[3 pts.] **b) Suggest a software strategy for getting back on the track:**

1) latch last direction and turn back

2) reverse path and go slow

3) spiral or zig-zag directed search.

Problem 12 (6 points)

Embedded systems can be required to run without operator intervention for many decades. Explain how some of the 6811 features can be used to make a more robust (crash-resistant) system.

1) Computer operating properly reset COP watchdog

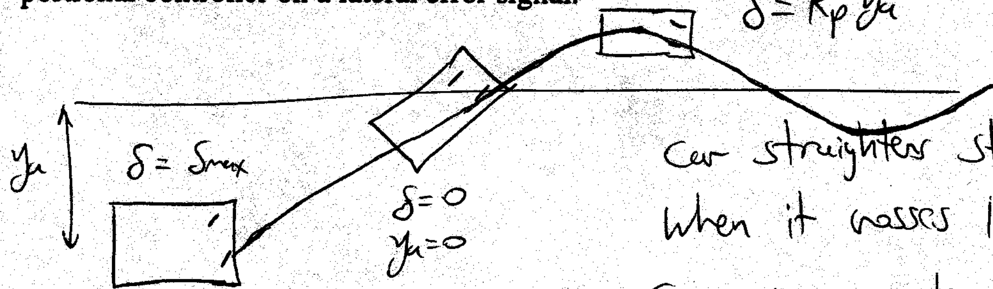
2) clock monitor, enable

3) ~~[illegible]~~ clock interrupts to check stack limits?
checksums?

Problem 13 (10 points) Steering Control

[5 pts.] **a)** Explain, with the aid of diagrams or equations, why steering overshoot is likely using a simple proportional controller on a lateral error signal.

$\delta = k_p y_a$

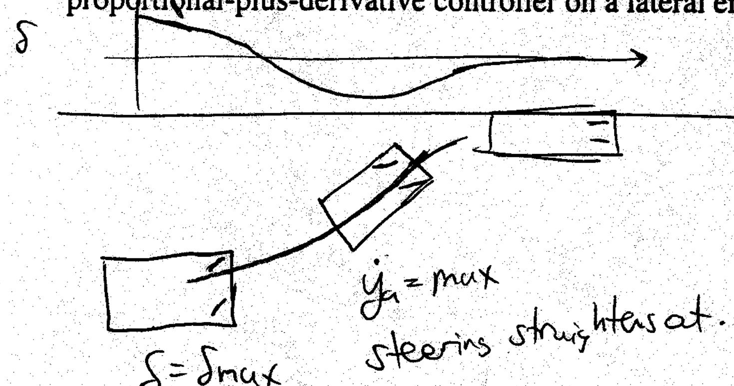


Car straightens steering only when it crosses line.

Car will cross line at an angle, leading to overshoot

[5 pts.] **b)** Explain, with the aid of diagrams or equations, why steering overshoot is less likely using a simple proportional-plus-derivative controller on a lateral error signal.

$\delta = k_p y_a + k_d \dot{y}_a$



With P+D, ideally car will start quickly approaching line. If car approaches line at too sharp an angle, $\dot{y}_a$ will be large, hence δ will be reduced, causing a more gradual approach to line, ideally without overshoot.

Problem 14 (5 points) Control

In discussing control principles for steering, we examined simple proportional and proportional-plus-derivative control, assuming that the steering system was adequately described by a linear differential equation, a "linear plant." In practice, at least at the vehicle speeds people were using, this mostly worked okay.

List 5 situations where or reasons why this assumption is not valid.

1) Steering angle $|\delta|$ or car orientation $|\theta| > 20°$

2) if car speed changes due to steering, i.e. not constant

3) steering servo dynamics are slow compared to turning rate

4) Steering angle saturates

5) if sampling rate is too low, need discrete time model

6) sensor quantization and nonlinearity

Problem 15 (6 points)

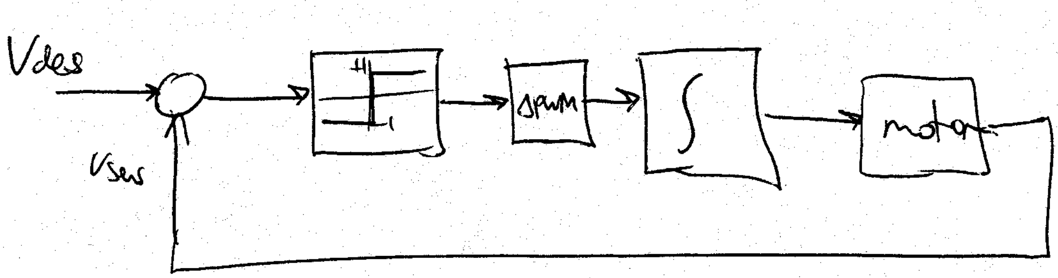
Several groups proposed to control the car's speed using the following algorithm running at 100 Hz:

- measure car's speed
- if speed is too low, increase PWM by adding a constant to current PWM value
- if speed is too high, decrease PWM by adding a constant to current PWM value

Explain why or why not this method would work well for speed control.

this is basically integral control with a fixed slope

$$PWM = \sum \Delta PWM$$



this control will take a long time to respond to large errors while waiting for the summation to increase. Dynamic performance is likely to be quite poor.