Carleton UNIVERSITY

Final EXAMINATION December 2017

DURATION: 3 HOURS No. of Students: 60

Department Name & Course Number: Systems and Computer Engineering SCE 3203

Course Instructor(s): Andy Adler

AUTHORIZED MEMORANDA
1) One 8.5” × 11” sheet of notes (double sided),
2) A Non network-connected calculator

Students MUST count the number of pages in this examination question paper before beginning to write, and report any discrepancy to a proctor. This question paper has 17 pages (including the cover page).

This examination question paper MAY NOT be taken from the examination room.

In addition to this question paper, students require: an examination booklet yes **no**; a scantron sheet yes **no**

Please print your name and student number in the boxes below:

Family Name	First Name	Student Number

Instructions:

- This test has **17** pages and **7** questions. Answer all questions and subparts. Marks are indicated.
- You have **180 minutes** to complete this exam.
- Answers should be written in this exam document. Write your answers in the space provided. If you require more space, use the back of exam pages, and indicate that extra space was used.
- All electronics components may be assumed ideal, unless stated otherwise.

#	Mark	/
1		/15
2		/20
3		/15
4		/15
5		/15
6		/15
7		/15

Background:

Concussion is the most common type of traumatic brain injury. Symptoms include headache, a feeling of being "in a fog", and emotional changeability. Common causes include sports injuries, bicycle accidents, car accidents, and falls.[1] Treatment normally involves rest, but recent evidence shows that mild activity can accelerate healing.[2] However, it is important to limit exercise — too much activity impedes healing and may make symptoms worse.

After graduation you get a job working for a sports medicine research institute where they are trying to help concussion patients get exercise, but give them an alarm if they do too much. Your job is to perform the biomedical electronics design tasks in the following pages.

Two parameters will be measured:

- **Heart Rate** – using an ECG measurement via electrodes attached to the chest.
- **Walking Rate** – using a compression sensor in a shoe.

The **alarm** will use an off-axis motor to give a "buzzing" feeling to the patient.

You may need the following table of filter properties.

N	F_s(40dB)	F_s(60dB)	F_s(80dB)	f_n	ζ	f_n	ζ	f_n	ζ	f_n	ζ
FILTER = Chebychev 0.05dB											
2	21.58	68.23	215.77	2.162	0.668						
4	3.37	5.89	10.42	0.885	0.833	1.221	0.250				
6	1.90	2.67	3.85	0.569	0.860	0.870	0.412	1.091	0.120		
8	1.48	1.86	2.39	0.422	0.870	0.670	0.464	0.912	0.228	1.050	0.069
FILTER = Chebychev 0.10dB											
2	18.11	57.28	181.13	1.820	0.652						
4	3.10	5.41	9.55	0.789	0.808	1.153	0.229				
6	1.81	2.54	3.64	0.513	0.834	0.834	0.375	1.063	0.108		
8	1.43	1.79	2.30	0.382	0.843	0.645	0.423	0.894	0.204	1.034	0.062
FILTER = Chebychev 0.20dB											
2	15.21	48.08	152.05	1.535	0.628						
4	2.85	4.95	8.75	0.701	0.774	1.095	0.205				
6	1.72	2.40	3.44	0.460	0.799	0.803	0.335	1.038	0.095		
8	1.39	1.73	2.21	0.343	0.807	0.623	0.377	0.878	0.179	1.021	0.054
FILTER = Chebychev 0.50dB											
2	11.99	37.84	119.67	1.231	0.579						
4	2.55	4.42	7.78	0.597	0.709	1.031	0.170				
6	1.61	2.23	3.19	0.396	0.731	0.768	0.276	1.011	0.077		
8	1.33	1.64	2.09	0.297	0.739	0.599	0.310	0.861	0.144	1.006	0.043
FILTER = Chebychev 1.00dB											
2	9.95	31.41	99.31	1.050	0.523						
4	2.34	4.03	7.08	0.529	0.637	0.993	0.140				
6	1.54	2.11	3.01	0.353	0.657	0.747	0.227	0.995	0.062		
8	1.29	1.58	2.01	0.265	0.664	0.584	0.256	0.851	0.117	0.997	0.035
FILTER = Chebychev 2.00dB											
2	8.13	25.59	80.91	0.907	0.443						
4	2.14	3.65	6.41	0.471	0.538	0.964	0.109				
6	1.46	1.99	2.82	0.316	0.555	0.730	0.176	0.983	0.048		
8	1.25	1.52	1.93	0.238	0.560	0.572	0.197	0.842	0.090	0.990	0.027

[1] en.wikipedia.org/wiki/Concussion

[2] ND Silverberg, GL Iverson, "Is Rest After Concussion The Best Medicine?: Recommendations for Activity Resumption Following Concussion in Athletes, Civilians, and Military Service Members" J Head Trauma Rehabilitation: 28:250–259, 2013

1 Electrodes and Electrical Safety

Electrodes made of Ag/AgCl are placed on the patient's chest in order to measure the ECG signal. A capacitive sensor is placed in the patient's shoe to measure the compression of each foot step.

- (5 marks) What is a polarizable electrode? Are these electrodes polarizable?

  ANSWER:

  A polarizable electrode like stainless steel or platinum does not have ions which are soluble in the body. Instead it acts like a capacitor.
  These electrodes are non-polarizable.

- (5 marks) Is this a good thing (whether or not they are polarizable) considering that the ECG signal is mostly low frequency.

  ANSWER:

  Yes, non-polarizable electrodes have better low-frequency response, and are thus a good thing in this application.

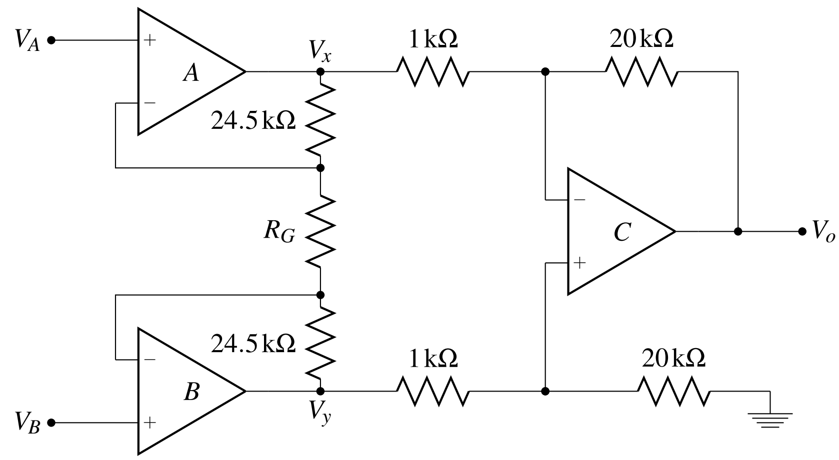
- (5 marks) What kind of shock hazard is possible if the capacitive sensor fails, considering that the sensor is placed in the patient's shoe?

  ANSWER:

  This is also a macro-shock hazard, although the risk is low, since the foot is far from sensitive organs like the heart.

2 Instrumentation Amplifiers

An instrumentation amplifier is used to amplify an ECG signal measured at electrodes on the chest. Initially, assume all components are ideal.



- (5 marks) What is the gain, $G = \dfrac{V_o}{V_B - V_A}$, when $R_G = 1.0\,\text{k}\Omega$?

ANSWER:

$$G = \left(1 + \frac{2 * 24.5k}{1.0k}\right)\frac{20k}{1k} = 1000$$

- (5 marks) What is the ratio, $\frac{V_y - V_x}{V_B - V_A}$, when $R_G = 1.0\,\mathrm{k}\Omega$?

ANSWER:

$$Ratio = \left(1 + \frac{2 * 24.5k}{1.0k}\right) = 50$$

- (5 marks) What is the gain for an input signal at $f = 10\,\text{kHz}$ if opamp C has an $f_T = 120\,\text{kHz}$ (while the other opamps are still ideal)?

ANSWER:

If opamp C has a $G \times f = f_T$, then $G_{max} = f_T/f = 120k/10k = 12$. However, the desired gain of the last stage is $\frac{20k}{1k} = 20$, so we get a gain of 12 instead.
Thus, $G = \left(1 + \frac{2*24.5k}{1.0k}\right) \times 12 = 50 \times 12 = 600$

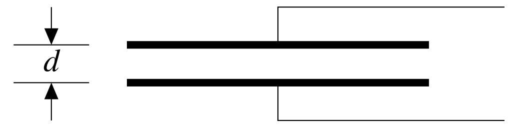
- (5 marks) Briefly explain one way to achieve high gain values if f_T is low (as here). (you do not need to draw a circuit)

ANSWER:

If f_T is low, then it will not be possible to achieve high gain values in one circuit. Instead multiple amplifier stages will allow the high gain to be achieved

3 Sensors

The displacement sensor in the shoe uses a capacitive sensor. Two plates are separated by a distance d are measured to have a capacitance of $\varepsilon \frac{A}{d}$, where $\varepsilon = 10^{-10}\,\frac{\mathrm{F}}{\mathrm{m}}$ (the permittivity of the capacitor dielectric), where A is the area of the capacitor, and d is the separation between capacitor plates.



- (5 marks) If a square $3\,\mathrm{cm} \times 3\,\mathrm{cm}$ square sensor is used, what is the capacitance if $d = 0.5mm$?
  ANSWER:

$$C = 10^{-10}\frac{F}{m} \times (.03\,m)^2/5 \times 10{-}4m = 180\,\mathrm{pF} = 0.18\,\mathrm{nF}$$

- (5 marks) What is the sensitivity of the sensor (in $\frac{pF}{mm}$) if the sensor is squeezed by $\Delta d = 0.1mm$?

ANSWER:

If $\Delta d = 0.1\,\text{mm}$, then the new $d = 0.4\,\text{mm}$.

$$C = 10^{-10}\frac{F}{m} \times (.03\,m)^2/4 \times 10{-}4m = 225\,\text{pF} = 0.225\,\text{nF}$$

The sensitivity = $\Delta\text{output}/\Delta\text{input} = (225 - 180\text{pF})/0.1\text{mm} = 450\text{pF}/\text{mm}$

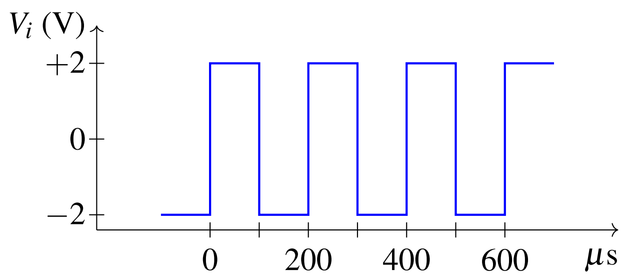
- (5 marks) This type of capacitive sensor is a "non-linear" sensor. Briefly explain one biomedical instrumentation scenario in which a linear sensor is required and a non-linear sensor would not be useful.

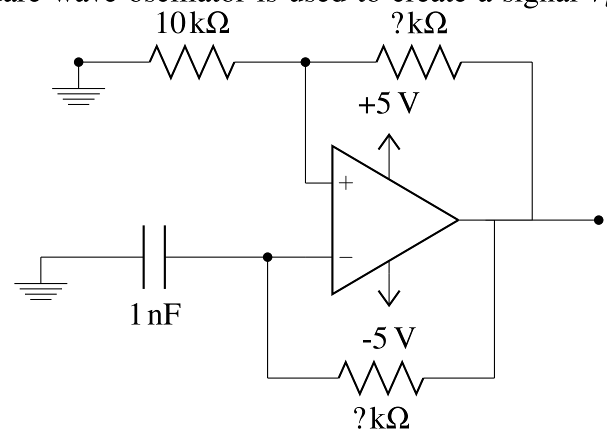
ANSWER:

A non-linear sensor can be useful for contact detection, but not for measuring a range of motion.
One example would be the measurement of blood pressure, where displacement of a diaphragm results is measured and converted to pressure units.

4 Oscillators

In order to measure the capacitance of the sensor, a square wave oscillator is used to create a signal V_i, with an amplitude of $\pm 2\,\text{V}$ and a frequency of $5\,\text{kHz}$.





- (15 marks) **Calculate the required values** of the resistors indicated with ? kΩ. **Indicate which point** on the circuit has the output of $\pm 2\,\text{V}$.

ANSWER:

The output of the opamp has $\pm 5\,\text{V}$.
Calculate resistor, R_1 to get $\pm 2\,\text{V}$.

$$
\begin{aligned}
2 &= 5\frac{10k}{10+R_1} \\
2(10k+R_1) &= 50k \\
2R_1 &= 50k-20k = 30k \\
R_1 &= 15k
\end{aligned}
$$

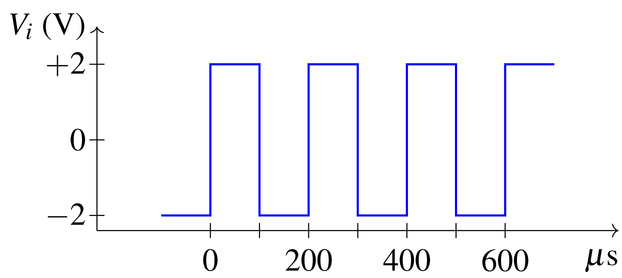
Transition requires $V_i = -2\,\text{V}$, $V_f = +2\,\text{V}$, and $V_\infty = +5\,\text{V}$.

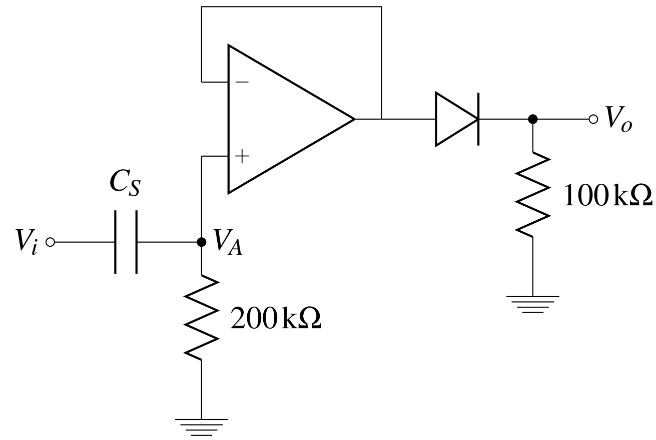
$$
\begin{aligned}
(V_f - V_\infty) &= (V_i - V_\infty)e^{-t/\tau} \\
(+2\,\text{V} - +5\,\text{V}) &= (-2V - +5V)e^{-100\,\mu\text{s}/\tau} \\
-3\,\text{V} &= -7Ve^{-100\,\mu\text{s}/\tau} \longrightarrow 3/7 = e^{-100\,\mu\text{s}/\tau} \\
ln(3/7) &= -100\,\mu\text{s}/\tau \longrightarrow \tau = -100\,\mu\text{s}/ln(3/7) = 118\,\mu\text{s}
\end{aligned}
$$

So $RC = 118\,\mu\text{s}$, and $R = 118\,\mu\text{s}/1\,\text{nF} = 118\,\text{k}\Omega$
Output should be taken at the point connected to the opamp V_+.

5 RC Filters and Diodes

In order to convert the sensor capacitance, C_S, into a signal voltage, a square wave signal V_i, shown, is input to the circuit. (This is the output from the oscillator in the previous queston, via a buffer)





- (5 marks) When the sensor $C_S = 100\,\text{pF}$, sketch V_A, between $150\,\mu\text{s}$ and $450\,\mu\text{s}$. Indicate time constants.

ANSWER:

Output is +ve and -ve spikes with exponential decay going to $\pm 4\,\text{V}$ with a time constant $\tau = RC = 100\,\text{pF} \times 200\,\text{k}\Omega = 20\,\mu\text{s}$.
Since each squarewave pulse is $100\,\mu\text{s}$, the exponential decay lasts about 20% of the time.

- (5 marks) When the sensor is compressed, $C_S = 200\,\text{pF}$. Sketch V_A, between $150\,\mu\text{s}$ and $450\,\mu\text{s}$. Describe the changes from the previous question.

  ANSWER:

  Output is +ve and -ve spikes with exponential decay going to $\pm 4\,\text{V}$ with a time constant $\tau = RC = 200\,\text{pF} \times 200\,\text{k}\Omega = 40\,\mu\text{s}$.
  Since each squarewave pulse is $100\,\mu\text{s}$, the exponential decay lasts about 40% of the time.

- (5 marks) Sketch the output, V_o, for the two previous cases: $C_S = 100\,\text{pF}$ and $C_S = 200\,\text{pF}$. The diode forward voltage, $V_D = 0.7\,\text{V}$.

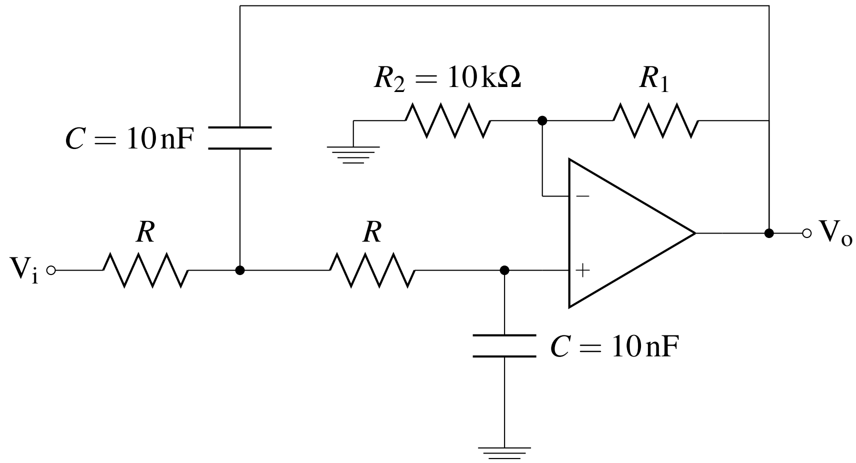
ANSWER:

The diode will block all voltages $< 0.7\,\text{V}$ and set them to zero. Voltages above this value will be reduced by $0.7\,\text{V}$.
This means that the output will be a +ve waveform of spikes which get longer when $C = 200\,\text{pF}$.

6 Filters

The output from the opamp/diode circuit is low-pass filtered to calculate the average value.

You are required to design a 2nd-order Salen-Key Low pass filter for a cut-off frequency of $f_c = 1\,\text{kHz}$. The maximum permissible passband deviation is $\pm 2\%$.



- (10 marks) Design the required filter as illustrated above. Use $R_2 = 10\,\text{k}\Omega$ and $C = 10\,\text{nF}$.

ANSWER:

Requirements are $\pm 2\% \longrightarrow 20\log_{10}(1 + .02) = 0.17$ and $\log_{10}(1 - .02) = -0.18$.
So we need the Chebychev 0.1 dB table. This table has $f_n = 1.820$ and $\zeta = 0.652$.
Using $2\zeta = 3 - G \longrightarrow G = 3 - 2\zeta = 3 - 2 \times 0.652 = 1.70$.
Gain is $G = 1 + R_1/10k \longrightarrow R_1 = 10k \times (G - 1) = 7.0\,\text{k}\Omega$.
For this filter, $\omega_n = 2\pi f_c \times f_n = 11435\text{rad/s}$.
$RC = (\omega_n)^{-1} \longrightarrow R = \frac{1}{\omega_n C} = (11435\text{rad/s} \times 10\,\text{nF})^{-1} = 8.7\,\text{k}\Omega$.

- (5 marks) Estimate the attenuation that this filter can achieve for inputs at 20 kHz (use the table).

ANSWER:

The Chebychev 0.1 dB table has $F_s(40\,\text{dB}) = 18.11$ and $F_s(60\,\text{dB}) = 57.28$.
At $F_s = 20k/1k = 20$, our filter will do a little better than 40 dB. Estimate value of 41 – 43 would be good.

7 A/D converters, Motors and Actuators

The ECG measurement and step sensor output are acquired to be processed by a microcontroller. Here we consider an A/D converter recording the output of the filter in the previous section.

- (5 marks) The step sensor ouput, V_o, varies over the range 0–3.7 V. If the A/D converter range is ±5 V, how many bits of converter accuracy are required so that the resolution is 0.1% of the range of V_o.

ANSWER:

0.1% of $(3.7 - 0\,\text{V}) = 3.7\,\text{mV}$
use resolution = Range/L $\longrightarrow 3.7\,\text{mV} = (5\,\text{V} - (-5\,\text{V}))/L \longrightarrow L = 10\,\text{V}/3.7\,\text{mV} = 2702$
$2^{11} = 2048$ (not enough) $2^{12} = 4096$ (enough).
A 12 bit converter is needed.

- (5 marks) What sampling frequency is required so that the aliasing contribution is less than $-60\,\text{dB}$ of the signal (hint, use the filter table).

ANSWER:

From the filter table, $F_s(60\,\text{dB}) = 57.28$, so we need to get to $57.28 \times 1\,\text{kHz} = 57.28\,\text{kHz}$. To avoid aliasing we need greater than 2 times this frequency, so sample at $\geq 2 \times 57.28\,kHz = 115\,kHz$.

If the software decides the patient's exercise level is too high, a relay is activated which turns on a DC motor. This motor is connected to an off-axis load. It will buzz next to the patient, warning them of their exercise level.

- (5 marks) As a function of time, sketch roughly the torque and current in a DC motor. Briefly explain the shape of the curves.
  ANSWER:
  Initially, both torque and current are high. As time goes on a backemf builds up which reduces current. The torque and current are proportional to each other.