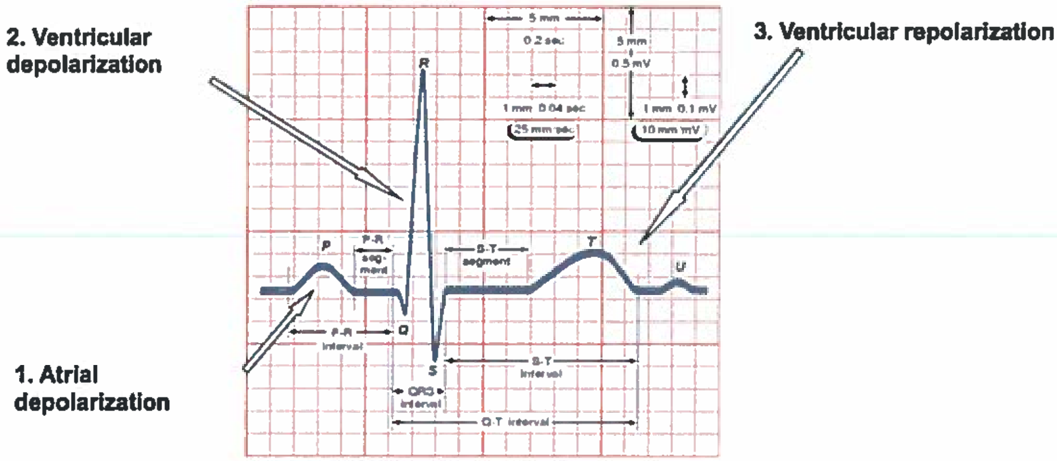
1. This question relates to the design of an instrument for measuring biopotentials.

   a) Sketch a typical ECG waveform labeling each segment. Explain briefly what each segment of the ECG waveform represents during a single heartbeat.



P wave represents the normal atrium (upper heart chambers) depolarization;
QRS complex (one single heart beat) corresponds to the depolarization of the right and left ventricles (lower heart chambers);
T wave represents the repolarization (or recovery) of the ventricles.
[2 marks for drawing with labels and 2 marks for brief explanations]

   b) Table 1.1 lists five commonly observed bio-potentials and their amplitude and frequency characteristics. A doctor requires an instrumentation system to record the ECG from the heart. The front end will use the instrumentation amplifier shown in Figure 1.1

   (i) Derive an expression for the output voltage V_{out} of the amplifier as a function of the differential voltage V_1-V_2 and select suitable resistor values to give you a gain of -11. You may use R_2=100KΩ.

Derivation from notes:

$I_1 = (V_1 - V_2)/R_1$

KCL: $I_2 = I_3 = I_1$

KVL: $V_{OUT} = (R_1 + 2R_2)(V_1 - V_2)/R_1$

$= (V_1 - V_2)(1+2R_2/R_1)$

[1 mark]

Second Op-amp input voltage:

$V_- = V_+ = V_2R_4/(R_3 + R_4)$

Solving for currents through V_1 branch:

$(V_1 - V_-)/R_3 = (V_- - V_{OUT})/R_4$

Solution:

$V_{OUT} = -(V_1 - V_2)R_4/R_3$

[1 mark]

Combining the two : $V_{OUT} = -(V_1 - V_2)(1 + 2R_2/R_1)(R_4/R_3)$

[1 mark]

For gain of 11 we select R4=R3= 100 KΩ and R1= 20 KΩ

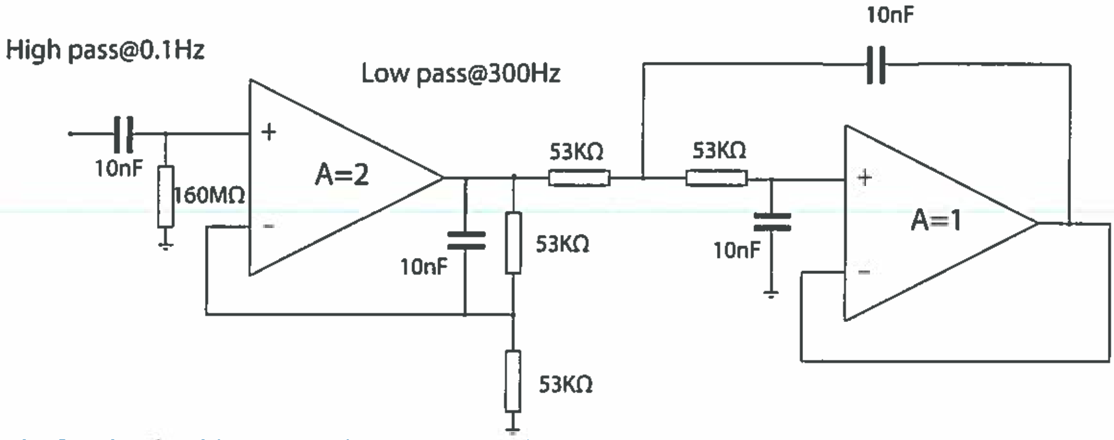
[1 mark]

   (ii) Design a suitable band pass filter to extract the signal of interest. You may assume a 60dB/decade roll off for the low-pass and a 20dB/decade roll off for the high pass sections. State equations for cut off frequencies and select suitable resistors. You may assume you have 10nF capacitors to your disposal.

60dB/decade roll off means third order low pass and 20dB/decade means first order highpass. Reading the frequencies from the table, we need a high pass cut off at 0.1Hz and a low pass cut off at 300KHz. High pass must go first.

- High pass value $R_2=1/2\pi C_1 f_{HPF}$ = $1/2\pi(10nF)(0.1Hz)=160M\Omega$ [0.5 mark]
- Low pass value $R_3=1/2\pi C_2 f_{LPF}$ = $1/2\pi(10n)(300Hz)=53K\Omega$ [0.5 mark]

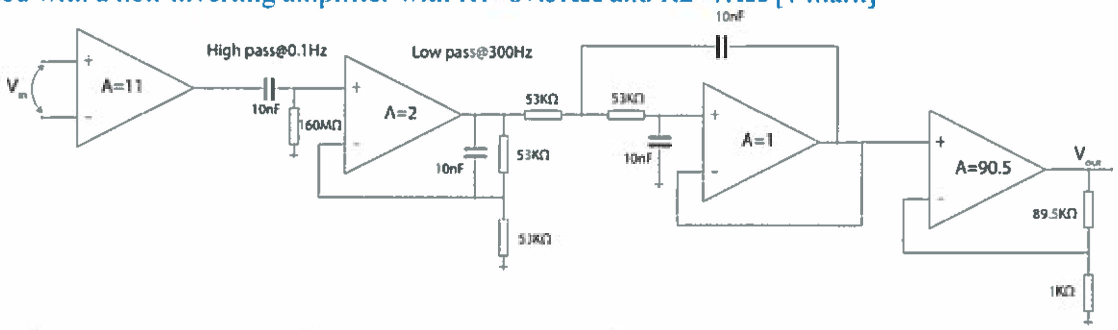
One potential solution:



[3 marks for circuit with annotated component values]

(iii) The instrumentation system will work off a 6 V coin cell battery. Using the circuits of parts b.i, and ii and any additional circuits, sketch the complete schematic of the instrumentation system that utilises the whole dynamic range of the system. Annotate on your schematic values of resistors and capacitors with a justification of the final choices. You may assume V_{DD}=3V and GND=0V and V_{SS}=-3V.

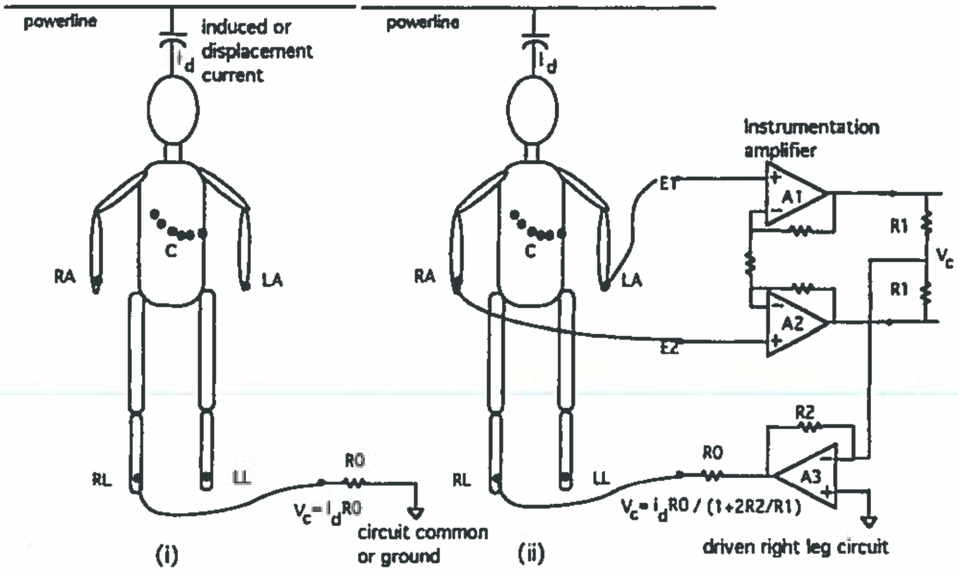
Max ECG = 3mV (from table)
V_{inptp} x A1 x A2=6V_{ptp}
A1=11 from part b.
3mVx11xA2=6V
A2= 181 (gain of filter and final stage) [1 mark]
Filter gain =2 (for this design)
Gain of final stage =90.5
Realised with a non-inverting amplifier with R1=89.5KΩ and R2=1KΩ [1 mark]



[2 marks for complete circuit with annotated component values]

c) i) Show how the circuit in Figure 1.1 can be modified with a "*driven right leg circuit*" to reduce the common mode voltage created by current capacitively coupled to the body from the power-lines.

Modification of instrumentation amplifier:



[2 marks for circuit]

ii) Show that the common mode voltage with this circuit reduces to:

$$V_{CM} = \frac{i_D R_0}{1+2\frac{R_2}{R_1}}$$

Derivation from notes:

$$\frac{V_{cm}}{R_1/2} + \frac{V_{out}}{R_2} = 0$$

$$V_{out} = -\frac{2R_2}{R_1} V_{cm}$$

$$V_{cm} = R_0 i_d + V_{out} \Rightarrow \frac{R_0 i_d}{1+2R_2/R_1}$$

[2 marks]

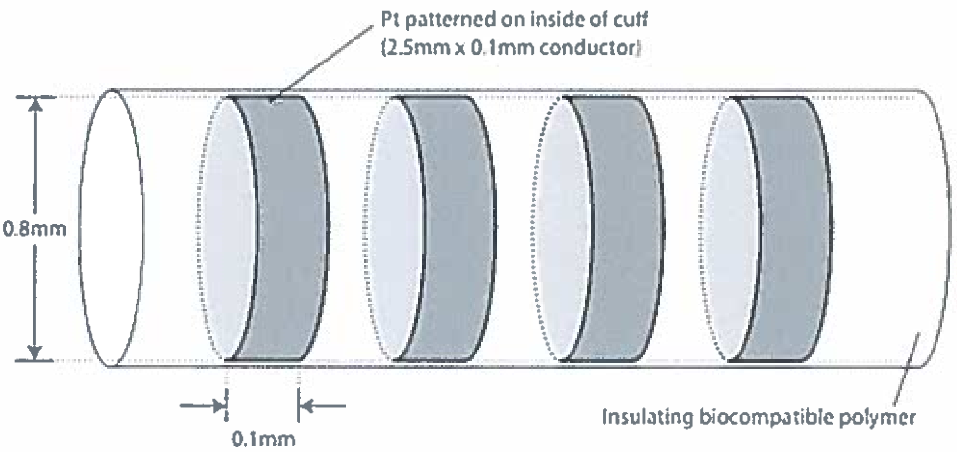
2.

(a) Three types of electrodes that are commonly used for PNS interfaces are cuff electrodes, Transverse Intrafascicular Multichannel Electrodes (TIME) and Longitudinal Intrafascicular Electrodes (LIFE). Cuff electrodes "wrap" around the nerve, whereas TIME and LIFE electrodes penetrate the nerve- TIME perpendicular to the nerve and longitudinal in parallel. TIME electrodes generally have penetrating "needles" whereas LIFE electrodes are generally threaded into the nerve itself. Cuff electrodes are therefore considered minimally invasive to the nerve and for this reason cuff electrodes are the most popular in clinical applications. However, TIME and LIFE electrodes provide opportunity for more selective stimulation- multiple electrodes can be patterned along the length of the probe and can thus target individual fascicles within the nerve. As the cuff is effectively outside the nerve, any stimulation generally activates all fascicles.

[1 mark describing different types, 1 mark comparing re: selectivity, 1 mark comparing re: invasiveness]

(b) Given a maximum stimulus of 125nC, the minimum area of electrode (so max. charge density is kept to) is $250nC/100\mu C.cm^{-2}=0.0025cm^2=0.25mm^2$. If this is arranged as a cuff electrode, the conductor surface area will be cylindrical to be in contact with the nerve around its circumference. For a nerve of 0.8mm diameter, circumference, L = 0.8mm x π = 2.5mm. Therefore width of conductor "ring" is given by: W = A/L = $0.25mm^2/2.5mm \approx 0.1mm$.

To have a cuff electrode providing 3 bipolar channels within a multipolar configuration would require 4 such identical electrodes.



[1 mark for 4-electrodes, 1 mark for geometry calculations, 1 mark for annotated sketch]

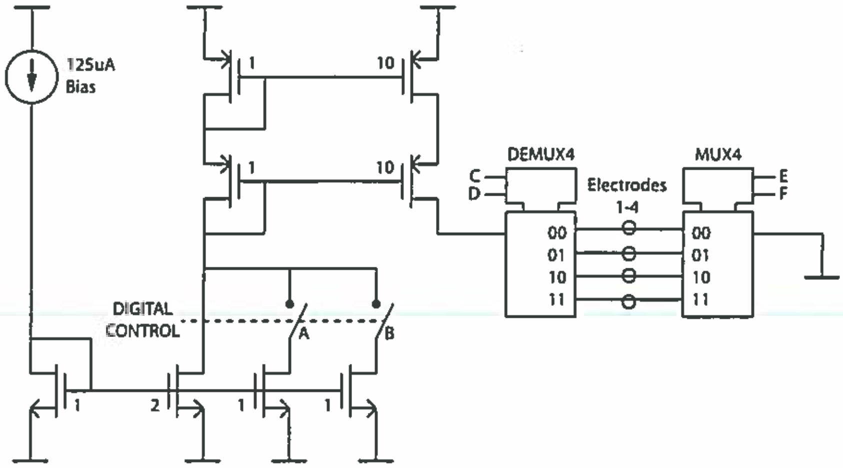
(c) (i) Key components needed to design circuit:

- Finite state machine (FSM)
  - Clearly has 6 states (2 per cycle per channel)
  - Clock frequency = 1/50us = 20kHz

- Current generation circuit (current mirrors)
  - Determine maximum stimulation current. From Figure 1 – each cathodic/anodic phase = 50us. Therefore since Q=It (for fixed current) -> iMax = 250nC/50us = 5mA.
  - Stimulation currents required for channel 1 = 5mA, channel 2 = 3.75mA, channel 3 = 2.5mA.
  - Power supply needed >50V = 5mA x 10k

- Current output stage (to drive relatively high impedance electrodes) and switch network
  - Can use cascoded mirror to interface to electrodes.
    - Switch network to MUX current output onto different electrodes. Need to be able to switch source to 1 of 4 electrodes, and ground to 1 of 4 – simply a 2 input MUX.

(ii) Circuit schematic is as follows:



(iii) FSM needs to generate control signals A-F. Simplest way is to use a token-based serial shift register that will have generate state signals S1-S6. These state signals can then be used to generate control signals using simple SOP expressions.

State/Ctrl	A	B	C	D	E	F
S1	1	1	0	0	0	1
S2	1	1	0	1	0	0
S3	1	0	0	1	1	0
S4	1	0	1	0	0	1
S5	0	0	1	0	0	1
S6	0	0	1	1	1	1

[3 marks for identifying relevant features required in the circuit, 5 marks for circuit schematic and 2 marks for design of FSM]

(d) The easiest way to ensure there is no residual charge is by using a DC blocking capacitor - to be placed in series with electrodes. For a stimulus magnitude of 250nC -> design capacitor to store at least 10x to 100x this amount of charge => 2.5μF. This is however a large capacitance (unfeasible for an integrated circuit).

Other methods also possible are to introduce a "shorting phase" that would short electrodes together (and to ground) after every few stimulation cycles, however this would require changes to FSM (i.e. to introduce a "break" in stimulation pattern every few cycles and short electrodes together) and also the RC time constant may limit the maximum repetition rate of stimulation.

[1 mark for DC blocking or shorting phase and alteration to design, 1 mark for identifying benefit/drawback of suggested method].

(e) Advanced multipolar stimulation strategies can dynamically combine (i.e. group together) electrodes or share the stimulus across multiple paths, for example, a 3 mA cathodic current can be split into 3x 1mA currents sourced into electrodes 1-3, with electrode-4 sinking the return 3mA current. This can have the effect of focusing the stimulus or beam steering to improve stimulation resolution (i.e. spatial).

[1 mark for understanding multipolar configuration – splitting stimulus, 1 mark for demonstrating understanding that this is for improving resolution]

3. This question relates to the design of a novel integrated sensor for chemical measurement.

a) Electrochemical measurement has as a basis a redox reaction. Explain what is meant by a redox reaction using reaction equations where necessary.

Bookwork

Definition of reduction with equation [2 marks]
Definition of oxidation with equation [2 marks]

b) Figure 1 shows a new pixel architecture to be used a part of an array in an integrated CMOS based diagnostic device. The total pixel size is 150um x150um with a total sensing area of 100um x 100um which is capable of sensing both glucose and pH. The working electrode is coated with glucose oxidase to give a peak current to glucose at V_{Cell}=0.7 V according to the following reaction:

$$\text{glucose} + O_2 \xrightarrow{\text{glusoce oxidase}} \text{gluconic acid} + H_2O_2 \quad (1)$$

$$H_2O_2 \rightarrow O_2 + 2H^+ + 2e^-$$

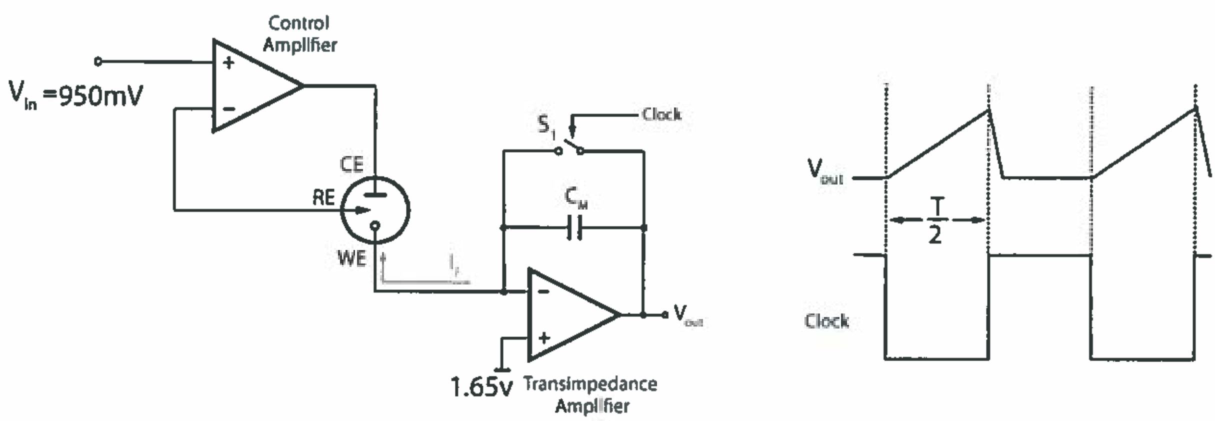
i) The sensor shall be used to measure a physiological glucose range of 0-20mM. The peak redox current for a scan rate of 1V/s is given by the following equation:

$$i_p = 2.69\times10^5 n^{3/2} A D^{\frac{1}{2}} C$$

where the diffusion coefficient D=4.38X10^{-8} m^2/s. Calculate the maximum range of the WE current, using the dimensions shown in Figure 1, to capture the physiological range of glucose.

Total area of WE=50umx20um=1000um^2 [1 mark]
Number of electrons =2
Peak current at 20mM
Ip=2.69x10^{5}x2$^{3/2}$x50x10^{-6} x 20x10^{-6} x20x10^{-3}=15.2uA [1 mark]

ii) The amperometric sensor in the pixel shall be driven by a potentiostat and transimpedance amplifier which uses an integration capacitor, CE to convert the sensed current to a voltage. The circuit operates of a single supply with V_{DD}=3.3V and V_{SS}=0V. Sketch the schematic of a suitable measurement system used to interface to the amperometric sensor and label the voltages of all electrodes

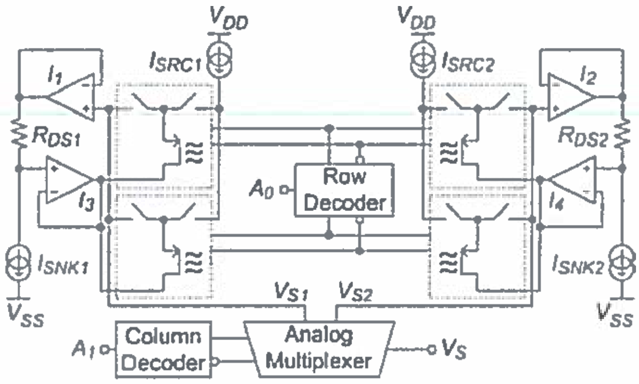


Potentiostat [2marks]
Tansimpedance amplifier [2 marks]
Correct voltages [2 marks]

iii) The transimpedance amplifier has a poly-silicon integration capacitor determined by the remainder of the area in the pixel shown in Figure 1. A capacitance per unit area of poly-silicon is 4x10^{-4} pF/um^2. Calculate a suitable clock frequency that maximizes the dynamic range of the pixel for glucose measurement using the current calculated in b.i.

Voutmax = IF(T/2CM)=1.65V for single supply [1 mark]
Capacitor size = (50um x150um) + (50um x100um)=12500um^2
Total capacitance = 12500um^2 x 4x10^{-4} pF /um^2 =5pF [1 mark]
F_{max}=IF/2$C_M$$V_{out}$=15.2x10^{-6} / (2x5x10^{-12} x 1.65) =921KHz [2 marks]

iv) Sketch a suitable schematic to interface to the pH sensor including switches to interface to more than one pixel.



[2 marks for readout of single pixel]
[2 marks for inclusion of switches and two pixels]

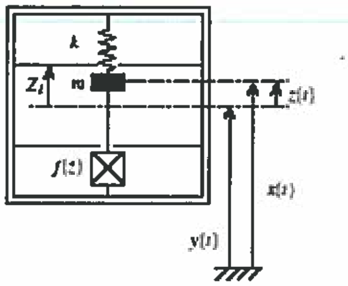
4. This question concerns energy harvesting and wireless power supplies for body worn and implanted medical electronics.

a) It is proposed that a medical implant in the abdomen is to be powered from an inertial energy harvester device.

i) Explain how such a device works. Use a diagram and include in your answer a brief discussion of the possible transducer technologies that could be used.

[4]

[bookwork]



[1]

As shown, a proof mass is suspended on a spring suspension. When the frame of the device experiences acceleration, the mass moves relative to the frame. The relative motion is used to do work against a transduction mechanism. The transducer can be implemented via several mechanisms, the most common being piezoelectric, electrostatic and electromagnetic. Electrostatic devices need some form of pre-charge energy to start generating, whereas piezo and electromagnetic can cold start

[3]

ii) The power output of a harvester at resonance can be shown to be:

$$P_{res} = \frac{1}{2} Y_0 \omega^3 m Z_l$$

Where Y_0 is the amplitude of the driving motion, ω is the driving frequency, m is the proof mass and Z_l is the amplitude of the mass travel. Explain why it is logical that the power is proportional:

- the proof mass
- the cube of frequency

[3]

[understanding of basic physics]

By Newton II. the force on the mass (and hence transducer) is proportional to the proof mass (for a given acceleration) hence the proportionality of power to mass.

[1]

The acceleration is proportional to the square of frequency so the force on the transducer is proportional also to the square of frequency. This means the energy generated per cycle is proportional to the proof mass. The power therefore depends on energy per second, which is energy per cycle times frequency, hence the proportionality of power to the cube of frequency.

[2]

ii) The position profile at the place of the proposed implant was measured as shown in Figure 1. Estimate the output power of a resonant harvester attached at this location with the a proof mass of 1 g and a maximum amplitude of mass displacement of 1 mm. State the assumptions you are making.

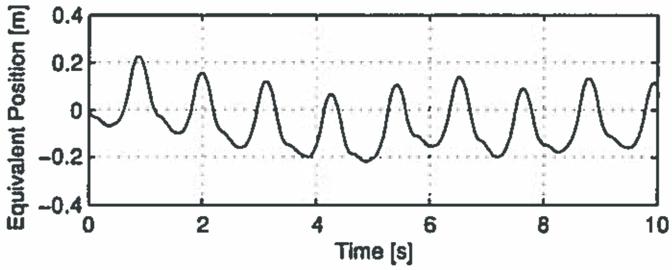


Figure 1 Position of generator attachment point whilst walking

[4]

[Application of knowledge]
We have to assume that the motion is sinusoidal. From the graph, the peak to peak motion is around 0.3 m, amplitude is thus 0.15 m and the frequency is around 0.75 Hz.

[2]

Thus, the power can be readily calculated from $P_{res} = \frac{1}{2} Y_0 \omega^3 m Z_l$, *i.e.:*

*P=0.5*0.15*(2*pi*0.75)^3*1e-3*1e-3=7.8µW*
(Allow answers within this range as estimating qualities from the graph is subject to error)

[2]

iii) In reality the power output will be less than this. State two effects that reduce the power output of the system.

[2]

[Understanding of basic physics]

Two of these three are acceptable:

- *There will be losses in the electronics*
- *There are losses in the beam suspension*
- *There is air damping (assuming the system is not vacuum packaged)*

[2]

b) A wireless power transfer system is to be used to power an implanted actuator which closes the valve between the stomach and oesophagus in a person with acid reflux disease.

i) A suggestion is made to increase the link efficiency of the system by adding ferromagnetic materials to the coils. Explain why this may increase efficiency.

[3]

[Application of knowledge]
The link efficiency is given by:

$$\eta_{link} = \frac{k^2 Q_{TX} Q_{RX}}{\left(1+\sqrt{1+k^2 Q_{TX} Q_{RX}}\right)^2}$$

Thus, increasing the coupling factor k will increase the link efficiency and hence the system efficiency.

[2]

ii) It is then proposed that the Q-factors can be increased by operating the system at higher frequency. Explain why this is thought, and what factors should be considered when increasing the system frequency.

[4]

[Application of knowledge]
The coil Q-factor increases with frequency as ωL/R. Thus it seems sensible to increase frequency to increase Q. However, Q does not increase as quickly as might be expected because of skin effect, causing R to increase with frequency. Increasing frequency indefinitely does not keep increasing Q, however, as eventually the coil radiates.

[3]

In addition, the electronics (driver and rectifier) may suffer a reduction in efficiency as frequency increases.

5.

(a) Neural prostheses can be categorised into sensory, cognitive and motor.

Sensory prosthesis – uses an external sensor, processor and stimulator to bypass a dysfunctional element in the sensory pathway. Can interface onto either the CNS or PNS. Examples include cochlear implants, retinal implants, etc.

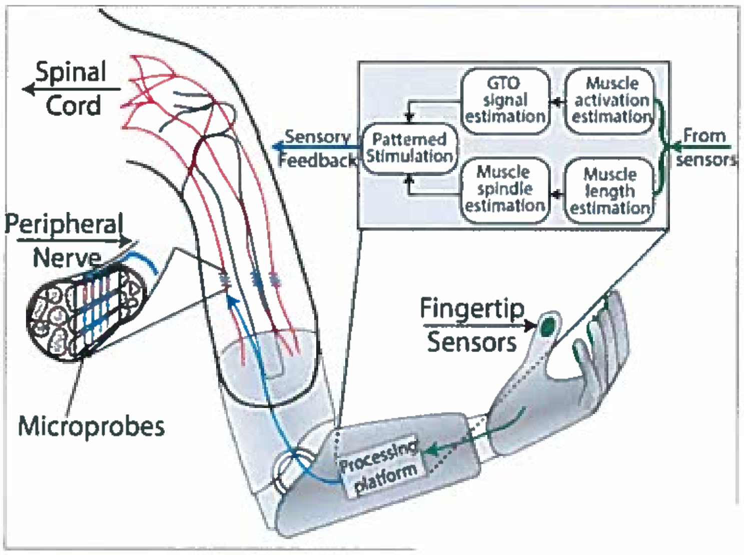
Cognitive prosthesis – often referred to as neural "pacemakers". These apply a stimulus to the nervous system to overcome some neurological condition. Can interface onto either the CNS or PNS. Examples include Deep Brain Stimulation therapy for Parkinson's and essential tremor, vagus nerve stimulation therapy for epilepsy and depression, etc.

Motor prosthesis – also referred to as a brain machine interface (BMI) or brain computer interface (BCI). These are devices that monitor neural activity to decode motor intention to achieve some control action. These typically include some electrical recording hardware, processor and actuator. Examples include an actuated prosthetic arm, or "thought"-controlled computer interface.

Sensory prostheses typically communicate signals to the brain (or nervous system) whereas motor prostheses record signals from the brain (or nervous system). Cognitive prostheses can combine both, i.e. closed loop stimulation.

[1 mark per prosthesis type for description, ½ mark per prosthesis type per example. 1½ marks for differentiating in terms of I/O]

(b) The sensory pathway would feedback touch, temperature and proprioceptive inputs to the PNS (via electrical stimulation). Components for the sensory part would include: (1) sensors with sensor interface instrumentation (for touch sensors, etc), (2) sensory processor (for sensory feedback), (3) electrical stimulator circuit, (4) electrode interface (electrodes) and (5) battery.



[1 mark describing overall system, 2 marks for listing components, 3 marks for system diagram]

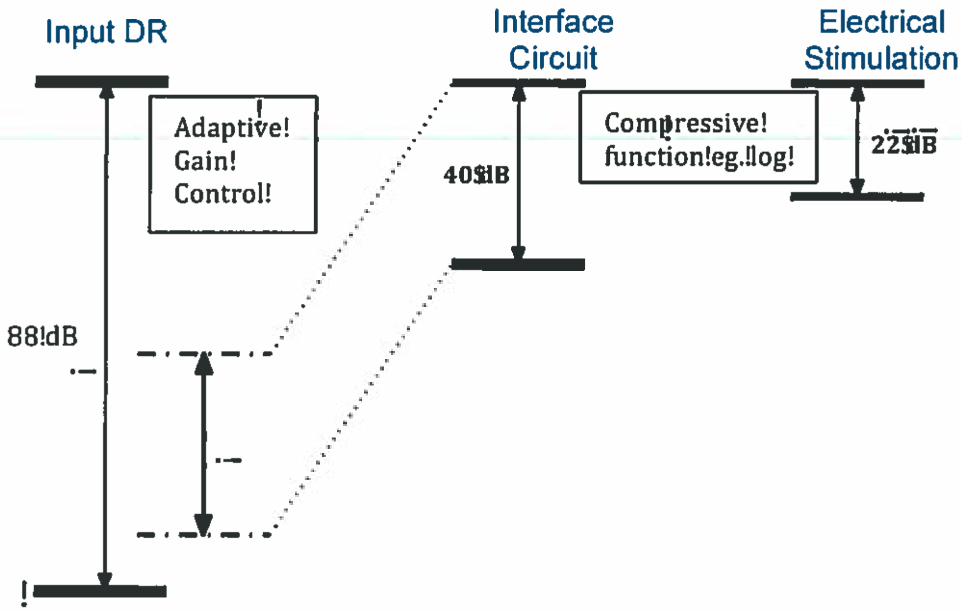
(c) Given the input dynamic range (DR) is much higher than the stimulation output DR, there needs to be some compression or mapping function. Can apply similar techniques as used in cochlear implants to map the DR of hearing onto that of the stimulator.

In the specific example:

DR (input) = 25,000 = 20log(25000) = 88dB.

DR (interface circuit) = 40dB.
DR (stimulator) = 1.2/0.1 = 20log(12) = 22dB.

To map the DR of the interface circuit onto the input dynamic range can use an automatic gain control similar to automatic volume control in cochlear implants or hearing aids. Then to map 40dB of interface circuit onto 22dB of stimulator need to apply some compressive function, e.g. logarithm or square root, etc.



[1 marks for applying analogy from cochlear implants, 2 marks for specific reference to example, 1 mark for illustrating through diagram]

(d) Assuming the prosthetic hand will be active for 14 hours per day (switched off during sleep) and during the 14 hours it is active, it will be "sensing" for 20% the time.

The average current consumption during the 14 hours = 100uA + 2.5mA x 0.2 = 0.6mA.

To achieve a 7V supply from 3V and 3.7V would require a DC-to-DC converter. Assuming a power efficiency of 80%:

- Average current consumption for a 3V battery = 0.6mA x 7/3 / 0.8 = 1.75mA.
- Average current consumption for a 3.7V battery = 0.6mA x 7/3.7 / 0.8 = 1.42mA.

Given battery capacity of non-rechargeable battery is 10Ah (3.7V). This would correspond to a battery lifetime of 10,000/1.42 = 7042 hours. Assuming 14 hours operation per day = 7042/14 = 503 days. This would mean that the battery needs to be replaced once every 18 months. This is not desirable since this would require surgery. Normally implanted batteries are replaced every 5-10 years. Eg. In DBS or pacemakers.

Given battery capacity of rechargeable battery is 0.05Ah (3V). This would correspond to a battery life (per charge) of 50/1.75 = 28.6 hours. Assuming 14 hours operation per day = 28.6/14 = 2 days. This means an implant with rechargeable battery would need to be recharged every 48 hours. However lifetime of the implanted battery would be 2 days x 1000 = 2000 days = 5.5 years.

Therefore the rechargeable battery would be preferable.

[1 mark for estimating duty cycle, etc. 1 mark for valid assumptions, 1 mark for calculations (battery lifetimes), 1 mark for justifying why rechargeable]