UNIVERSITY OF SWAZILAND
MAIN EXAMINATION, DECEMBER 2015

FACULTY OF SCIENCE AND ENGINEERING

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING

TITLE OF PAPER:	**INSTRUMENTATION SYSTEMS**
COURSE NUMBER:	**EE521**
TIME ALLOWED:	**THREE HOURS**

INSTRUCTIONS:

1. There are six questions in this paper. **Answer any FOUR questions.**
2. Each question carries 25 marks.
3. Marks for different sections are shown on the right hand margin.
4. Show the steps clearly in all your calculations including any assumptions made. This is because marks may be awarded for method and understanding, even in the event of incorrect answers.
5. A table of standard values of 1% tolerance resistors and a table of common capacitor values are attached at the end of the question paper for your use in designs.

THIS PAPER IS NOT TO BE OPENED UNTIL PERMISSION HAS BEEN GIVEN BY THE INVIGILATOR

THIS PAPER HAS EIGHT (8) PAGES INCLUDING THIS PAGE

QUESTION 1 ***(25 marks)***

(a) For each of the following sensor devices, briefly describe the device and how it produces its output signal:

(i) Thermocouple *(4 marks)*

(ii) Metal Film strain gauge *(4 marks)*

(b) The transfer characteristic of a PT100 platinum resistance sensor is given by

$$R(T) = R_o\left(1+\alpha T+\beta T^2\right)$$

where $R_o = 100\ \Omega$, $\alpha = 3.9\times10^{-3}\ \mathrm{K}^{-1}$, $\beta = -5.8\times10^{-7}\ \mathrm{K}^{-2}$ and T is temperature in °C. Calculate the **maximum** non-linearity error relative to the straight line $R(T) = R_o\left(1+\alpha T\right)$ in a temperature -50°C to 100°C, expressing your answer

(i) As a percentage. *(5 marks)*

(ii) In °C. *(2 marks)*

(c) The corner frequency of a two-pole Sallen-Key filter is given by the equation

$$f_o = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$$

(i) Evaluate the corner frequencies of the filter shown in Fig. Q1c. *(2 marks)*

(ii) What type of response is given by each stage? *(3 marks)*

(iii) If 13 Hz, 500 Hz and 15 kHz signals are each passed through the three stages, qualitatively describe how the amplitude of the signal changes as it passes through each stage. Exact calculations are not expected in your answer. *(5 marks)*

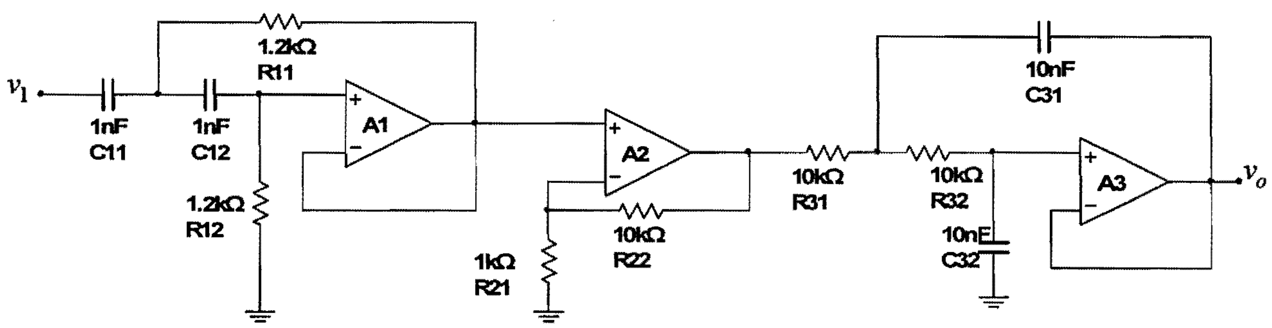

Fig. Q1c

QUESTION 2 ***(25 marks)***

(a) A Butterworth anti-aliasing low-pass filter is required which meets the following specifications:

Gain is greater than 0.9 for frequencies below 20 kHz

Gain is less than 0.001 for frequencies that alias below 20 kHz

The sampling frequency is 100 kHz

The filter has the lowest order.

(i) Determine a suitable order n of the filter *(10 marks)*

(ii) Determine the filter cut-off frequency *(3 marks)*

(iii) Check whether the sampling frequency is adequate *(2 marks)*

(b) Design a circuit which uses a strain gauge of nominal resistance 120 Ω and gauge factor 2 to convert a strain, $\Delta L/L$, of 0.1% into an output voltage of 1 V. *(10 marks)*

QUESTION 3 ***(25 marks)***

(a) A linear straight-track potentiometric sensor of total resistance $R = 800\ \Omega$ is used as a position sensor for distances between 0 and 20 mm. The potentiometer is excited by a dc voltage V_{EX} and position is derived as a voltage V_o from its wiper position as shown in Fig. Q3a. The output voltage is measured using a voltmeter of internal resistance $R_L = 100\ \text{k}\Omega$. Assume that the wiper divides the potentiometer into two parts xR and $(1-x)R$ respectively.

(i) Show that $\dfrac{V_o}{V_{EX}} = \dfrac{x}{1 + x(1-x)\left(\dfrac{R}{R_L}\right)}$ *(7 marks)*

(ii) Using the fact that $R_L >> R$, obtain an approximate expression for the non-linearity error. You may use Taylor series approximation. *(3 marks)*

(iii) Determine the value of x at which the non-linearity error is maximum. Use differentiation. *(2 marks)*

(iv) Evaluate the maximum non-linearity error (in mm) in this measurement set up. *(3 marks)*

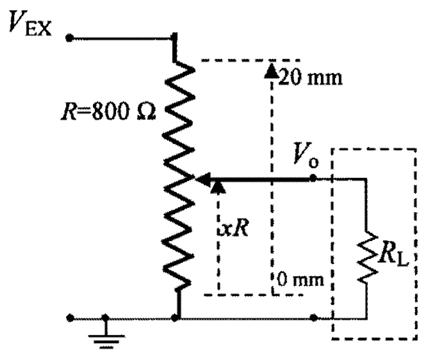

Fig. Q.3a

(b) Design a circuit to transmit a 0 to 4 V analogue signal over a 4 mA to 20 mA current transmission loop. Assume that load is grounded and that amplifiers saturate at ±13 V. What are limits of the load resistance at the receiver? *(10 marks)*

QUESTION 4 ***(25 marks)***

The aim of this question is to compare the performance of two types of instrumentation amplifiers.

(a) For the amplifier shown in Fig Q4a,

(i) Derive an equation for the common mode gain $\frac{V_4+V_3}{V_2+V_1}$ of the **first stage.** *(4 marks)*

(ii) Derive an equation for the differential mode gain $\frac{V_4-V_3}{V_2-V_1}$ of the **first stage.** *(3 marks)*

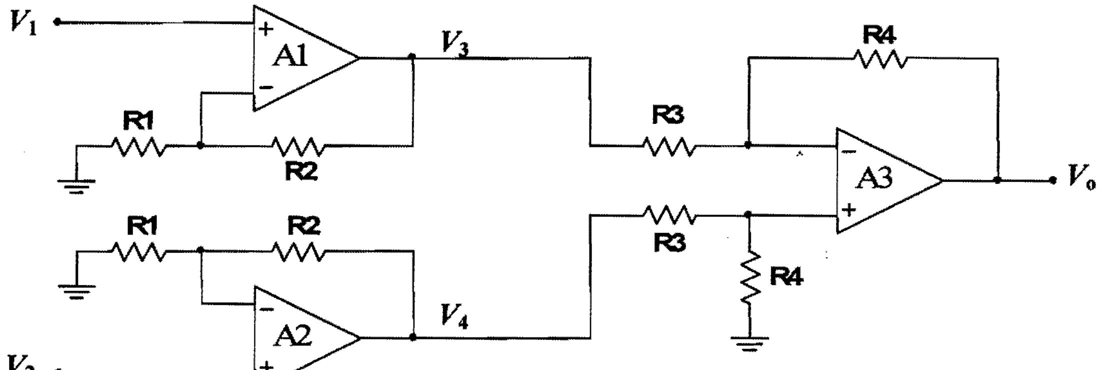

Fig. Q4a

(a) For the amplifier shown in Fig Q4b,

(i) Derive an equation for the common mode gain $\frac{V_4+V_3}{V_2+V_1}$ of the **first stage.** *(4 marks)*

(ii) Derive an equation for the differential mode gain $\frac{V_4-V_3}{V_2-V_1}$ of the **first stage.** *(5 marks)*

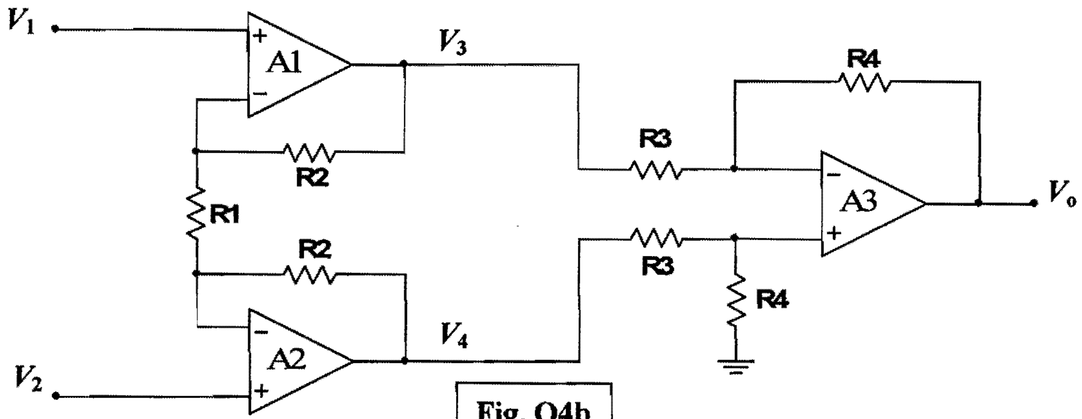

Fig. Q4b

(c) Which of the two instrumentation amplifiers in (a) and (b) is better and why? *(3 marks)*

(d) Give a design of the better amplifier in (c) with an overall differential gain of 800. *(6 marks)*

QUESTION 5 ***(25 marks)***

(a) A thermocouple has a sensitivity of 50 μV/°C. We require a thermocouple-based opamp circuit for measuring the temperature of a furnace over the temperature range from 25 °C to 500 °C. Sketch and design a circuit which gives an output voltage of $V_a = 0.25$ V when the temperature difference between the sensing and the reference junction is 25 °C and $V_a = 5.00$ V when the temperature difference is 500 °C. Assume that the reference junction is at 0°C and that instrumentation amplifiers of desired specified gain are available. *(10 marks)*

(b) It desired that the reference junction used in (a) be at room temperature and not at 0°C. in order to detect the room temperature, a solid state temperature sensor which passes a current $I = (1\mu A)T$ where T is the absolute temperature, is used. The supply voltage to the sensor in anywhere in the range 3 V to 40 V. Sketch and design a circuit that converts the solid-state temperature sensor current into a voltage V_b that has the same overall sensitivity (in V/°C) as the thermocouple circuit in (a). *(8 marks)*

(c) The voltage produced by the solid state sensor circuit in (b) is used for compensation of the thermocouple output in (a) for lack of 0°C ice bath. Sketch a circuit which shows how you can combine the two circuits to give voltage V_c that is proportional to the furnace temperature (0.25 V at 25°C and 5.00 V at 500°C) and does not depend on the room temperature. Note that 0°C is $T = 273$ K. *(7 marks)*

QUESTION 6 ***(25 marks)***

A system is required which converts a sound signal from a microphone into light for transmission through an optical fiber link and then converts the optical signal back into sound via a loud speaker. The following may be assumed:

You have a microphone which produces a maximum differential signal of 100 mV p-p at maximum sound intensity.

The micro phone wires have 50 Hz pick up 10 10 mV which is common-mode

You have a light emitting diode at one end of the fiber that should be driven 100 mA p-p when the microphone signal is maximum

You have a photo diode at the other end of the fiber that produces 1 mA p-p when the LED is producing maximum signal of 100 mA p-p.

You have a loud speaker of 10 Ω impedance which should be driven at 10 V p-p at maximum signal

There are non-linearities in the system so that sound is not distorted.

Design a transmitter and receiver for the system described. Please do note that diodes only conduct or produce current in one direction only therefore appropriate offsets must be applied to the signal whenever required..

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VALUES OF STANDARD 1% TOLERANCE RESISTORS

100	140	196	274	383	536	750
102	143	200	280	392	549	768
105	147	205	287	402	562	787
107	150	210	294	412	576	806
110	154	215	301	422	590	825
113	158	221	309	432	604	845
115	162	226	316	442	619	866
118	165	232	324	453	634	887
121	169	237	332	464	649	909
124	174	243	340	475	665	931
127	178	249	348	487	681	953
130	182	255	357	499	698	976
133	187	261	365	511	715	
137	191	267	374	523	732	

COMMON STANDARD VALUES OF CAPACITORS

10	15	22	33	47	68	pF	Non-polarized
100	150	220	330	470	680	pF	Non-polarized
1	1.5	2.2	3.3	4.7	6.8	nF	Non-polarized
10	15	22	33	47	68	nF	Non-polarized
100	150	220	330	470	680	nF	Non-polarized
1	1.5	2.2	3.3	4.7	6.8	µF	Non polarized /Polarized
10	15	22	33	47	68	µF	(Polarized)
100	150	220	330	470	680	µF	(Polarized)
1000	1500	2200	3300	4700	6800	µF	(Polarized)

Butterworth HP filter $\left|\frac{v_o}{v_{in}}\right| = \frac{f/\mathrm{f}_c}{\sqrt{1+(f/\mathrm{f}_c)^2}}$, Butterworth LP filter $\left|\frac{v_o}{v_{in}}\right| = \frac{1}{\sqrt{1+(f/\mathrm{f}_c)^2}}$

First order response $a_1\frac{ds_o}{dt} + a_o s_o = b_o s_i$ or $\tau\frac{ds_o}{dt} + s_o = Ks_i$ and for step response $s_o / s_i = K(1-e^{-t/\tau})$