Technische Universiteit **Eindhoven** University of Technology

Student name:

Student number:

Examination cover sheet

(to be completed by the examiner)

Course name: Sensing, Computing, Actuating — Course code: 5AIB0

Date: 2-7-2019

Start time: 9:00 — End time : 12:00

Number of pages: 8

Number of questions: 3

Maximum number of points/distribution of points over questions: 90

Method of determining final grade: divide total of points by 9

Answering style: open questions

Exam inspection: make appointment via email with the responsible lecturer

Other remarks:

Instructions for students and invigilators

Permitted examination aids (to be supplied by students):

- ☐ Notebook
- ☑ Calculator
- ☐ Graphic calculator
- ☐ Lecture notes/book
- ☐ One A4 sheet of annotations
- ☐ Dictionar(y)(ies). If yes, please specify:
- ☐ Other:

Important:

- examinees are only permitted to visit the toilets under supervision
- it is not permitted to leave the examination room within 15 minutes of the start and within the final 15 minutes of the examination, unless stated otherwise
- examination scripts (fully completed examination paper, stating name, student number, etc.) must always be handed in
- the house rules must be observed during the examination
- the instructions of examiners and invigilators must be followed
- no pencil cases are permitted on desks
- examinees are not permitted to share examination aids or lend them to each other

During written examinations, the following actions will in any case be deemed to constitute fraud or attempted fraud:

- using another person's proof of identity/campus card (student identity card)
- having a mobile telephone or any other type of media-carrying device on your desk or in your clothes
- using, or attempting to use, unauthorized resources and aids, such as the internet, a mobile telephone, etc.
- using a clicker that does not belong to you
- having any paper at hand other than that provided by TU/e, unless stated otherwise
- visiting the toilet (or going outside) without permission or supervision

Final Exam
5AIB0 Sensing, Computing, Actuating
2-7-2019, 9:00-12:00

- This final exam consists of 3 questions for which you can score at most 90 points. The final grade for this exam is determined by dividing the number of points you scored by 9.
- The solutions to the exercises should be clearly formulated and written down properly. Do not only provide the final answer. Explain your choices and show the results of intermediate steps in your computation.
- The use of a simple calculator is allowed. No graphical calculator or laptop may be used during the exam.

Formulae sheet

Characteristic temperature of material: $B_{T_1/T_2} = \frac{ln\left(\frac{R_2}{R_1}\right)}{\frac{1}{T_1}-\frac{1}{T_2}}$

Resistance: $R = \frac{m}{ne^2\tau}\frac{l}{A} = \rho\frac{l}{A}$

Strain: $\epsilon = \frac{dl}{l}$

Stress: $\sigma = \frac{F}{A} = E\frac{dl}{l}$

Poisson's ratio: $v = -\frac{dt/t}{dl/l}$

Change in specific resistance due to volume change (for metals): $\frac{d\rho}{\rho} = C\frac{dV}{V}$

Change in resistance due to strain: $\frac{dR}{R} = G\epsilon$

Capacitance of flat plate capacitor: $C = \frac{q}{V} = \epsilon_0\epsilon_r\frac{A}{d}$

Capacitance of cylindrical capacitor: $C = \frac{q}{V} = \epsilon_0\epsilon_r\frac{2\pi\cdot l}{ln(b/a)}$

Energy stored in capacitor: $E = \frac{C\cdot V^2}{2}$

Reluctance: $\Re = \frac{1}{\mu\mu_0}\frac{l}{A}$

Inductance: $L = \frac{N\cdot\Phi}{i} = \frac{N^2}{\Re}$

Flux: $\Phi = \mathbf{B}\times\mathbf{S}$

Magneto-motive force: $F_m = \Phi\cdot\Re = N\cdot i$

Amplitude response of Butterworth LPF: $|H\left(f\right)| = \frac{1}{\sqrt{1+\left(\frac{f}{f_n}\right)^{2n}}}$

Sideways force on electron moving through magnetic field: $\mathbf{F} = q\cdot\mathbf{v}\times\mathbf{B}$

Transverse Hall potential: $V_H = \frac{1}{N\cdot c\cdot q}\frac{i\cdot B}{d}sin(\alpha)$

Radius of warping of bimetal sensor: $r \approx \frac{2j}{3(\alpha_x-\alpha_y)(T_2-T_1)}$

Displacement of bimetal sensor: $\Delta = r(1-cos(\frac{180L}{\pi r}))$

Flow velocity and temperature difference: $v = \frac{K}{\rho}\left(\frac{e^2}{R_S}\frac{1}{T_s-T_0}\right)^{1.87}$

Voltage across P-N junction (quality factor 1): $V = \frac{kT}{q}ln\left(\frac{I}{I_0}\right)$

Saturation current through PN-junction (quality factor 1): $I_0 = BT^3e^{-E_g/kT}$

Thomson effect: $Q = I^2\cdot R - I\cdot\sigma\frac{dT}{dx}$

Peltier coefficient: $\pi_{AB}(T) = T\cdot(\alpha_A-\alpha_B) = -\pi_{BA}(T)$

Exercise 1: resistive pressure sensor **(30 points)**

Strain gauges are used amongst others to measure pressure. Figure 1 shows two strain gauges that are attached to a thin metal strip (E $= 200 \cdot 10^9$ N/m^2). The strain gauges are combined with two resistors with a fixed value into a complete bridge. When unloaded, each strain gauge has a resistance of 150 Ω. The fixed resistors also have a resistance of 150 Ω. The strain gauges have a gage factor of 2.50. To prevent damage to the strain gauges, the maximal current through them should be limited to 20 mA.

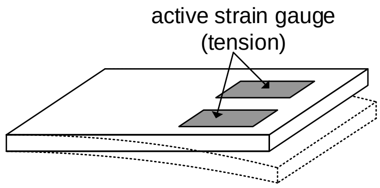

Figure 1: Metal strip with two active strain gauges.

The two strain gauges and the two fixed resistors are connected in a bridge circuit with a voltage supply V_r. The electrical equivalent circuit of this sensor is shown in Figure 2.

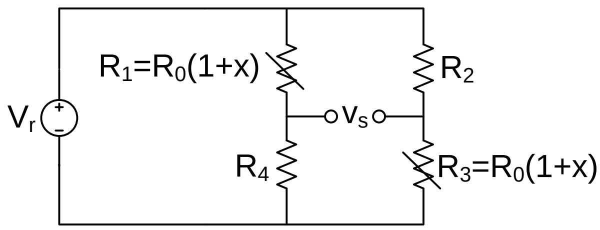

Figure 2: Bridge circuit with two strain gauges.

(5p) (a) Show that the output voltage v_s of the sensor circuit is equal to:

$$v_s = -\frac{x}{2+x} V_r$$

(5p) (b) Does the sensor circuit shown in Figure 2 show a non-linear response when pressure is applied to the sensor? (Explain your answer)

(5p) (c) What value should the voltage supply V_r have to maximize the sensitivity of the sensor circuit shown in Figure 2 for a change in x?

(5p) (d) Show that the output voltage v_s of the sensor circuit shown in Figure 2 is equal to -4.7 mV when a pressure of $100 \cdot 10^6$ N/m^2 is applied to the metal strip and $V_r = 7.5$ V.

Exercise continues on next page

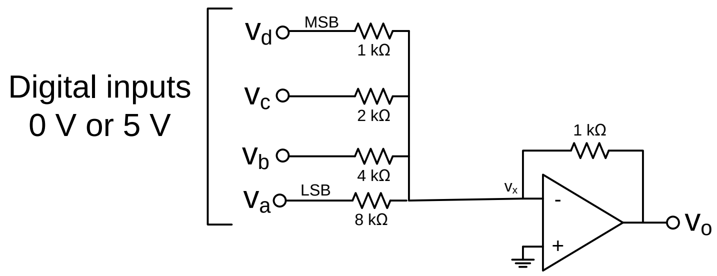

Figure 3: DA converter using summing op-amp.

(5p) (e) A summing DA converter is shown in Figure 3. Which binary input has been applied to the DA converter if it has an output voltage v_o of -3.1V?

(5p) (f) Electromagnetic radiation with a wavelength between 400nm and 700nm with sufficient strength can be seen by our eyes as light. Light with a specific wavelength creates a specific color impression, but the reverse is not true, a specific color impression does not tell us which wavelength this light has. Explain why this is the case.

Exercise 2: Electronic Stability Progam **(30 points)**

ESP assists a driver to keep a vehicle on the road during dangerous driving conditions. For this purpose, the ESP system uses a large number of sensors in the vehicle. One of these sensors measures the angle of the steering-wheel and steering-column and the speed with which the driver changes this angle (note that one sensor measures both quantities). The RVDT (rotary variable differential transducer) from Figure 4 can be used to measure the angle (and its rate of change). When the driver moves the steer from the central position ($\Theta = 0°$) to the left or to the right, then this will lead to a change in the output voltage of the sensor. This electrical signal can then be send to the ESP computer. The primary winding of this RVDT is connected to a voltage supply that produces a sinusoidal voltage with an amplitude of 5V and a frequency of 10 Hz. The RVDT has a sensitivity S of 500 μV/(°/V). The output voltage of the RVDT is equal to:

$$v_s = v_2 - v_1 = S \cdot \Theta \cdot v_r$$

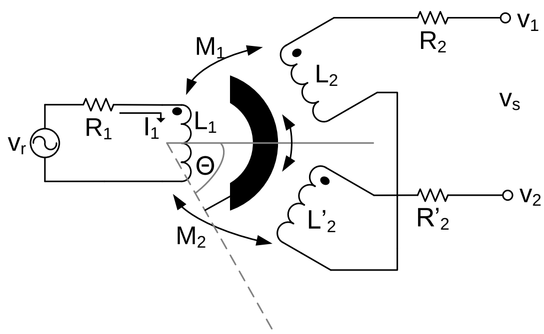

Figure 4: Measuring an angle using an RVDT.

(4p) (a) Is the RVDT shown in Figure 4 when used to sense a rotation an example of a complex sensor? (Explain your answer)

(5p) (b) Show that the output voltage of the sensor, v_s, is equal to:

$$v_s = \frac{s k_\Theta \Theta v_r}{s L_1 + R_1}$$

with $(M_2 - M_1) = k_\Theta \Theta$.

(5p) (c) Assume that the resistor R_1 has a resistance of 250 Ω and the inductor L_1 has an inductance of 20 mH. What is the value of the coupling coefficient k_Θ?

(4p) (d) A driver moves the steering wheel in 0.5 seconds from an angle $\Theta = +15°$ to an angle $\Theta = -15°$. Draw the output voltage v_s as a function of time t. (Clearly show the dimensions on both axis.)

Exercise continues on next page

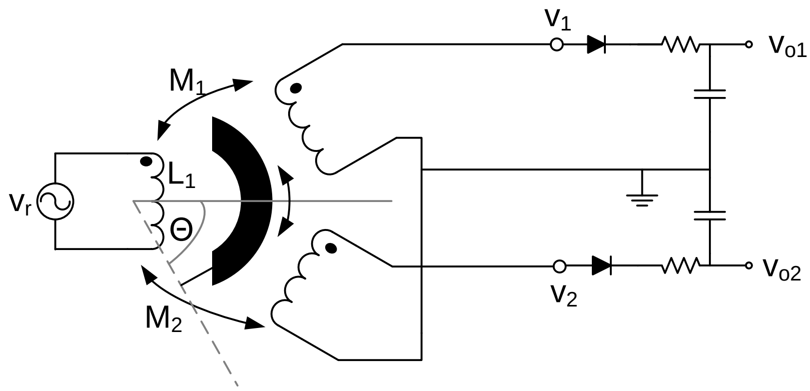

Figure 5: Double-sided rectifier with low-pass filter.

(4p) (e) The output signal of the RVDT shown in Figure 4 is connected to a double-sided rectifier with a low-pass filter as is shown in Figure 5. Draw the output voltage, $v_{o2} - vo1$, when the steering wheel is moved in 0.5 seconds from an angle $\Theta = +15°$ to an angle $\Theta = -15°$.

(4p) (f) For an application you need to select between an inductive or resistive displacement sensor to sense a rotation between $+15°$ and -15°. The transducer will be subject to frequent movement while it should have a long lifetime. Which of the two sensors (inductive or resistive) would you select? (Explain your answer)

(4p) (g) Draw a diagram that shows the physical construction of a two-phase six-pole permanent magnet step motor.

Exercise 3: exhaust gas temperature measurement (30 points)

It is necessary to change the ratio between fuel and air in a combustion engine to maximize the efficiency of the engine. The objective is to keep the temperature of the gasses going through the exhaust pipe within a certain temperature range. Because of the high temperature of these gases, it is necessary to use a thermocouple to measure this temperature. A thermocouple can only measure a temperature difference. Therefore it is necessary to also add a reference sensor to the circuit. This sensor is then used to measure the absolute temperature at the reference junction.

The thermocouple in Figure 6 contains a reference junction compensation based on a RTD temperature sensor. The output voltage of this sensor (v_{ref}) is given by the following transfer function: $v_{ref} = 16mV/^{\circ}C \cdot T_a$ with T_a the environmental temperature at the reference junction. The output of the reference temperature sensor is connected to the reference input of the instrumentation amplifier. It holds for this instrumentation amplifier:

$$v_o - v_{ref} = \left(1 + k + \frac{R_2 + R_4}{R_g}\right)(v_2 - v_1) = G(v_2 - v_1)$$

The ratio of the resistors in the instrumentation amplifier is equal to: $k = R_4/R_3 = R_2/R_1 = 1$. The thermocouple itself is a J-type (Cn/Fe) thermocouple with a sensitivity $S_J = 54\mu\text{V/K}$.

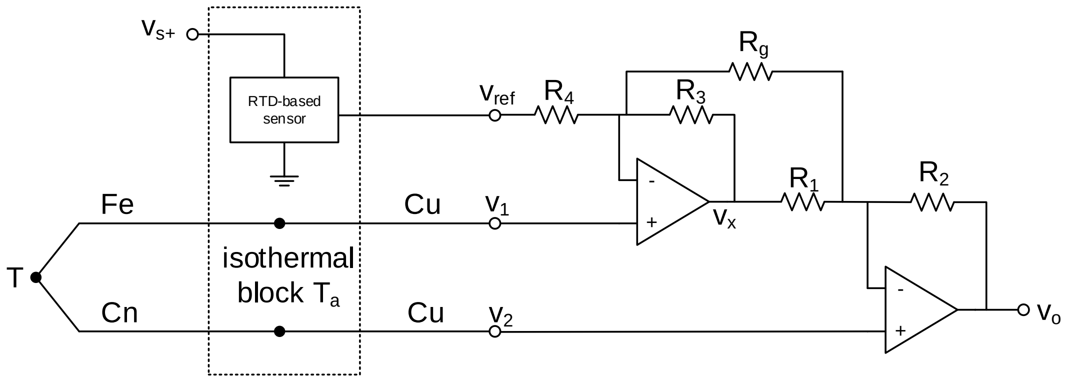

Figure 6: Compensation with a RTD-based sensor and instrumentation amplifier.

(5p) (a) There are three important law that you can use when analysing thermocouples, namely the law of the homogeneous circuits, the law of intermediate metals, and the law of intermediate temperatures. Show using these laws that the voltage across the thermocouple shown in Figure 6 is equal to:

$$v_2 - v_1 = V_T - V_{T_a} = S_J \cdot (T - T_a)$$

Hint: The Seebeck coefficient $\alpha_{Cn/Fe}$ of a J-type thermocouple is equal to: $\alpha_{Cn/Fe} = S_J$.

(5p) (b) What gain, G, should the instrumentation amplifier have to get an output voltage v_o that is independent of the environmental temperature?

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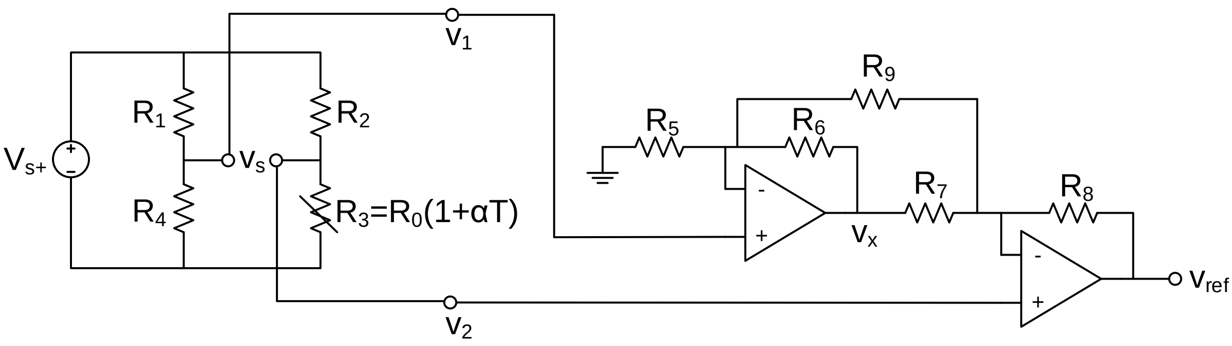

Figure 7: Implementation of "RTD-based sensor" block of Figure 6.

(5p) (c) The circuit shown in Figure 7 is used to generate the reference voltage v_{ref} for the thermocouple sensor shown in Figure 6. In other words, Figure 7 shows the internals of the block "RTD-based sensor" in Figure 6. Assume that the supply voltage v_{s+} is equal to 4 V. Assume further that resistor R_3 is a temperature dependent resistor (RTD) of type PT100. Its relation between temperature and resistance (transfer function) can be approximated with the following linear equation: $R_3(T) = R_0(1 + \alpha T)$, with R_0 equal to 100Ω and $\alpha = 0.004/°$C. Assume also that $R_4 = R_5 = R_6 = R_7 = R_8 = R_9 = R_0$ and $R_1 = R_2 = k \cdot R_0$. What resistance should the resistor R_2 have to ensure that the "RTD-based sensor" has a sensitivity of $16mV/°C$?

(5p) (d) Does the RTD-based circuit show a non-linear relation between temperature and output voltage? If so, how could these non-linearities be reduced. (Explain your answer)

(5p) (e) Would it be possible to use a sensor based on the pyro-electric effect in the circuit shown in Figure 7 instead of an RTD for an application where the environmental temperature is constant? (Explain your answer)

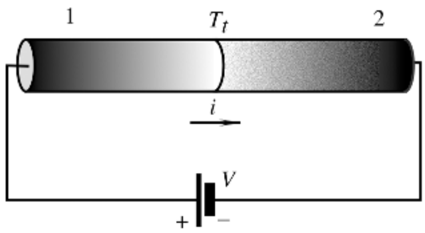

Figure 8: Peltier effect in single junction.

(5p) (f) Figure 8 shows a single junction of two different materials. Explain (in maximally 200 words) why the Peltier effect results in the production or liberation of energy at a junction when a current is passed through this junction.