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: 13-8-2019

Start time: 9:00 | End time : 12:00

Number of pages: 6

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
13-8-2019, 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: $|H(f)| = \frac{1}{\sqrt{1+\left(\frac{f}{f_n}\right)^{2n}}}$

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 among others to measure pressure. Figure 1 shows one strain gauge that is attached to a thin metal strip (E = $200 \cdot 10^9$ N/m^2). The strain gauge is combined with three resistors with a fixed value into a complete bridge. When unloaded, the strain gauge has a resistance of 200 Ω. The fixed resistors also have a resistance of 200 Ω. The strain gauge has a gage factor of 2.00. To prevent damage to the strain gauge, the maximal current it them should be limited to 25 mA.

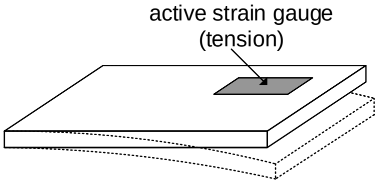

Figure 1: Metal strip with one active strain gauge.

The strain gauge and the three 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.

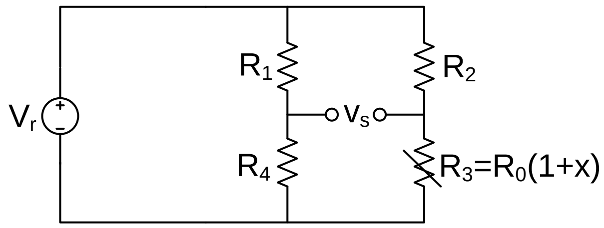

Figure 2: Bridge circuit with one strain gauge.

(5p) (a) Show that the output output voltage v_s of the sensor circuit shown in Figure 2 is equal:

$$v_s = v_s = \frac{-x}{4+2x} V_r$$

(5p) (b) The sensor output voltage v_s has a non-linearity error in terms of the signal x. How could this non-linearity error be removed? (Explain your answer)

(5p) (c) Show that the output voltage v_s of the sensor circuit shown in Figure 2 is equal to 2.5 mV when a pressure of $100 \cdot 10^6$ N/m^2 is applied to the metal strip and $V_r = 10$ V.

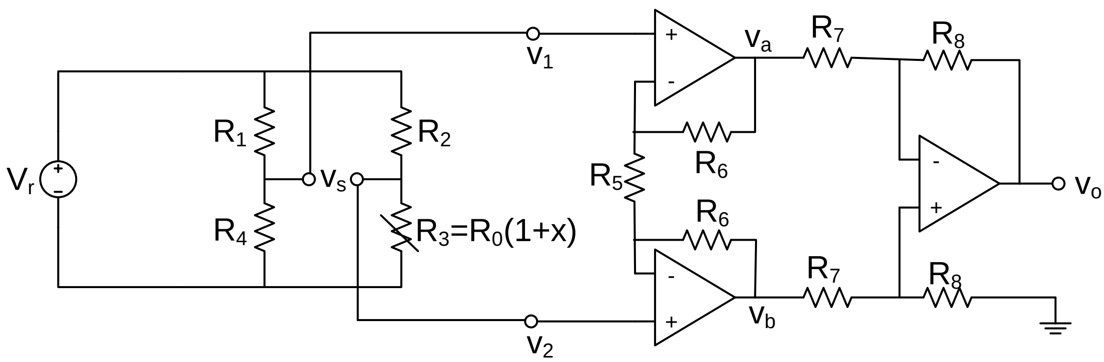

Figure 3: Sensor circuit with processing circuit.

(5p) (d) The sensor circuit from Figure 2 is connected to an instrumentation amplifier (see Figure 3). Show that the output voltage v_o of the circuit shown in Figure 3 is equal to:

$$v_o = \left(1 + \frac{2R_6}{R_5}\right) \frac{R_8}{R_7} \frac{-x}{4+2x} V_r$$

Exercise continues on next page

(5p) (e) Assume that $V_r = 10$ V, $R_6 = R_7 = R_8 = 100k\Omega$. What value should the resistor R_5 have to ensure that the output voltage v_o of the circuit shown in Figure 3 is equal to 2.5 V when a pressure of $200 \cdot 10^6\ N/m^2$ is applied to the metal strip.

(5p) (f) The operation of the strain gauge is based on the piezeoresistive effect. Explain how this effect works in metal strain gauges when used as pressure sensor.

Exercise 2: inductive sensor **(30 points)**

Figure 4 shows a two coil based linear displacement transformer that can be used to sense the displacement of an object over a distance x. The two coils each consist of N windings and are connected in series to each other. An excitation voltage v_e is placed over the two coils. The voltage drop over one of the coil (i.e., lower coil in Figure 4) is used as the output voltage v_o of the sensor.

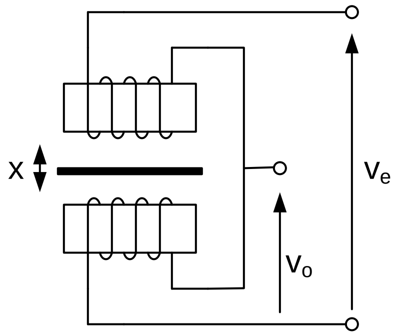

Figure 4: Inductive sensor based on two coils in series.

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

$$v_o = \frac{1-x}{2} v_e$$

(5p) (b) Is the sensor shown in Figure 4 when used to sense a displacement an example of a complex sensor? (Explain your answer)

(5p) (c) For an application you need to select between an inductive or resistive displacement sensor to sense a displaceent between -15μm and $+15\mu m$. The transducer will be subject to frequent movements while it should have a long lifetime. Which of the two sensors (inductive or resistive) would you select? (Explain your answer)

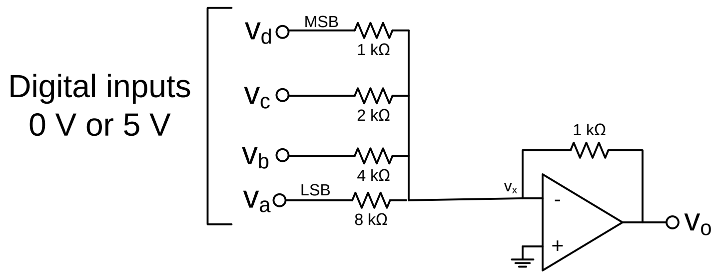

Figure 5: DA converter using summing op-amp.

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

(5p) (e) Electromagnetic radiation with a wavelength between 400nm and 700nm with sufficient strength can be seen by our eyes as light. We can make our eyes believe that an object has a yellow color (575 nm) by using light with wavelengths 437nm, 498nm, and 564nm. Explain what condition needs to be met for our eyes to observe this mixture of these three wavelengths as yellow?

(5p) (f) For an application it is important that the step motor remains in its position even when the motor is not energized. Can you use a variable reluctance step motor for this application? (Explain your answer)

Exercise 3: temperature sensors **(30 points)**

Systems with a thermal capacity such as a thermocouple require a transfer of heat, Q, from the environment to the sensor in order to show a change in temperature. This change in energy, E, as a function of time is described by the following first-order differential equation:

$$Q = \frac{dE}{dt} = mC_V \frac{dT_s(t)}{dt} = hA_s \left(T_o(t) - T_s(t)\right)$$

, with m the weight of the sensor, C_v the specific heat of the sensor, h the heat transfer coefficient, A_s the contact surface (area) of the sensor, T_o the environmental temperature, en T_s the sensor temperature.

(5p) (a) Show that the transfer function of the sensor $T_s(s)/T_o(s)$ is equal to:

$$\frac{T_s(s)}{T_o(s)} = \frac{k}{\tau s + 1}$$

, with $k = 1$ and $\tau = \frac{mC_v}{hA_s}$.

(5p) (b) The response of the sensor to a step function on its input is given by:

$$T_s(t) = k\left(1 - e^{-t/\tau}\right)$$

Assyme that the sensor has an initial temperature $T_s(0) = T_i$ when the sensor is suddenly exposed to a constant environmental temperature T_o. Show that the response of the sensor is equal to:

$$T_s(t) = T_o + (T_i - T_o)\, e^{-t/\tau}$$

(5p) (c) To determine the time constant τ the sensor is exposed from $t = 0$ to a (constant) environmental temperature. The temperature is measured every 4 seconds. This results in the following series of readings:

Time (s)	0	4	8	12	16	20	24	28
Temperature (°C)	5.00	56.55	70.14	73.72	74.66	74.91	74.98	74.99

What is the time constant τ from this sensor?

The circuit in Figure 6 can be used to measure the in-car temperature. This circuit is designed to operate between -40°C and +40°C. The resistor R_2 is a temperature dependent resistor (RTD) of type PT100. The relation between temperature and resistance (transfer function) can be approximated with the following linear equation: $R_2(T) = R_0(1 + \alpha T)$, with R_0 equal to 100Ω and $\alpha = 0.004/°C$. The resistor R_1 has a fixed value ($R_1 = R_0 \cdot k$). The reference voltage V_r is equal to 5 V. The RTD is surrounded by air with a dissipation factor $\delta = 20$ mW/K.

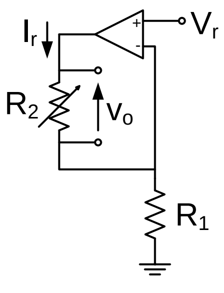

Figure 6: Temperature sensor.

(5p) (d) What resistance should the resistor R_1 have to ensure that the self-heating in the RTD R_2 is less then 0.1°C?

(5p) (e) What resistance should the resistor R_1 have to ensure a sensitivity of 1 mV/°C in the output voltage v_o?

(5p) (f) Would it be possible to use a sensor based on the pyro-electric effect to measure the absolute temperature of its environment? (Explain your answer)