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: 4-7-2017

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
4-7-2017, 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 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 200 Ω. The fixed resistors also have a resistance of 200 Ω. The strain gauges have a gage factor of 2.00. To prevent damage to the strain gauges, the maximal current through them should be limited to 25 mA.

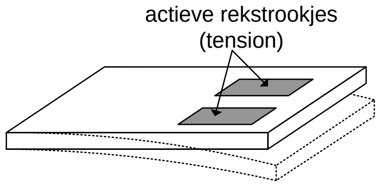

Figure 1: Metal strip with two active strain gauges.

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.

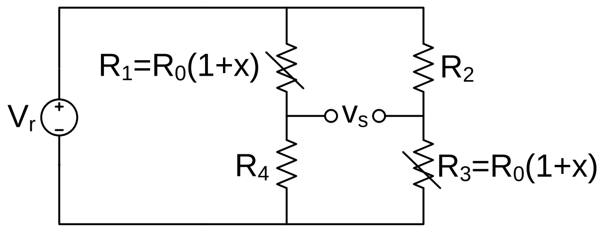

Figure 2: Bridge circuit with two strain gauges.

(5p) (a) The sensor circuit in Figure 2 contains two active strain gauges. You can also design a pressure sensor with only one strain gauge and three fixed resistors. Mention at least one advantage of the circuit shown in Figure 2 compared to a solution with only one active strain gauge.

(5p) (b) Show that the output voltage v_s of the sensor circuit shown in Figure 2 is equal to 5.00 mV when a pressure of $100 \cdot 10^6$ N/m^2 is applied to the metal strip and $V_r = 10$ V.

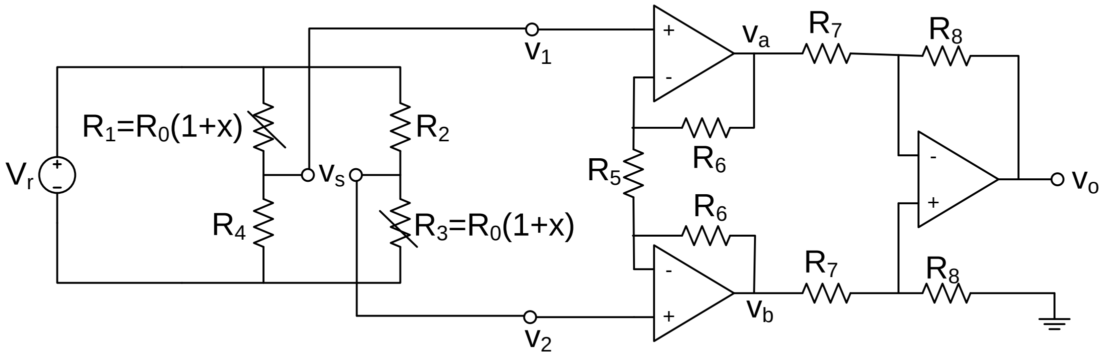

Figure 3: Sensor circuit with processing circuit.

(5p) (c) 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:

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

Exercise continues on next page

(5p) (d) 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) (e) The resistance of the strain gauges, $R(x)$, does not only depend on the deformation of the strain gauges, the resistance is also influenced by the temperature of the environment. This influence of the environmental temperature on the resistance can be seen as a thermal signal y. The resistance of R_1 and R_3 is then equal to $R_0(1 + x + y)$. Show that the absolute error in the output voltage of the circuit, v_s, due to the temperature dependency of the strain gauges is equal to:

$$\epsilon = \left| \frac{2y}{(2 + x + y)(2 + x)} V_r \right|$$

(Assume that the temperature dependency of the fixed resistors R_2 and R_4 can be ignored.)

(5p) (f) What happens to the absolute error when the sensing circuit shown in Figure 2 is connected to an instrumentation amplifier while the strain gauges show a temperature dependency as analyzed in exercise 1.e? (Explain your answer)

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 10V and a frequency of 5 Hz. The RVDT has a sensitivity S of 250 μV/(°/V). The output voltage of the RVDT is equal to:

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

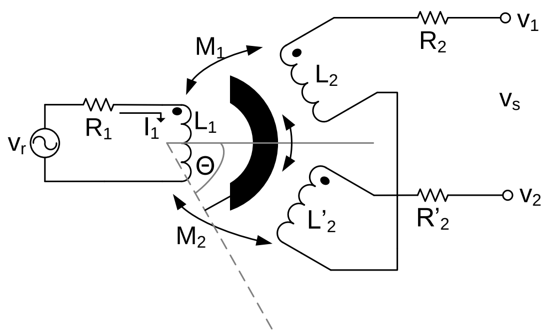

Figure 4: Measuring an angle using an RVDT.

(5p) (a) 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) (b) Assume that the resistor R_1 has a resistance of 250 Ω and the inductor L_1 has an inductance of 40 mH. What is the value of the coupling coefficient k_Θ?

(5p) (c) A driver moves the steering wheel in 1 second 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

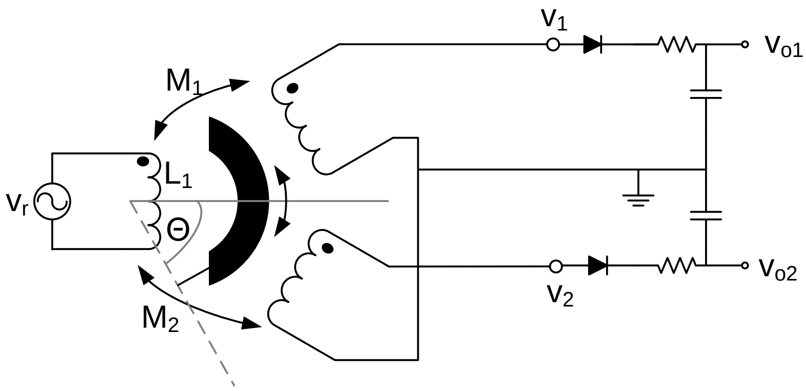

Figure 5: Double-sided rectifier with low-pass filter.

(3p) (d) 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 1 second from an angle $\Theta = -15°$ to an angle $\Theta = +15°$.

(3p) (e) The output of the sensor (v_s in Figure 4) can be connected directly to an AD converter. Alternatively the output of the sensor could be connected to a phase sensitive detector whose output is then connected to the AD converter. Give at least one reason why we prefer to use a phase sensitive detector in front of the AD converter instead of directly connecting the output of the sensor to the AD converter.

(3p) (f) Instead of using an inductive displacement sensor, you could also use a resistive displacement sensor. Give at least two advantages of using an inductive displacement sensor over a resistive displacement sensor.

(3p) (g) An RVDT measures the rotation of an object through the change in coupling between a primary and two secondary coils. Another way to measure a rotation would be to use a Hall effect sensor. Explain the operation of a Hall effect sensor. Clearly indicate how you can use the sensor to measure a rotation.

(3p) (h) Give at least three reasons why we prefer transducers who produce a signal in the electrical domain over transducers that produce a signal in any of the other signal domains.

Exercise 3: climate control system **(30 points)**

Automatic climate control systems are found in many cars that are sold nowadays. The system allows the driver or its passengers to set the desired in-door temperature. The climate control system will cool or heat the in-door air till the desired temperature is reached. The temperature inside the car is an important factor in the operation of the control system. Since this temperature is not known at the time the system is designed, it must be measured using a sensor. This sensor reading can then be processed by the control algorithm to compute the required actuation action (i.e., heat or cool the in-door environment).

Figure 6: Climate control.

The circuit in Figure 7 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.

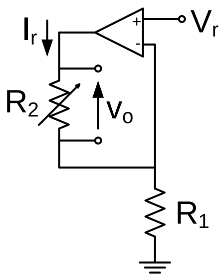

Figure 7: Temperature sensor.

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

(2p) (c) The operation of a temperature dependent resistor (RTD) is based on the thermo-resistive effect. Explain briefly (maximal 200 words) how this effect works in metals.

Exercise continues on next page

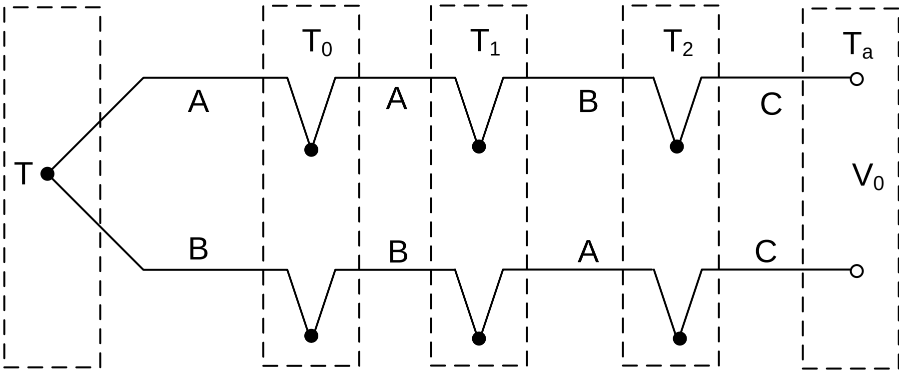

Figure 8: Simulate reference junction at 0°C.

(5p) (d) Figure 8 shows a circuit in which three types of wires (A, B, C) are combined into several thermocouples with three intermediate temperatures T_0, T_1, and T_2 and a temperature T at the measurement junction. What relation must T_0, T_1 and T_2 have such that the output voltage only depends on T?

(5p) (e) The Seebeck effect can only be observed when two (or more) different materials are joined in two (or more) junctions. Explain (in maximally 200 words) why the Seebeck effect can only be observed if the circuit contains at least two junctions with on either side of the junction a different material.

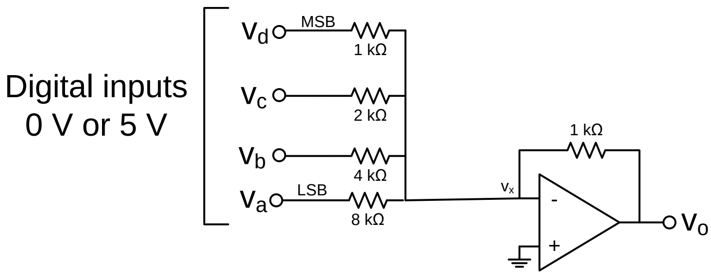

Figure 9: DA converter using summing op-amp.

(5p) (f) A summing DA converter is shown in Figure 9. Which binary input has been applied to the DA converter if it has an output voltage v_o of -3.1V?

(3p) (g) Give a definition (maximally 100 words) for the following terms:

- Transducer
- Sensor
- Sensitivity of a sensor