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: 15-8-2017

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
15-8-2017, 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 150 Ω. The fixed resistors also have a resistance of 150 Ω. The strain gauges have a gage factor of 1.50. To prevent damage to the strain gauges, the maximal current through them should be limited to 10 mA.

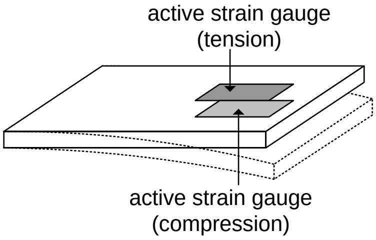

Figure 1: Metal strip with two active strain gauges.

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.

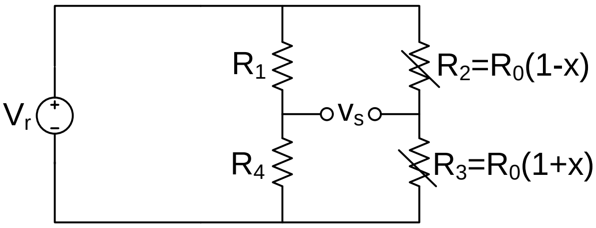

Figure 2: Bridge circuit with two strain gauges.

(2p) (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.

(2p) (b) Show that the output voltage v_s of the sensor circuit is equal to:

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

(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 -1.13 mV when a pressure of $100 \cdot 10^6$ N/m^2 is applied to the metal strip and $V_r = 3$ V.

Exercise continues on next page

(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_2 and R_3 is then equal to respectively $R_0(1-x+y)$ and $R_0(1+x+y)$. 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:

$$\epsilon = \left| \frac{-xy}{2(1+y)} V_r \right|$$

(Assume that the temperature dependency of the fixed resistors R_1 en R_4 can be ignored.)

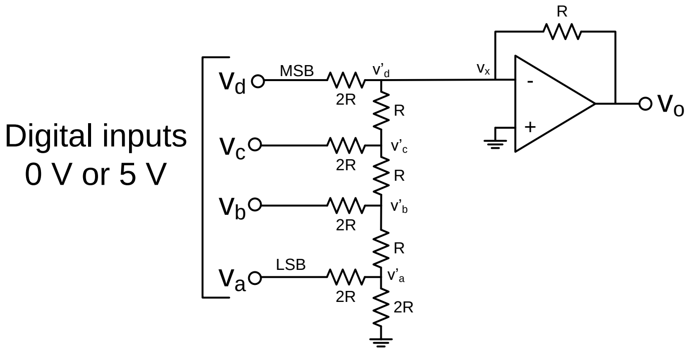

Figure 3: DA converter using ladder network.

(5p) (f) A ladder DA converter is shown in Figure 3. What is the output voltage of this DA converter when the binary input 0100 is applied to it?

(6p) (g) Give a definition (maximally 100 words) for the following terms:

- Transducer
- Actuator
- Transfer function of a sensor

Exercise 2: Active suspension (30 points)

An active suspension system measures the displacement x between the wheels and the car body. This can be done using a linear variable differential transformer (LVDT). The sensor uses the magnetic coupling between a primary and two secondary coils to measure the displacement of a ferromagnetic core. Figure 4 shows the electrical equivalent circuit of a LVDT sensor that is connected to a voltage supply v_r with a frequency of 5 Hz and an amplitude of 10 V. There is no load connected to the output of the sensor. The LVDT has a sensitivity S of 250 (μV/V)/μm. The output voltage of the LVDT is equal to:

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

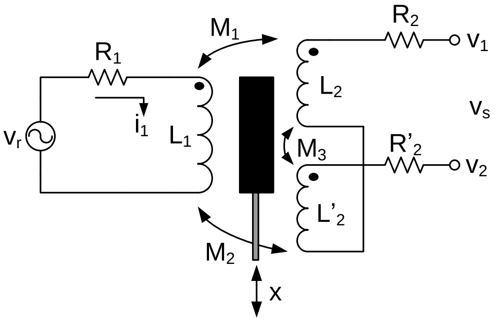

Figure 4: Measuring a displacement using an LVDT.

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

$$v_s = \frac{s k_x x v_r}{s L_1 + R_1}$$

with $(M_2 - M_1) = k_x x$.

(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_x?

(5p) (c) A driver moves over a speed bump in 1 second causing the LVDT to move from a position $x = -15\ \mu m$ to a position $x = +15\ \mu m$. Draw the output voltage v_s as a function of time t. (Clearly show the dimensions on both axis.)

Exercise continues on next page

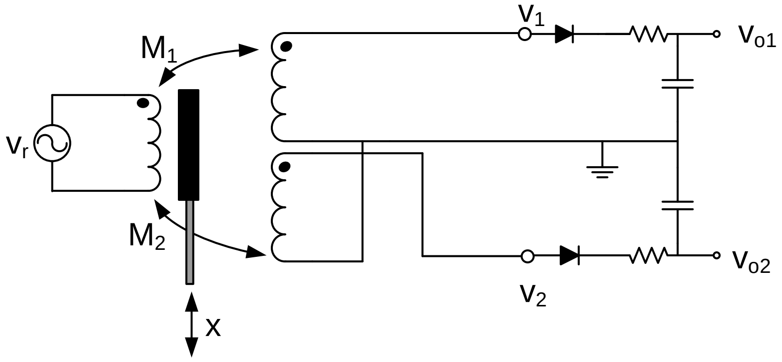

Figure 5: Double-sided rectifier with low-pass filter.

(3p) (d) The output signal of the LVDT 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, $v_{o2} - v_{o1}$, when the position of the core in the LVDT changes in 1 second from $x = -15\ \mu m$ to $x = +15\ \mu m$.

(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 LVDT 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: thermocouple **(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:

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

, 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_a the ambient temperature, and T_s the sensor temperature. The transfer function of such a thermocouple sensor $T_s(s)/T_a(s)$ is equal to:

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

, with $k = 1$ and $\tau = \frac{mC_v}{hA_s} = 3.00$ s.

(3p) (a) Because of temperature fluctuations in the environment, the ambient temperature T_a changes according to: $T_a(t) = 0.50°\text{C}{\cdot}sin(0.01t) + 74.99°\text{C}$. What is the steady-state output $T_s(t)$ of the sensor?

(2p) (b) Assume that the ambient temperature T_a changes according to: $T_a(t) = 30°\text{C}{\cdot}sin(0.001t) + 75.35°\text{C}$. Is the sensor suitable to measure these changes? (Explain your answer)

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

(5p) (d) The thermocouple sensor is connected in the sensing circuit as shown in Figure 6. This circuit 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: $v_{ref} = 5mV/°C \cdot T_a$ with T_a the ambient 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 K-type (NiCr/Ni) thermocouple with a sensitivity $S_K = 41\mu\text{V/K}$.

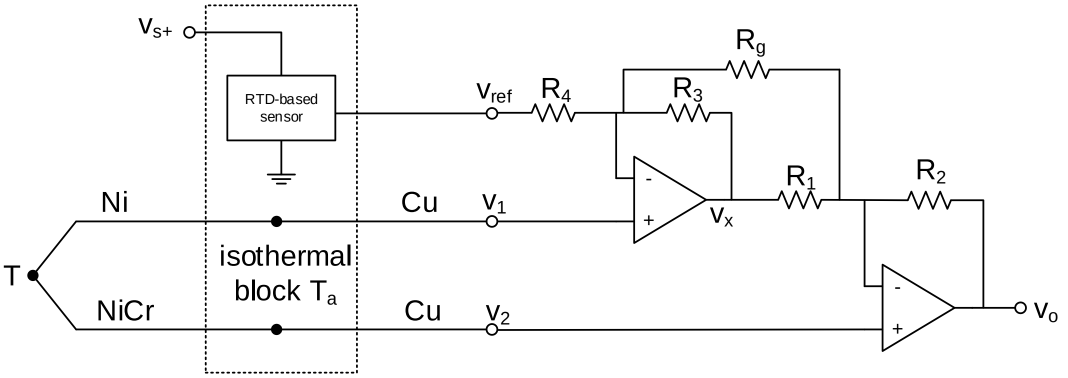

Figure 6: Compensation with a RTD-based sensor and instrumentation amplifier.

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:

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

Hint: The Seebeck coefficient $\alpha_{NiCr/Ni}$ of a K-type thermocouple is equal to: $\alpha_{NiCr/Ni} = S_K$.

Exercise continues on next page

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

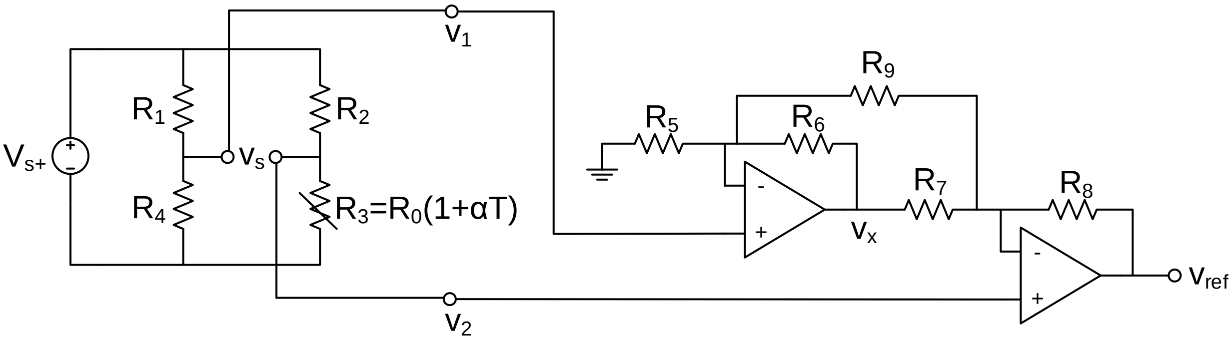

Figure 7: Implementation of “RTD-based sensor" block of Figure 6.

(5p) (f) 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 5 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 $\alpha = 0.004/°\text{C}$. 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 $5mV/°C$?

(5p) (g) 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)