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: 3-7-2018

Start time: 9:00 — End time : 12:00

Number of pages: 7

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
3-7-2018, 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: temperature sensor **(30 points)**

A resistive temperature detector (RTD) can be used to measure the temperature of an object. Figure 1 shows a bridge circuit with an RTD which is exposed to a temperature T. This temperature will be in the range [-30°C, 80°C]. The RTD is a PT100 sensor with $R_0 = 100\ \Omega$ and $\alpha = 0.004/°\mathrm{C}$ at 0°C.

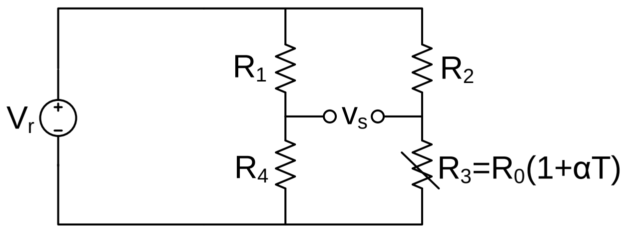

Figure 1: Bridge circuit with a RTD temperature sensor.

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

$$v_s = -\frac{k\alpha T}{(k+1)(k+1+\alpha T)}V_r$$

, with $k = R_1/R_4 = R_2/R_0$.

(7p) (b) What ratio k should the resistors R_2/R_0 have to ensure that the non-linearity error is less then 0.8% of the reading while maximizing the sensitivity?

(7p) (c) Assume that $k = 38.7$. Assume further that the dissipation constant of the environment $\delta = 1$ mW/K. What value should the supply voltage V_r have to keep the self-heating below 0.002% of the full-scale output (FSO)?

(5p) (d) 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.

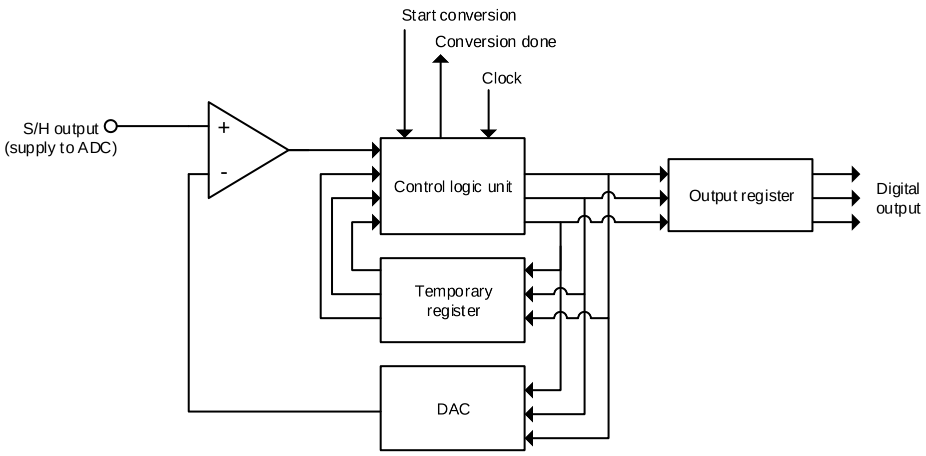

Figure 2: Successive approximation AD converter.

(6p) (e) The output voltage v_s of the bridge circuit shown in Figure 1 can be digitized using a successive approximation AD converter like the one shown schematically in Figure 2. Explain (maximal 500 words) how the successive approximation AD converter works. You may also draw a figure to illustrate its operation.

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

Figure 3 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 3) is used as the output voltage v_o of the sensor.

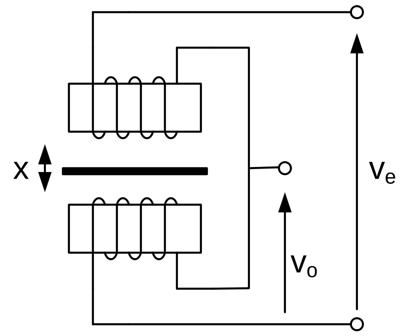

Figure 3: Inductive sensor based on two coils in series.

(4p) (a) Show that the output voltage of the sensor is equal to:

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

(4p) (b) Is this sensor suitable to measure large displacements? (Explain your answer)

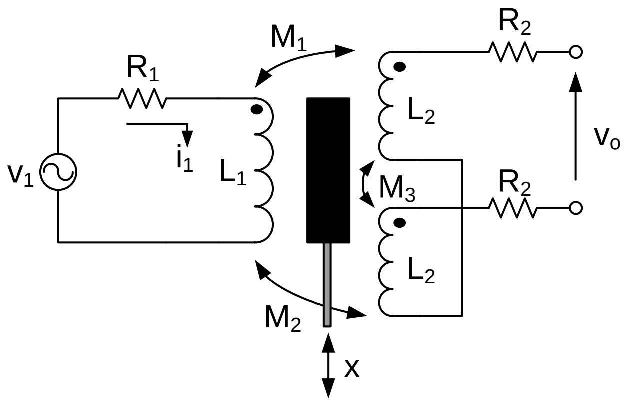

Figure 4: LVDT sensor.

(5p) (c) The linear variable differential transducer (LVDT) shown in Figure 4 is often used to sense displacements instead of the two coil sensor shown in Figure 3. When a purely resistive load R_L is connected to the output of the sensor, its output voltage is equal to:

$$V_o = \frac{j\omega k_x x R_L}{-(j\omega)^2 2L_1L_2 - j\omega(R_{2c}L_1 + 2R_1L_2) - R_1R_{2c}} V_1$$

, with $R_{2c} = 2R_2 + R_L$. For a specific LVDT holds that its primary winding has a DC resistance of 76 Ω and each of its two secondary windings have individually a DC resistance of 1600 Ω. The primary winding has an inductance of 45 mH and the two secondary windings have a combined inductance of 366 mH. How large is the phase shift between the input and output voltage when an excitation frequency of 1500 Hz is used and a load resistance of 10 $k\Omega$ is connected to the output of the sensor?

Exercise continues on next page

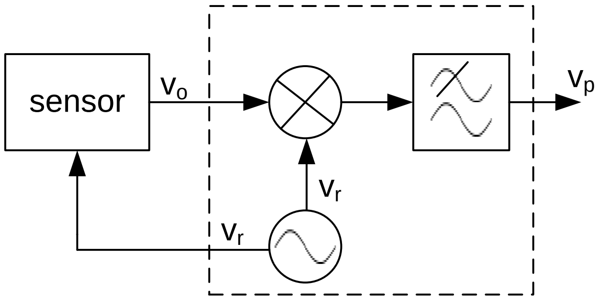

Figure 5: Sensor with phase sensitive detector.

(5p) (d) The displacement sensor from Figure 4 is connected to a phase sensitive detector. This detector consists of an analog multiplier connected to a low-pass filter. Using this processing circuit, it is possible to recover the magnitude and direction of the displacement from the output signal of the sensor. The block diagram of a phase sensitive detector is shown in Figure 5. The displacement of the object is given as a function $x(t)$. Assume further that the reference voltage v_r is equal to:

$$v_r(t) = V_r cos\left(\omega_r \cdot t\right)$$

The output voltage v_o of the sensor circuit is then equal to:

$$v_o(t) = S \cdot x(t) \cdot v_r(t)$$

, with S the sensitivity of the sensor.

Show that the output voltage of the phase sensitive detector, v_p, is equal to:

$$v_p(t) = S \cdot x(t) \cdot \frac{V_r^2}{2}$$

Hint: $cos(A)cos(B) = \frac{1}{2}\left(cos\left(A+B\right) + cos\left(A-B\right)\right)$.

(4p) (e) The output of the phase sensitive detector can be connected to an AD converter. Alternatively the output of the sensor could immediately be connected to an 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.

(4p) (f) A LVDT measures the displacement of an object through the change in coupling between a primary and two secondary coils. Another way to measure a displacement 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 displacement.

(4p) (g) Give at least two 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:

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

, 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?

(5p) (d) Because of temperature fluctuations in the environment, the environmental temperature T_o changes according to: $T_o(t) = 0.50°\text{C} \cdot sin(0.01t) + 74.99°\text{C}$. Assume that the time constant τ is equal to 3.00 s. What is the steady-state output of this sensor $T_s(t)$?

Exercise continues on next page

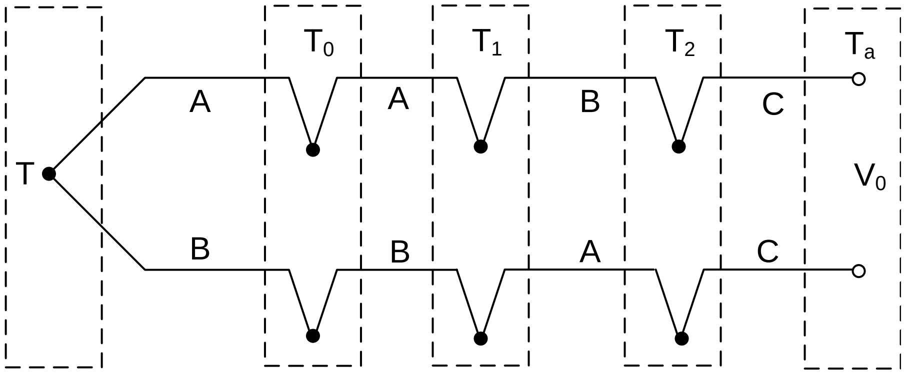

Figure 6: Simulate reference junction at 0°C.

(5p) (e) Figure 6 shows a circuit in which three types of wires (A, B, C) are combined into several thermocouples with two intermediate temperatures T_1 and T_2 and a temperature T at the measurement junction. What relation must T_1 and T_2 have such that the output voltage only depends on T?

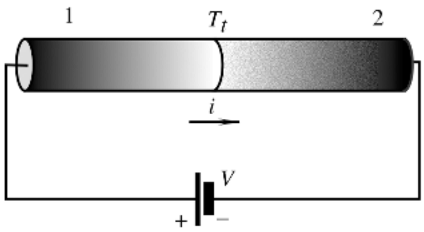

Figure 7: Peltier effect in single junction.

(5p) (f) Figure 7 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.