Version PAR/3

EGT3
ENGINEERING TRIPOS PART IIB

Monday 18 April 2016 2 to 3.30

Module 4B13

ELECTRONIC SENSORS AND INSTRUMENTATION

*Answer not more than **three** questions.*

All questions carry the same number of marks.

*The **approximate** percentage of marks allocated to each part of a question is indicated in the right margin.*

Write your candidate number __not__ your name on the cover sheet.

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed
Engineering Data Book

10 minutes reading time is allowed for this paper.

You may not start to read the questions printed on the subsequent pages of this question paper until instructed to do so.

1 An ultrasonic Doppler system to monitor the velocity of cyclists in a velodrome comprises a pair of transducers positioned to view along a straight section of track. The transducers operate at 75 kHz and have the following physical properties: 5 cm diameter, electrical impedance for transmitting 150 Ω, electrical impedance for receiving 1 kΩ, conversion efficiency 15 %, beam cone half-angle 10° and acoustic impedance 1800 Rayls.

(a) Sketch a block diagram of a system to produce an electrical signal at the Doppler frequency and determine the scale factor between the velocity and signal frequency. [25%]

(b) If the average cross-section of a cyclist is 0.5 m^2 and the transmitter transducer is driven with a signal of 48 V_{pp}, what is the open-circuit amplitude of the raw signal detected by the receiver transducer when a cyclist is at a range of:

(i) 10 m and,

(ii) 20 m ? [35%]

(c) To compensate for variations in the speed of sound in air, a temperature sensor is employed to monitor the ambient air temperature. A 2 mA constant current is supplied to an NTC thermistor. The thermistor has a resistance of 1 kΩ at a temperature of 0 °C and a β' value of 3800.

Calculate the voltage across the thermistor at an air temperature of 20 °C and the non-linearity of the signal over the range 10 °C to 30 °C. [25%]

(d) An alternative Doppler system has been proposed which uses a 24 GHz microwave radar module. How would the velocity scale factor of this module compare with that of the ultrasonic system, and which approach is likely to be most accurate ? [15%]

State all assumptions and approximations made.

Density (kg m^{-3})	Speed of Sound (m s^{-1})	Attenuation (dB m^{-1})
1.2	340	0.25

Table 1: Physical properties of air

2 (a) Explain the concept of *surface micromachining* and describe the process steps required for the fabrication of relevant MEMS devices. When is monolithic integration of MEMS with CMOS electronics desirable ? [30%]

(b) Explain the differences between operating a capacitive MEMS accelerometer in *open-loop* mode versus *force-feedback* mode. [15%]

(c) A single-axis acceleration sensor comprises a rectangular section silicon proof mass of 2 μg suspended on spring beams at each corner, providing a total spring constant along the sensing axis of 10 N m^{-1}. The proof mass carries 100 sets of inter-digitated electrodes with equal width and gaps of 1 μm and lengths of 600 μm. The out-of-plane thickness of the electrodes is 7 μm.

(i) Calculate the resonant frequency of the sensor and the open-loop deflection of the proof mass under an acceleration of 20 m s^{-2}. [20%]

(ii) If half of the capacitor electrodes are used for sensing and half are used for force-feedback, calculate the feedback voltage applied when the sensor experiences an acceleration of 20 m s^{-2}. [20%]

(iii) By how much does each force-feedback capacitor electrode bend by (i.e. tip deflection relative to proof mass) for the accelerometer conditions in (ii) above ? [15%]

State all approximations and assumptions made.

3 An infra-red pyrometer system to provide thermal images of the outside of the International Space Station contains a 100 × 100 array of micro-machined thermocouples, on a substrate with outline dimensions of 5 mm × 5 mm. The thermocouple array is positioned 10 cm behind a ZnSe lens of diameter 5 cm.

(a) What is the maximum change in total infra-red power falling on the sensor array when the system views large panels, with an emissivity of 0.5, over a temperature range of ± 100 °C ? [25%]

(b) Calculate the field of view of the thermal camera at a range of 10 m, and estimate the minimum size of surface thermal features which could be reliably imaged. [10%]

(c) The thermocouple sensor array has a total mass of 1 mg and is fabricated from thin Ni/Cr metal alloy films, separated from a large base-plate by a low density polymer foam insulation layer 20 μm thick with a thermal conductivity of 0.025 W m^{-1} K^{-1}. The metal films have a Seebeck coefficient of 50 μV $K^{-1}$and a specific heat capacity of 450 J kg^{-1} K^{-1}.

(i) What is the thermal rating for the elements, and what is the difference in raw voltage signals when viewing areas at 0 °C and 10 °C ? [20%]

(ii) What is the response bandwidth and rise-time of the thermal sensor array ? [20%]

(d) Each thermocouple pixel in the array has an electrical resistance of 1 kΩ and is connected to an operational amplifier, configured to give a gain of × 1000 by means of a 1 MΩ feedback resistance. If the operational amplifier has an input noise current density of 0.3 pA $Hz^{-1/2}$ and a noise voltage density of 1 nV $Hz^{-1/2}$, what is the minimum thermal temperature difference at around 0 °C which may be detectable at the maximum image frame rate, if the camera ambient temperature is also 0 °C ? [25%]

State all approximations and assumptions made.

4 A general purpose laboratory current probe, for measuring currents in cables fed through the central hole of a toroid arrangement, utilises a combination of 3 sensing techniques integrated into a single sensor head. This arrangement allows a single instrument to measure currents over a wide range of magnitude and frequency. The toroid comprises a 25 mm mean diameter ring of high permeability ferrite, into which a 0.25 mm slot has been cut to house a Hall effect sensor element. The cross-section of the toroid ring is 80 mm^2 and the ferrite material has a relative permeability of 7500. In addition a winding of 250 turns of wire is wound around the toroid core section, to allow the sensor to operate in induction or flux-gate modes.

(a) Describe, including a schematic block diagram, the basic operating principles of a flux-gate magnetometer. [20%]

(b) When the sensor is being used in flux-gate mode, with the same coil providing both drive and pick-up functions, derive the responsivity of the current sensor when operating with a gating drive frequency of 10 kHz. [25%]

(c) When the sensor operates as an induction coil, derive the relationship between the voltage induced across the coil terminals and the current carried in the cable under test. [15%]

(d) For larger currents, the sensor signal is derived from the Hall effect element; comprising a slice of silicon with dimensions of 0.5 mm × 0.5 mm × 0.01 mm, excited by a 5 Vdc supply. What is the amplitude of the Hall sensor output signal when the test cable carries a current of 20 A ? [20%]

(e) In order to achieve a flat frequency response over a wide bandwidth, what type of circuitry would be required to process the induction coil signal, and what cross-over frequency should be used when combining the Hall effect and induction coil signals together into a single output signal for the current probe ? [20%]

State all assumptions and approximations made.

Note: the carrier mobility in Si = 0.16 $m^2\ V^{-1}\ s^{-1}$ and the demagnetising factor for a circulating magnetic field around a toroid ring is negligible.

END OF PAPER

THIS PAGE IS BLANK

4B13 2016 – Numerical answers

1 (a) 441 Hz/ ms^{-1}
(b) 10 m: 2.5 mV or 5 mV open cct., 20 m: 0.36 mV or 0.72 mV open cct.
(c) 38 % non-linearity from gradient at 10 °C, or 4.7 % from mid-range gradient
(d) 160 Hz/ ms^{-1}

2 (c)(i) 11.25 kHz, 4 nm
(c)(ii) Csense = Cforce = 1.86 pF, Vfeedback = 0.207 V
(c)(iii) 0.26 μm

3 (a) 0.643 μW (round pixels) or 818 μW (square pixels)
(b) target area 0.5 m across - minimum features 5 mm across
(c)(i) 32 °C/W, 48 nV (or 61 nV)
(c)(ii) 11 Hz
(d) 13.4 μVrms noise, ~ 2 °C detectable

4 (b) 1.93 V/A
(c) $6.06 \times 10^{-4}\ f_I\ I$
(d) 20 A → 0.0967 T in air gap, 77.4 mV
(e) ~ 20 kHz cross-over freq.