UNIVERSITY OF KWAZULU-NATAL

Discipline of Electrical, Electronic and Computer Engineering
ENEL4IN Instrumentation

Main Examination | 10 June 2026
Duration: 120 minutes | Maximum Marks: 80

Internal Examiner: Dr SS Patel | Independent Moderator: Prof T Walingo
External Moderator: Mr B Hadebe

Instructions to Students

- This examination is **Open-Book**
  - Students may use any paper-based physical material (including notes, lecture slides, textbooks, research articles, etc.) as reference material when answering the questions.
  - No digital devices (tablets, smartphones, etc.) are permitted.
- All questions are compulsory.
  Questions may be answered in any order, however, sub-questions should be answered consecutively.
- Answers should be written using a pen with blue or black ink. The use of highlighters and other forms of stationery are permitted if necessary.
  - Answers written in pencil will not be considered with the exception of graphs, sketches or diagrams.
- The use of a non-programmable calculator is permitted.
- Students are advised to plan their time carefully.
- **State any assumptions clearly and justify why they were made.**

Including this cover page, the examination question paper has 7 pages.

Students are advised to check that they have all pages of the question paper before commencing with the examination.

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	## Question 1 [15 Marks]	
	A large industrial tank is equipped with an ultrasonic instrument to measure the fluid level, which is transmitted to a central control system. The tank is initially at steady state with a fluid level denoted as H_0. At $t = 0$, a valve opens and fluid is poured into the tank, causing the average fluid volume to increase such that the surface level rises vertically at a constant speed of $v = 0.5$ m/s. As the fluid is poured, the surface of fluid is disturbed. Ripples form on the surface of the fluid, resulting in oscillations with a natural frequency of ω_n. The level indicator instrument works by transmitting an ultrasonic wave which reflects of the surface of the fluid. The level of the fluid is determined based on the time-of-flight for the transmitted and reflected ultrasonic waveforms, denoted as $\tau_{\text{transmitted}}$ and $\tau_{\text{reflected}}$.	
1.1	Explain what is meant by each of the following terms:	
a	Dynamic characteristics (of an instrument)	(1)
b	Time constant (of a first-order system/instrument)	(2)
c	Damping factor (of a second-order system/instrument)	(2)
1.2	Sketch a simple P&ID that shows the following: • The tank • A single inlet pipe with a manual gate valve to control its flow • The level indicator instrument, which should also be equipped with a transmitter to send the measured level of the tank to the central SCADA system.	(5)
	The rippling surface of the fluid in the tank is described by the second-order response: $$h(t) = \frac{1}{\omega_n^2}\frac{d^2h}{dt^2} + \frac{0.9}{\omega_n}\frac{dh}{dt} + h \qquad \text{(Eq. 1)}$$	
1.3	Based on (Eq. 1), what is the damping factor of the system?	(1)
1.4	Interpret the damping factor from your answer to Question 1.3. What can be deduced about the damping of the system? A. The system is critically damped B. The system is underdamped C. The system is overdamped D. The system is undampened E. None of the above	(1)

1.5	Based on your answer to Question 1.4, what assumption is there about the how the ripples formed on the water surface behave over time?	(2)
1.6	The speed of sound in air is approximately 343 m/s. Based on this, explain why the time-of-flight $\tau_{\text{transmitted}} + \tau_{\text{reflected}}$ does *not* result in significant first-order instrument dynamics.	(1)
	Question 2 [15 Marks]	
	Consider the calculus rule for the propagation of uncertainty in a multivariable scenario given by: $$\delta Q = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial Q}{\partial x_i}\delta x_i\right)^2}, \qquad \text{(Eq. 2)}$$ where δQ is the total uncertainty in the measurement of variable $Q = f(x_1, x_2, \dots, x_n)$, and the arguments of function f have respective uncertainties $\delta x_1, \delta x_2, \dots, \delta x_n$.	
2.1	Explain what is meant by the sensitivity of a measurement, and hence, explain which factor/term of (Eq. 2) can be used to understand how sensitive the measurement Q is to each respective variable $x_1, x_2, \dots, x_n$.	(3)
2.2	Explain the difference between accuracy and precision.	(3)
2.3	Using your answer to Question 2.2, explain whether any factor/term of (Eq. 2) is linked to measurement accuracy.	(2)
2.4	Using your answer to Question 2.2, explain whether any factor/term of (Eq. 2) is linked to measurement precision.	(2)
2.5	Consider the following statement: *"Effective calibration techniques can compensate for instrument inaccuracies, but not imprecision, therefore precision is more important than accuracy in practice."*	
a	State whether the statement given is True or False.	(1)
b	Justify your answer to Question 2.5a. In your justification, you must mention whether single-point calibration or multi-point calibration is being referred to as "effective" in this context.	(4)

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Question 3 [20 Marks]

You are working on an electric vehicle and designing the soft-sensor that measured the expected distance the vehicle can travel based on its present state-of-charge (SoC). This is modelled by the equation:

$$d(t) = \frac{S(t) \cdot E_{\max}}{\eta(t)}, \qquad \text{(Eq. 3)}$$

where $d(t)$ is the estimated distance at time t, $S(t)$ is the instantaneous SoC percentage between 0 (completely depleted) and 1 (fully charged), $E_{\max} = 80$ kWh is the maximum energy capacity of the electric vehicle's battery and $\eta(t)$ is a time-varying parameter that represents the instantaneous driving efficiency.

The driving efficiency is modelled as:

$$\eta(t) = 150 + 10[a(t) + g\sin\theta(t)], \qquad \text{(Eq. 4)}$$

where $g = 10$ m/s^2 is the acceleration due to gravity, $\theta(t)$ is the instantaneous inclination of road measured by a gyroscope on the vehicle and $a(t)$ is the instantaneous acceleration of the vehicle.
The equation for $a(t)$ is given by:

$$a(t) = \frac{\Delta\omega(t)}{\Delta t} r, \qquad \text{(Eq. 5)}$$

where $\omega(t)$ is the angular speed of the wheel rotation at time t and r is the radius of the wheels. Assume that Δt is constant sampling period for the system, set based on the polling frequency of the microcontroller that is implementing the soft sensor.

3.1 Given the following information, determine an expression for the absolute uncertainty in the instantaneous driving efficiency, $\delta_{\eta(t)}$: **(10)**

- The wheel radius is specified as 30 cm ± 1 mm by the manufacturer.
- A hall-effect sensor on the vehicle is able to measure the angular speed with an absolute accuracy of ± 0.2 rad/s.
- The gyroscope that measure the inclination of the road has a range of $|\theta| < 45° \pm 1\%$ f.s.d.

Hint: $\Delta\omega(t) = \omega(t) - \omega(t-1)$

Leave your answer in surd form.

3.2	Hence, if the battery management system measures the SoC with a relative uncertainty of 3%, what is the total absolute uncertainty of the distance estimate? Give your answer in terms of variables $\eta(t)$ and $\delta_{\eta(t)}$.	(5)
3.3	Practically, the battery of the electric vehichle should never be allowed to be fully depleted. The estimation of the remaining distance calculation is updated to reflect this, resulting in (Eq. 6), where $S_{\min}$ is the minimum state of charge that the battery should maintain. Without recalculating from scratch, explain how the change from (Eq. 3) to (Eq. 6) affects your answer to Question 3.2. $$d(t) = \frac{(S(t) - S_{\min})\, E_{\max}}{\eta(t)} \qquad \text{(Eq. 6)}$$	(3)
3.4	Suggest why it is safer for the vehicle to display a low battery warning when $S(t)$ is close to $S_{\min}$ rather than displaying the estimate of $d(t)$. Hint: consider the relative uncertainty in the distance estimation.	(2)
	## Question 4 [15 Marks]	
	Given a certain zeroth-order pressure sensor that outputs a signal described by $s(t) = 10\text{mA} + 25\text{mA}/100\text{kPa}$, you are required to design a pressure measurement instrument. The typical use-case for the instrument will be to measure motor vehicle tyre pressure.	
4.1	Explain why it is important to have a finite range for your design and, by making a realistic assumption, what range of pressures would you expect the instrument to typically measure? Note: atmospheric pressure at sea level is approximately 101.8 kPa.	(2)
4.2	You wish to use a simple current sensing resistor to convert the current signal to a voltage signal. Describe two desirable characteristics that should be specified when selecting the current sensing resistor.	(2)
4.3	Give two reasons why it is better to use a monolithic instrumentation amplifier integrated circuit in this design, compared to using a monolitic operational amplifier integrated circuit.	(2)
4.4	Explain why null-type instrument designs are typically superior to deflection-type instrument designs.	(2)

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4.5 Design and sketch a circuit that does the following: **(7)**

1. Convert the current signal to a voltage signal in the range 1V to 4V using a current sensing resistor and a monolithic instrumentation amplifier integrated circuit. Use your range estimation from Question 4.1.
2. Uses a microcontroller with a built-in digital-to-analogue converter (DAC) and a discrete comparator IC to implement a null-type instrument design.

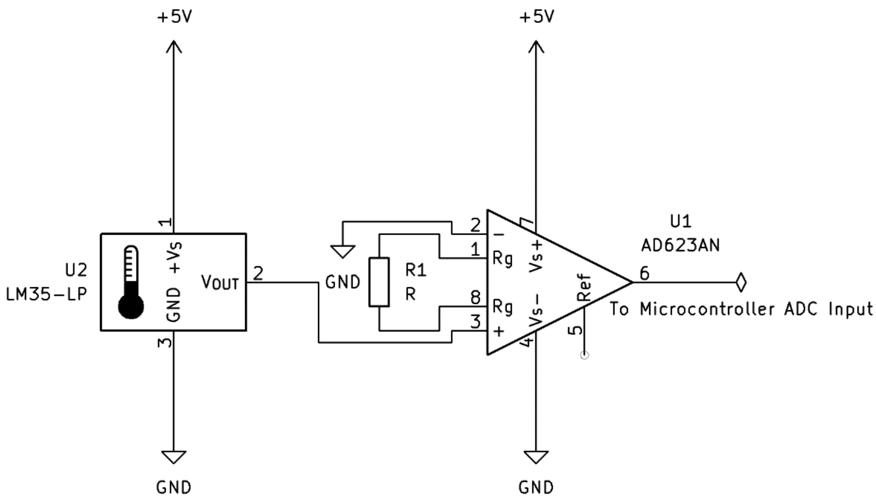
Assume a single-rail, 5V supply and that the the gain of the instrumentation amplifier is given by:

$$\frac{v_o - v_{\mathrm{ref}}}{v_+ - v_-} = A_v = 1 + \frac{50\ \mathrm{k\Omega}}{R_g} \qquad \text{(Eq. 6)}$$

Explain how your design works, showing how the design achieves null-type behaviour. The behaviour of the microcontroller only has to be explained at a basic level.
If any further assumptions are made, state them clearly.

Question 5 [15 Marks]

Consider the schematic diagram below, which shows a temperature measurement instrument that sends an amplified ground-referenced voltage from an LM35 to a microcontroller. Use the diagram to inform your answers to the questions that follow:



The following two-layer PCB was designed based on the schematic given. A four-pin header connector is connected to the 5V power rail, ground, and pins 5 and 6 of the in-amp so that these can be easily connected to the microcontroller.

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	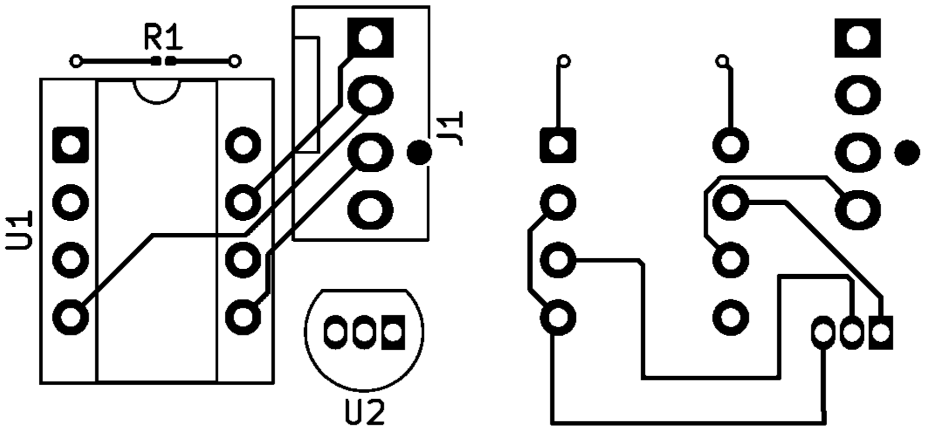 Top View Bottom View	
5.1	Analyse the Bottom View of the PCB and comment on why reflection noise can be predicted in this design.	(2)
5.2	Analyse the Bottom View of the PCB and comment on why ground bounce noise can be predicted in this design.	(2)
5.3	What test setup would you use to test for radiated emissions from this PCB? Justify your selection.	(3)
5.4	Explain, in general, why signal integrity problems need to be considered in modern designs, even for microcontrollers running at fairly low clock frequencies (~4 MHz).	(3)
5.5	Explain why infra-red thermometers do not exhibit the first-order instrument dynamics typical of temperature measurement instruments, but the LM35 does.	(5)