Exam in Sensor system, 7.5 credits.
Course code: et2009
Date: 2011-08-26

Allowed items on the exam:
Tables of Mathematical formulas.
Calculator.

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Maximum points: 28.
In order to pass the examination with a grade 3 a minimum of 12 points is required.
To get a grade 4 a minimum of 17 points is required, and to get a grade 5 a minimum of 23 points is required.

Give your answer in a readable way and motivate your assumptions.

Good Luck!

Questions of 2 points.

1.
A non-linear temperature sensor has an input range of 0 to 400 ˚C and an output range of 0 to 20 mV. The output signal at 100 ˚C is 4.5 mV. Find the non-linearity in millivolts and as a percentage of span.

2.
A force sensor has an input range of 0 to 10 kN and an output range of 0 to 5 V at a standard temperature of 20 ˚C. At 30 ˚C the output range is 0 to 5.5 V.
Quantify the environmental effect, i.e. find K_M and K_I.

3.
A level measurement system consists of three ideal linear elements in series with sensitivities of K_1=0.050, K_2=21.5 and K_3=0.99. Find the system error for a true value input of 5.0 metres.

4.
A potentiometer has a total length of 10 cm and a resistance of 100 Ω.
a) Calculate the supply voltage so that the power dissipation = 1 W.
b) Draw the Thevenin equivalent circuit for 7 cm displacement.
c) The potentiometer is connected to a recorder with a resistance R_L. Find R_L such that the recorder voltage is 5% less than the open circuit voltage at 7 cm displacement.

5.
A force sensor has a steady state sensitivity of 10^{-6} mN^{-1}.
If the force input has a range of 0 to 5 kN, find the corresponding displacement output range.

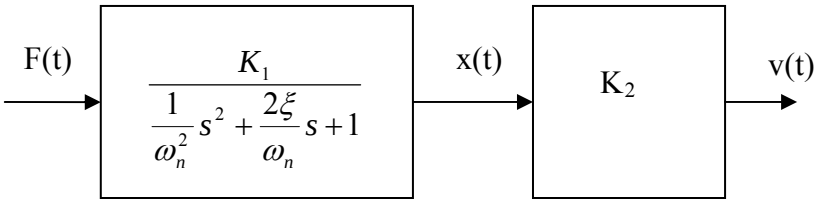
6.
The voltage of a type T thermocouple is measured to be 8.561 mV relative to a reference junction temperature of 20 ˚C. Use the table (reference junction at 0˚C, included in this exam) to find the temperature of the measured junction.

7.
A variable reluctance tachogenerator consists of a ferromagnetic wheel with 20 teeth rotating close to a bar magnet and coil. If the wheel is rotating at 6000 rpm, what is the frequency of the a.c. voltage induced in the coil?

8.
An AD-converter has an input range of [0, 5] V and incorporates a 10-bit binary encoder.
Find the maximum quantisation error.

Questions of 4 points.

9.
A load cell consists of an elastic cantilever and a displacement sensor.



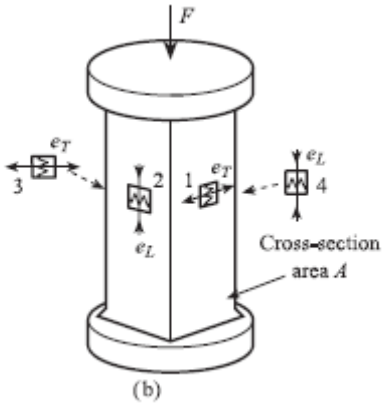
Cantilever data:
stiffness k=100 N/m
mass m=0.5 kg
damping constant λ=2 Ns/m
steady state sensitivity K_1=1/k
natural frequency $\omega_n = \sqrt{\frac{k}{m}}$ rad/s
damping ratio $\xi = \frac{\lambda}{2\sqrt{km}}$

Sensor data:
steady state sensitivity K_2=10 V/m

a) A package of mass 0.5 kg is suddenly dropped onto the load cell.
Calculate the steady state output v(t) (g=9.81 m/s^2). (2p)

b) The load cell is used to weigh packages moving along a conveyor belt at the rate of 120 per minute.
Use the unit step response equation:
$v(t) = K_1K_2\left(1-e^{-\xi\omega_n t}\left(\cos(\omega_d t)+b\sin(\omega_d t)\right)\right)$ where $\omega_d = \omega_n\sqrt{1-\xi^2}$ and $b = \frac{\xi}{\sqrt{1-\xi^2}}$
to explain if the load cell is suitable or not for this application. (2p)

10.
A load cell consists of a domed vertical steel cylinder 20 cm high and 15 cm in diameter. Four flat surfaces, at right angles to each other, are cut on the vertical surface so as to form 10 cm squares. Resistance strain gauges are attached to these flat surfaces so that two gauges (on opposite faces) suffer longitudinal compression and two gauges (on the other pair of opposite faces) suffer transverse tension.



The strain gauges have the following specification:
Resistance = 100 Ω
Gauge factor = 2.1
Maximum gauge current = 30 mA

Young's modulus for steel: $E = 2.1 \times 10^{11}\ \mathrm{Nm}^{-2}$
Poisson's ratio for steel: $\upsilon = 0.29$

Some useful formulas:

$$e = \frac{\nabla l}{l}$$

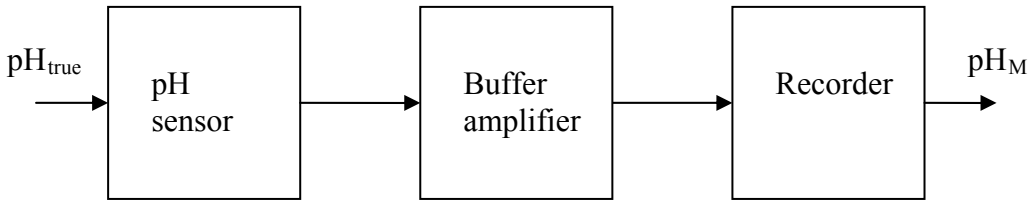
$$e_L = \frac{F}{A \cdot E}$$

$$e_T = -\upsilon \cdot e_L$$

a) Draw the circuit of the gauges connected in a Wheatstone bridge for optimum accuracy and sensitivity. Clearly label the gauges in the circuit and motivate their connection according to accuracy and sensitivity. (2p)

b) Calculate the maximum available bridge out-of-balance voltage for a compressive force of $F=10^5$ N. (2p)

11.
A glass pH electrode with a sensitivity of 59 mV/pH and a resistance of 10^9 Ω is used to measure pH in the range of 0 to 15. The electrode is to be connected to a recorder of input range 0 to 100 mV and resistance 100 Ω using a buffer amplifier of unity gain and output resistance 100 Ω.



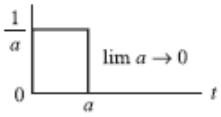
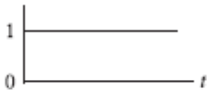
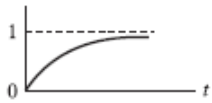
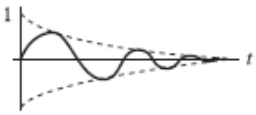
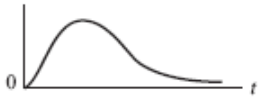
a) Draw the equivalent circuit of the pH measurement system. (1p)

b) Calculate the sensitivity of the recorder scale, and the input impedance of the amplifier necessary to obtain an accurate reading of pH. (2p)

c) The resistance of the electrode increases to 2×10^9 Ω due to chemical action. Calculate the resulting measurement error in the above system, as a percentage of full scale, for a true pH of 7. (1p)

Table 4.1 Laplace transforms of common time functions $f(t)$.[a]

$$\mathcal{L}[f(t)] = \bar{f}(s) = \int_0^\infty e^{-st} f(t)\,dt$$

Function	Symbol	Graph	Transform
1st derivative	$\frac{d}{dt}f(t)$		$s\bar{f}(s) - f(0-)$
2nd derivative	$\frac{d^2}{dt^2}f(t)$		$s^2\bar{f}(s) - sf(0-) - \dot{f}(0-)$
Unit impulse	$\delta(t)$		1
Unit step	$\mu(t)$		$\frac{1}{s}$
Exponential decay	$\exp(-\alpha t)$		$\frac{1}{s+\alpha}$
Exponential growth	$1 - \exp(-\alpha t)$		$\frac{\alpha}{s(s+\alpha)}$
Sine wave	$\sin \omega t$		$\frac{\omega}{s^2+\omega^2}$
Phase-shifted sine wave	$\sin(\omega t + \phi)$		$\frac{\omega\cos\phi + s\sin\phi}{s^2+\omega^2}$
Exponentially damped sine wave	$\exp(-\alpha t)\sin \omega t$		$\frac{\omega}{(s+\alpha)^2+\omega^2}$
Ramp with exponential decay	$t\exp(-\alpha t)$		$\frac{1}{(s+\alpha)^2}$

[a] Initial conditions are at $t = 0-$, just prior to $t = 0$.

Table Prob. 22 e.m.f. in mV for type T thermocouple (measured junction at T °C, reference junction at 0 °C).

Temp. °C	0	1	2	3	4	5	6	7	8	9	10
0	0.000	0.039	0.078	0.117	0.156	0.195	0.234	0.273	0.312	0.351	0.391
10	0.391	0.430	0.470	0.510	0.549	0.589	0.629	0.669	0.709	0.749	0.789
20	0.789	0.830	0.870	0.911	0.951	0.992	1.032	1.073	1.114	1.155	1.196
30	1.196	1.237	1.279	1.320	1.361	1.403	1.444	1.486	1.528	1.569	1.611
40	1.611	1.653	1.695	1.738	1.780	1.822	1.865	1.907	1.950	1.992	2.035
50	2.035	2.078	2.121	2.164	2.207	2.250	2.294	2.337	2.380	2.424	2.467
60	2.467	2.511	2.555	2.599	2.643	2.687	2.731	2.775	2.819	2.864	2.908
70	2.908	2.953	2.997	3.042	3.087	3.131	3.176	3.221	3.266	3.312	3.357
80	3.357	3.402	3.447	3.493	3.538	3.584	3.630	3.676	3.721	3.767	3.813
90	3.813	3.859	3.906	3.952	3.998	4.044	4.091	4.137	4.184	4.231	4.277
100	4.277	4.324	4.371	4.418	4.465	4.512	4.559	4.607	4.654	4.701	4.749
110	4.749	4.796	4.844	4.891	4.939	4.987	5.035	5.083	5.131	5.179	5.227
120	5.227	5.275	5.324	5.372	5.420	5.469	5.517	5.566	5.615	5.663	5.712
130	5.712	5.761	5.810	5.859	5.908	5.957	6.007	6.056	6.105	6.155	6.204
140	6.204	6.254	6.303	6.353	6.403	6.452	6.502	6.552	6.602	6.652	6.702
150	6.702	6.753	6.803	6.853	6.903	6.954	7.004	7.055	7.106	7.156	7.207
160	7.207	7.258	7.309	7.360	7.411	7.462	7.513	7.564	7.615	7.666	7.718
170	7.718	7.769	7.821	7.872	7.924	7.975	8.027	8.079	8.131	8.183	8.235
180	8.235	8.287	8.339	8.391	8.443	8.495	8.548	8.600	8.652	8.705	8.757
190	8.757	8.810	8.863	8.915	8.968	9.021	9.074	9.127	9.180	9.233	9.286
200	9.286	9.339	9.392	9.446	9.499	9.553	9.606	9.659	9.713	9.767	9.820
210	9.820	9.874	9.928	9.982	10.036	10.090	10.144	10.198	10.252	10.306	10.360
220	10.360	10.414	10.469	10.523	10.578	10.632	10.687	10.741	10.796	10.851	10.905
230	10.905	10.960	11.015	11.070	11.125	11.180	11.235	11.290	11.345	11.401	11.456
240	11.456	11.511	11.566	11.622	11.677	11.733	11.788	11.844	11.900	11.956	12.011
250	12.011	12.067	12.123	12.179	12.235	12.291	12.347	12.403	12.459	12.515	12.572
260	12.572	12.628	12.684	12.741	12.797	12.854	12.910	12.967	13.024	13.080	13.137
270	13.137	13.194	13.251	13.307	13.364	13.421	13.478	13.535	13.592	13.650	13.707
280	13.707	13.764	13.821	13.879	13.936	13.993	14.051	14.108	14.166	14.223	14.281
290	14.281	14.339	14.396	14.454	14.512	14.570	14.628	14.686	14.744	14.802	14.860
300	14.860	14.918	14.976	15.034	15.092	15.151	15.209	15.267	15.326	15.384	15.443
310	15.443	15.501	15.560	15.619	15.677	15.736	15.795	15.853	15.912	15.971	16.030
320	16.030	16.089	16.148	16.207	16.266	16.325	16.384	16.444	16.503	16.562	16.621
330	16.621	16.681	16.740	16.800	16.859	16.919	16.978	17.038	17.097	17.157	17.217
340	17.217	17.277	17.336	17.396	17.456	17.516	17.576	17.636	17.696	17.756	17.816