Question 1

Since the controller uses quadrature counter we need to multiply the given pulses per revolution by 4.

$$\therefore \textit{encoder's position resolution} = \frac{2\pi/\text{rev}}{(300 \text{ pulses/rev})(4)} = 5.236\times10^{-3} \text{ rad}$$

The maximum acceleration will occur when operating at the maximum torque and the minimum inertia.

$$\therefore \max\left(|a_{true}|\right) = \frac{\text{max. torque}}{\text{min. inertia}} = \frac{2 \text{ Nm}}{2\times10^{-3} \text{ kgm}^2} = \frac{2 \text{ (kgm/s}^2\text{)(m)}}{2\times10^{-3} \text{ kgm}^2} = 1000 \text{ rad/s}^2$$

We can now use (2.39) to obtain the worst case velocity estimation error as follows:

$$\begin{aligned}\Delta v_{est} &= \frac{T}{2}\max\left(|a_{true}|\right) + \frac{\text{encoder's position resolution}}{T} \\ &= \frac{(0.005 \text{ s})(1000 \text{ rad/s}^2)}{2} + \frac{5.236\times10^{-3} \text{ rad}}{0.005 \text{ s}} \\ &= 3.55 \text{ rad/s}\end{aligned}$$

Question 2

2. a) The accuracy, in the units of the measured quantity, is:

$$a_{sensor} = \pm(0.25\%)(\text{full scale}) = \pm(0.25\%)\left(400 \text{ N} - (-400 \text{ N})\right) = \pm 2 \text{ N}$$

b) The accuracy should encompass the largest error.

The largest error will occur at the maximum input magnitude.

The maximum input force magnitude = 400 N. The corresponding unloaded sensor output is:

$$\begin{aligned}V_s &= \left(20\frac{\text{mV}}{\text{N}}\right)\left(400 \text{ N}\right) \\ &= 8000 \text{ mV}\end{aligned}$$

The loaded sensor output is:

$$\begin{aligned}V_{loaded} &= V_s\left(\frac{R_{ADC,in}}{R_{ADC,in} + R_s}\right) \\ &= 8000 \text{ mV}\left(\frac{100 \text{ k}\Omega}{100 \text{ k}\Omega + 1 \text{ k}\Omega}\right) \\ &= 7920.8 \text{ mV}\end{aligned}$$

The voltage error due to loading is:

$$\begin{aligned}\Delta V_s &= V_s - V_{ADC,\,in}\\ &= 8000\text{ mV} - 7920.8\text{ mV}\\ &= 79.2\text{ mV}\end{aligned}$$

The worst case force error is:

$$\begin{aligned}\Delta F_{out} &= \left|F_{out}^{*}\right|\left(\left|\frac{\Delta K_{sensor}}{K_{sensor}}\right| + \left|\frac{\Delta K_{loading}}{K_{loading}}\right|\right)\\ &= \left|F_{in}\right|\left(\left|\frac{a_{sensor}}{F_{in}}\right| + \left|\frac{\Delta V_s}{V_s}\right|\right)\\ &= \left|400\text{ N}\right|\left(\left|\frac{\pm 2\text{ N}}{400\text{ N}}\right| + \left|\frac{\pm 79.2\text{ mV}}{8000\text{ mV}}\right|\right)\\ &= 2\text{ N} + 3.95\text{ N}\\ &= 5.95\text{ N}\end{aligned}$$

$\therefore$ The measurement system accuracy = ±6.0 N

c) The analog to digital converter accuracy

$$a_{ADC} = \pm\frac{V_{FS}}{2^{ENOB}} = \pm\frac{(10\text{ V} - (-10\text{ V}))}{2^{11.2}} = \pm 0.0085\text{ V}$$

As in (b), F_{in} = 400 N, V_s = 8000 mV and ΔV_s = 79.2 mV. .

The worst case force error is then:

$$\begin{aligned}\Delta F_{out} &= \left|F_{out}^{*}\right|\left(\left|\frac{\Delta K_{sensor}}{K_{sensor}}\right| + \left|\frac{\Delta K_{loading}}{K_{loading}}\right| + \left|\frac{\Delta K_{ADC}}{K_{ADC}}\right|\right)\\ &= \left|F_{in}\right|\left(\left|\frac{a_{sensor}}{F_{in}}\right| + \left|\frac{\Delta V_s}{V_s}\right| + \left|\frac{a_{ADC}}{V_{in}}\right|\right)\\ &= \left|400\text{ N}\right|\left(\left|\frac{\pm 2\text{ N}}{400\text{ N}}\right| + \left|\frac{79.2\text{ mV}}{8000\text{ mV}}\right| + \left|\frac{\pm 0.0085\text{ V}}{8\text{ V}}\right|\right)\\ &= 2\text{ N} + 3.95\text{ N} + 0.43\text{ N}\\ &= 6.4\text{ N}\end{aligned}$$

$\therefore$ The measurement system accuracy = ±6.4 N

d) Now we have F_{in} = 100 N. The corresponding unloaded sensor output is:

$$V_s = \left(20\frac{\text{mV}}{\text{N}}\right)(100\text{ N})$$
$$= 2000\text{ mV}$$

The loaded sensor output is:

$$V_{loaded} = V_s\left(\frac{R_{ADC,\,in}}{R_{ADC,\,in} + R_s}\right)$$
$$= 2000\,\text{mV}\left(\frac{100\text{ k}\Omega}{100\text{ k}\Omega + 1\text{ k}\Omega}\right)$$
$$= 1980.2\text{ mV}$$

The voltage error due to loading is:

$$\Delta V_s = V_s - V_{ADC,\,in}$$
$$= 2000\text{ mV} - 1980.2\text{ mV}$$
$$= 19.8\text{ mV}$$

The worst case force error is then:

$$\Delta F_{out} = \left|F_{out}^*\right|\left(\left|\frac{\Delta K_{sensor}}{K_{sensor}}\right| + \left|\frac{\Delta K_{loading}}{K_{loading}}\right| + \left|\frac{\Delta K_{ADC}}{K_{ADC}}\right|\right)$$
$$= \left|F_{in}\right|\left(\left|\frac{a_{sensor}}{F_{in}}\right| + \left|\frac{\Delta V_s}{V_s}\right| + \left|\frac{a_{ADC}}{V_{in}}\right|\right)$$
$$= \left|100\text{ N}\right|\left(\left|\frac{\pm 2\text{ N}}{100\text{ N}}\right| + \left|\frac{19.8\text{ mV}}{2000\text{ mV}}\right| + \left|\frac{\pm 0.0085\text{ V}}{2\text{ V}}\right|\right)$$
$$= 2\text{ N} + 0.99\text{ N} + 0.43\text{ N}$$
$$= 3.4\text{ N}$$

The ratio of the worst case errors from (d) and (c) is: $\frac{3.4\text{ N}}{6.4\text{ N}} = \frac{1}{1.9} > \frac{1}{4}$. So the error is (d) is larger than ¼ of the error in (c). In other words, the worse case error is not proportional to the input. The reason is not all of the sources of error have fixed percentages. A closer look at the two ΔF_{out} calculations reveals that the % error due to loading is constant (i.e. 79.2/8000 = 19.8/2000), but the sensor's and ADC's % errors increase when the input decreases (e.g. 2/100 > 2/400). This is a common situation that shows the importance of carefully analyzing sources of error and how they propagate.

Question 3

3. a) The dominant time constant is:

$$\begin{aligned}\tau_s &= 0.455 t_r \\ &= 0.455(1.5\,\text{ms}) \\ &= 0.6825 \text{ ms}\end{aligned}$$

The waiting time should satisfy:

$$t \geq -\tau_s \ln\left(\frac{0.1|a_y|}{\max\left(y_{max} - y_{sensed}(0), y_{sensed}(0) - y_{min}\right)}\right)$$

$$t \geq (-0.6825\,\text{ms})\ln\left(\frac{0.1|500\,\text{Pa}|}{\max\left(500 \text{ kPa} - 350 \text{ kPa},\ 350 \text{ kPa} - 100 \text{ kPa}\right)}\right)$$

$$t \geq (-0.6825\,\text{ms})\ln\left(\frac{0.1|500\,\text{Pa}|}{250\text{kPa}}\right)$$

$$t \geq 5.8\,\text{ms}$$

b) When t = 3 ms, the worst case measurement error is

$$\begin{aligned}\Delta y_{out}(t) &= |a_y| + \max\left(y_{max} - y_{sensed}(0), y_{sensed}(0) - y_{min}\right) e^{-\frac{t}{\tau_s}} \\ &= |\pm 500 \text{ Pa}| + \max\left(500 \text{ kPa} - 350 \text{ kPa, } 350 \text{ kPa} - 100 \text{ kPa}\right) e^{-\frac{3\text{ ms}}{0.6825\,\text{ms}}} \\ &= |\pm 500 \text{ Pa}| + (250 \text{ kPa})(1000 \text{ Pa/kPa}) e^{-\frac{3\text{ ms}}{0.6825\,\text{ms}}} \\ &= 3580 \text{ Pa or } 3.58 \text{ kPa}\end{aligned}$$

c) First, convert input frequency to rad/s as follows:

$$\omega = 2\pi f = 2\pi(100 Hz) = 628 \text{ rad/s}$$

The worst case error is then:

$$\Delta A_{sensed}(\omega) = |a_y| + \left(\sqrt{1+\omega^2\tau_s^2} - 1\right) A_{sensed}(\omega)$$

$$= |500 \text{ Pa}| + \left(\sqrt{1+\left(628 \text{ rad/s}\right)^2\left((0.6825\,\text{ms})\left(\frac{1 \text{ s}}{1000\,\text{ms}}\right)\right)^2} - 1\right)(5000 \text{ Pa})$$

=940 Pa or 0.940 kPa

Question 4

(a) From equation (2.15) in the notes

$$V_s = V_{in} + \frac{V_{in}}{R_{in}} R_s$$

Substiting in the data from two measurements gives

$$V_s = 5.0V + \frac{5.0V}{10000\Omega} R_s \tag{1}$$

$$V_s = 4.95V + \frac{4.95V}{5000\Omega} R_s \tag{2}$$

Equating (1) and (2), and simplifying gives

$$5.0V + \frac{5.0V}{10000\Omega} R_s = 4.95V + \frac{4.95V}{5000\Omega} R_s$$

$$\left(5.0V - 2(4.95V)\right) R_s = 10000\Omega(4.95V - 5.0V)$$

$$R_s = 102.04\,\Omega$$

This is the internal resistance of the sensor.

(b) <u>First method:</u>

Assuming V_{in}=5.0 V, substituting R_s back into (1) we obtain

$$V_s = 5.0V + \frac{5.0V}{10000\Omega}(102.04\Omega) = 5.05\text{ V} \qquad \text{(can also use equation (2) here)}$$

When $R_{in} = 20000\Omega$, using (2.16) we obtain,

$$V_{in} = V_s\left(\frac{R_{in}}{R_{in}+R_s}\right) = 5.05\text{ V}\times\frac{20000\Omega}{20000\Omega + 102.04\Omega} = 5.02\text{ V}$$

With no loading effect V_{in}=V_s, so the percentage error with the given load is

$$error = \frac{V_s - V_{in}}{V_s} = \frac{5.05\text{ V} - 5.02\text{ V}}{5.05\text{ V}}\times 100\% = 0.51\%$$

<u>Second method (easier):</u>

$$error = \left(1 - \frac{R_{in}}{R_{in}+R_s}\right)\times 100\%$$

$$= \left(1 - \frac{20000\Omega}{20000\Omega + 102.04\Omega}\right)\times 100\% = 0.51\%$$

Question 5

5. From equation 2.37: $\Delta v_{est} = \dfrac{T}{2}\max\left(\left|a_{true}\right|\right) + \dfrac{2\Delta p}{T}$

$$\therefore \frac{\partial \Delta v_{est}}{\partial T}(T) = \frac{\max\left(\left|a_{true}\right|\right)}{2} - \frac{2\Delta p}{T^2} \text{ and}$$

$$\frac{\partial^2 \Delta v_{est}}{\partial T^2}(T) = \frac{4\Delta p}{T^3}$$

First we'll show that $\frac{\partial \Delta v_{est}}{\partial T}(T_{opt}) = 0$:

Set $T = T_{opt}$ and simplify:

$$
\begin{aligned}
\frac{\partial \Delta v_{est}}{\partial T}(T_{opt}) &= \frac{\max\left(|a_{true}|\right)}{2} - \frac{2\Delta p}{T_{opt}^{\ 2}} \\
&= \frac{\max\left(|a_{true}|\right)}{2} - \frac{2\Delta p}{\left(\sqrt{\frac{4\Delta p}{\max\left(|a_{true}|\right)}}\right)^2} \\
&= \frac{\max\left(|a_{true}|\right)}{2} - \frac{2\Delta p}{\frac{4\Delta p}{\max\left(|a_{true}|\right)}} \\
&= \frac{\max\left(|a_{true}|\right)}{2} - 2\Delta p \times \frac{\max\left(|a_{true}|\right)}{4\Delta p} \\
&= \frac{\max\left(|a_{true}|\right)}{2} - \frac{\max\left(|a_{true}|\right)}{2} \\
&= 0
\end{aligned}
$$

Next, we'll show that $\frac{\partial^2 \Delta v_{est}}{\partial T^2}(T_{opt}) > 0$:

$$
\begin{aligned}
\frac{\partial^2 \Delta v_{est}}{\partial T^2}(T_{opt}) &= \frac{4\Delta p}{T^3} \\
&= \frac{4\Delta p}{\left(\sqrt{\frac{4\Delta p}{\max\left(|a_{true}|\right)}}\right)^3} \\
&= \frac{\left(\sqrt{\max\left(|a_{true}|\right)}\right)^3}{2\sqrt{\Delta p}}
\end{aligned}
$$

Since $|a_{true}|$ and Δp are positive values

$$\frac{\partial^2 \Delta v_{est}}{\partial T^2}(T_{opt}) = \frac{\left(\sqrt{\max(+ve)}\right)^3}{2\sqrt{+ve}} = \frac{+ve}{+ve} > 0$$

Since $\frac{\partial \Delta v_{est}}{\partial T}(T_{opt}) = 0$ and $\frac{\partial^2 \Delta v_{est}}{\partial T^2}(T_{opt}) > 0$, T_{opt} minimizes Δv_{est}.

Question 6

6. a) Linear regression with the sensor output as the dependent variable (Y) gives:

$$A = \frac{\sum xy}{\sum x^2} = \frac{3363\ \text{V}\cdot\text{kPa}}{53750\ \text{kPa}^2} = 0.0626\ \text{V/kPa}$$

b) Example calculation:

Pressure output in kPa for test #3 = (sensor output in V) / A
= (0.9 V) / (0.0626 V/kPa)
= 14.38 kPa

Test #	Pressure Input (kPa)	Mean Output (V)	Pressure Output (kPa)	Error Magnitude (kPa)
1	0	0	0	0
2	12.5	0.3	4.79	7.71
3	25	0.9	14.38	10.62
4	37.5	1.62	25.89	11.61
5	50	2.52	40.28	9.72
6	62.5	3.72	59.46	3.04
7	75	4.8	76.72	1.72
8	87.5	5.4	86.31	1.19
9	100	6	95.90	4.10
10	87.5	5.7	91.10	3.60
11	75	5.28	84.39	9.39
12	62.5	4.5	71.92	9.42
13	50	3.6	57.54	7.54
14	37.5	2.4	38.36	0.86
15	25	1.32	21.10	3.90
16	12.5	0.48	7.67	4.83
17	0	0	0	0

c) i) Accuracy = $\pm(\text{abs}(\max(P_{sensor} - P_{true}) + 3\sigma_{pressure})$
= ±(11.61 kPa + 3(0.746 kPa))
= ± 14.0 kPa

where $\sigma_{pressure} = \sigma_{volts}/A$ = 0.05 V / 0.0626 V/kPa = 0.746 kPa

ii) Sensitivity = ratio of sensor output / measured quantity

$= A =$ 0.0626 V/kPa

iii) Hysteresis = largest deviation between the load increasing and load decreasing sensor readings = (40.28 kPa - 57.54 kPa) = 17.3 kPa

iv) Linearity (or Non-linearity) $= \pm(\text{abs}(\max(P_{sensor} - P_{true})$
$= \pm(\text{abs}(\max(25.89\text{ kPa} - 37.5\text{ kPa})$
$= \pm 11.6$ kPa

v) Repeatability = $\pm 3\sigma_{pressure} = \pm 3\sigma_{volts}/A = \pm 3(0.05\text{V})/0.0626$ V/kPa = ±2.4 kPa

vi) Deadband = largest load for which output voltage is zero
= 0 kPa

d)

$$A = \frac{n\sum xy - \left(\sum x\right)\left(\sum y\right)}{n\sum x^2 - \left(\sum x\right)^2} = \frac{(17)(3363\text{ kPaV}) - (800\text{ kPa})(48.54\text{ V})}{(17)(53750\text{ kPa}^2) - (800\text{ kPa})^2} = 0.0670\text{ V/kPa and}$$

$$B = \frac{\sum y - A\sum x}{n} = \frac{48.54\text{ V} - (0.0670\text{ V/kPa})(800\text{ kPa})}{17} = -0.2973\text{ V}$$

Example calculation:

Pressure output in kPa for test #3 = (sensor output in V – B) / A
= (0.9 V – (-0.2973 V)) / 0.0670 V/kPa
= 17.87 kPa

Test #	Pressure Input (kPa)	Mean Output (V)	Pressure Output (kPa)	Error Magnitude (kPa)
1	0	0	4.44	4.44
2	12.5	0.3	8.92	3.58
3	25	0.9	17.87	7.13
4	37.5	1.62	28.62	8.88
5	50	2.52	42.05	7.95
6	62.5	3.72	59.97	2.53
7	75	4.8	76.09	1.09
8	87.5	5.4	85.04	2.46
9	100	6	94.00	6.00
10	87.5	5.7	89.52	2.02
11	75	5.28	83.25	8.25
12	62.5	4.5	71.61	9.11
13	50	3.6	58.18	8.18

14	37.5	2.4	40.26	2.76
15	25	1.32	24.14	0.86
16	12.5	0.48	11.60	0.90
17	0	0	4.44	4.44

i) Accuracy = $\pm(\text{abs}(\max(P_{sensor} - P_{true}) + 3\sigma_{pressure})$
= $\pm(\text{abs}(71.61 \text{ kPa} - 62.5 \text{ kPa}) + 3(0.746 \text{ kPa}))$
= ± 11.3 kPa

where $\sigma_{pressure} = \sigma_{volts}/A = 0.05 \text{ V} / 0.0670 \text{ V/kPa} = 0.746$ kPa

ii) Sensitivity = A = 0.0670 V/kPa

iii) Hysteresis = (Test #13 – Test #5) = (58.18 kPa - 42.05 kPa) = 16.1 kPa

iv) Linearity = $\pm(\text{abs}(\max(P_{sensor} - P_{true}) = \pm(\text{abs}(71.61 \text{ kPa} - 62.5 \text{ kPa})) = \pm 9.1$ kPa

v) Repeatability = $\pm 3\sigma_{pressure} = \pm 3\sigma_{volts}/A = \pm 3(0.05 \text{ V}/(0.0670 \text{ V/kPa})) = \pm 2.2$ kPa

vi) Same as in part c).

e) Advantages: Better accuracy, and better linearity. Here “better” means a value with a smaller magnitude.

Disadvantage: Requires more complex hardware (or software) to account for the B parameter.

Question 7

The conservative estimates for the time specifications should always be greater than or equal to the true values. If we do this, the sensor should never respond slower than our specifications indicate.

7 (a) The time constant is the time required for the response to reach 63.2% of its final value for a step change in the input.

63.2% of final value = (20 ^{o}C)(0.632) =12.64^{o}C

From the data, at 7.5 ms the output is 12.17 ^{o}C. At 8.0 ms it is 12.65^{o}C.
Therefore the conservative estimate of the time constant = 8.0 ms

7 (b) Rise time is the time required for the output to increase from 10% to 90% of its final value.

The corresponding temperatures are T_1=2^{o}C and T_2=18^{o}C.
The conservative estimate of the rise time is: 18.5 ms – 0.5 ms = 18 ms

7 (c) Settling time is the time required for the output to settle within ±1% of its final value for a step input.

With this data, since the output does not overshoot its final value, the settling time is the time when it reaches 99% of 20^{o}C = 19.8^{o}C. This happens at 37 ms, so the estimated settling time = 37 ms.

Question 8

To allow the equations from section 2.4 to be used, we define:

p ≡ temperature measurement,
v ≡ first derivative of the temperature and
a ≡ second derivative of the temperature

Since the repeatability is $\pm 0.5\,°\text{C}$, we know that $3\sigma_p = 0.5°\text{C}$.
For a sensor with an analog output: $\Delta p = 3\sigma_p$, $\therefore \Delta p = 0.5°\text{C}$.

Then the optimal sampling time can be found using equation (2.40):

$$T_{opt} = \sqrt{\frac{4\Delta p}{\max|a_{true}|}} = \sqrt{\frac{4(0.5°C)}{0.1°C/s^2}} = 4.472\text{ s}$$

The corresponding worst case error in the estimated first derivative is:

$$\begin{aligned}\Delta v_{est} &= \frac{T_{opt}}{2}\max\left(|a_{true}|\right) + \frac{2\Delta \text{p}}{T_{opt}} \\ &= \frac{(4.472\text{ s})(0.1\,°\text{C/s}^2)}{2} + \frac{2(0.5\,°\text{C})}{4.472\text{ s}} \\ &= 0.447\,°\text{C/s}\end{aligned}$$

Question 9

a) Define h as the height of the liquid, and ρ as the density.

$$\begin{aligned}\text{Differential pressure of 2 cm of liquid } &= \rho g h \\ &= \left(1100\frac{\text{kg}}{\text{m}^3}\right)\left(9.81\frac{\text{m}}{\text{s}^2}\right)(0.02\text{ m}) \\ &= 215.82\text{ Pa}\end{aligned}$$

This means the differential pressure sensor accuracy has to be better (i.e. have a smaller magnitude) than ±215.82 Pa

Maximum differential pressure = full tank pressure $= \rho g h$

$$= \left(1100 \frac{\text{kg}}{\text{m}^3}\right)\left(9.81 \frac{\text{m}}{\text{s}^2}\right)(6\text{ m})$$

$$= 64750\text{ Pa}$$

When the tank is empty, differential pressure =0 Pa
Thus the range of the differential pressure required is 0 to 64750 Pa

Therefore differential pressure sensor B is suitable.

b) Define A as the cross sectional area of the tank

Weight of liquid= $A\rho g h$

Weight of 3 cm of liquid $= A\rho g h$

$$= \pi(3\text{ m})^2\left(1100 \frac{\text{kg}}{\text{m}^3}\right)\left(9.81 \frac{\text{N}}{\text{kg}}\right)(0.02\text{ m})$$

$$= 6099\text{ N}$$

This means the force sensor accuracy has to be better (i.e. have a smaller magnitude) than 6099 Pa

Weight of tank $= mg = (5000\text{ kg})\left(9.81 \frac{\text{N}}{\text{kg}}\right) = 4.91 \times 10^4\text{ N}$

Max. weight = tank weight + liquid weight

= tank weight + $A\rho g h$

$$= 4.91 \times 10^4\text{ N} + \pi(3\text{ m})^2\left(1100 \frac{\text{kg}}{\text{m}^3}\right)\left(9.81 \frac{\text{N}}{\text{kg}}\right)(6\text{ m})$$

$$= 1.88 \times 10^6\text{ N}$$

Thus the required force sensor range is at least $4.91 \times 10^4\text{ N}$ to $1.88 \times 10^6\text{ N}$,

Therefore pressure sensor C is a suitable choice.

Question 10

a) Strain gauge type and piezoelectric type.

b) Thermistor.

c) Adds delay (or phase lag) and amplifies high frequency noise.

d) Triangulation and time-of-flight.

e) Advantage: Does not require power. Disadvantage (any of these answers): object being sensed must come into contact and apply a small force to activate the switch; dynamics of the spring and mass can cause false outputs; or subject to wear.

f) They do not wear.

g) For safety-critical applications, distributed control is always preferable to centralized control

h) The absolute encoder needs to have a larger diameter. The reason is the absolute encoder requires a disk containing multiple tracks with different radii while the disk for an incremental encoder only needs to have a single track.

i) Small. The sensor should only detect the gradual (low frequency) changes in the level that occur as the car consumes the gasoline. It should not respond to the faster (high frequency) changes that happen when the gasoline sloshes (or splashes) around in the tank. A small bandwidth will cause the sensor to filter out those high frequency changes.

j) Controller, amplifier, actuator, process, sensor and signal conditioner (or signal conditioning).

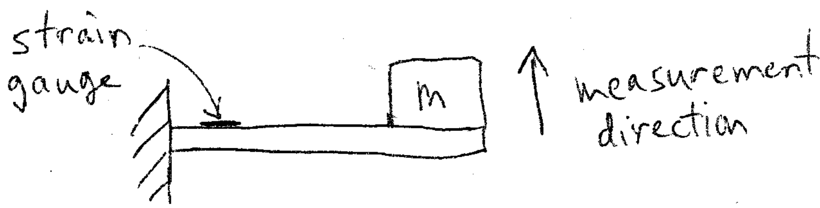
k) If the stiffness of a strain gauge-based force sensor is decreased then its bandwidth (alternative answer: upper frequency limit) specification will worsen and its sensitivity specification will improve.

l) They allow preliminary mechatronic designs to be tried out quickly, inexpensively and safely (Only need to provide two of these three reasons).

m) Hysteresis equals the maximum difference between the calibrated sensor outputs for continuously increasing and continuously decreasing inputs

n) Settling time, rise time and time constant.

o) Drawing should be similar to this:



p) Flow nozzle

q) Ranking (best to worst): Between the A/D and the microcontroller; between the amplifier and the low-pass filter; and between the sensor and the amplifier.

Reasoning: Long cables pick up electrical noise from their surroundings. Digital signals have better noise immunity. The cable between the A/D and microcontroller is the only one of the three cables that is transmitting a digital signal so it is the best choice for being long. The cable between the amplifier and filter is the second best choice since the amplifier will make the signal from the sensor stronger (higher voltage and/or higher current) so it will be less affected by the added noise. The worst choice is the cable between the sensor and amplifier since the signal is both analog and relatively weak so it will be the one most affected by noise.

r) Inductive and photoelectric