SINGLE-AXIS TILT-SENSOR SYSTEMS

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This paper presents two designs for low–cost tilt-sensor systems. The first design uses a tilt-sensing element, which consists an electrolytic resistive bridge for single-axis measurements. The second design uses a tilt sensor with capacitive detection. In both designs the electronic signal processing has been realized using the Universal Transducer Interface (UTI) and a microcontroller. For the resistive element, experimental results show a standard deviation of about 1 arcsec for a measurement time of 1 s and a rather linear behaviour. The main advantage of capacitive sensing element concerns the simplicity of the construction. However, its performance is inferior to that of the resistive elements.

1. INTRODUCTION

With tilt sensors the angle is measured with respect to a reference plan, for instance the plane perpendicular to the gravity field. Up to now spirit levels belong to the most common instruments implemented for such measurements. Nowadays many tilt sensors have been implemented with electronic detection systems, which enables their application in control loops and improves the accuracy and allows data storage. These advanced instruments are applied in a lot of applications, such as: construction lasers, instruments for wheel alignment, optical systems and more in general in many applications in the field of mechatronics, geophysical monitoring, machine tool leveling, medical positioning – monitoring and many others. The research work presented in this paper concerns investigations for the design of sensor systems based on the use of low-cost interface systems (Fig. 1).

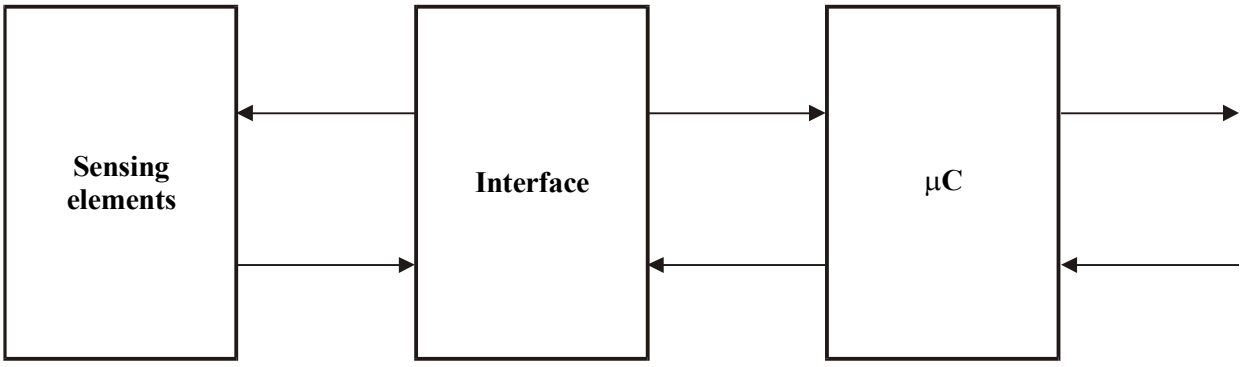


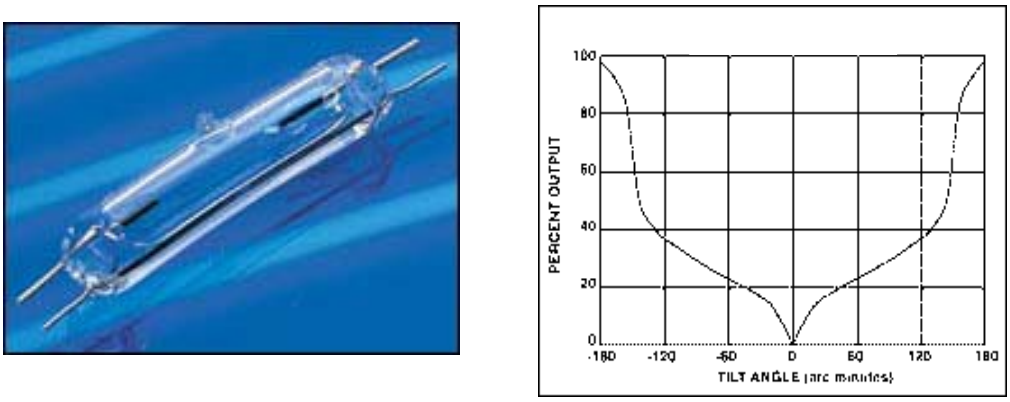
Figure 1 *Block diagram of the low-cost electronic system for tilt sensing.*

In a first design the applied tilt sensing element [1] consists of an electrolytic resistive bridge. In a second design a capacitive sensing element has been fabricated by attaching electrodes to an ordinary level spirit. In both cases, for the electronic signal

processing a microcontroller and a universal transducer interface (UTI) [2] have been used. The properties of both designs have been explained and the experimental results have been compared.

2. ELECTROLYTIC RESISTIVE TILT SENSOR

The single-axis electrolytic tilt sensor [1] consists of a glass container filled with conductive liquid in a gas bubble (Fig. 2). Three electrodes have been inserted to enable resistive tilt detection. When completed with two more resistors a Wheatstone-bridge configuration can been obtained. The modulus of the relative output voltage of such a bridge has been depicted in Fig. 2(b) versus the tilt angle.



(a) (b)

Figure 2 *(a) A single-axis electrolytic tilt-sensing element; (b) Output characteristics of the sensor in a Wheatstone-bridge configuration [1].*

The main operating specifications of the electrolytic tilt-sensing element have been listed in Table 1:

Table 1 *Operation specification of the single-axis electrolytic tilt-sensing element*

Parameters	Values
Operating Range	± 3°
Linear Range	± 5 arc minute
Null Voltage	≤ 0.005 Volts
Null Impedance (nom)	1000 Ohms (25°)
Null Repeatability	≤3 arc seconds
Operating Temperature	-20°C to + 50°C

Note: The drive circuit must be free of direct current

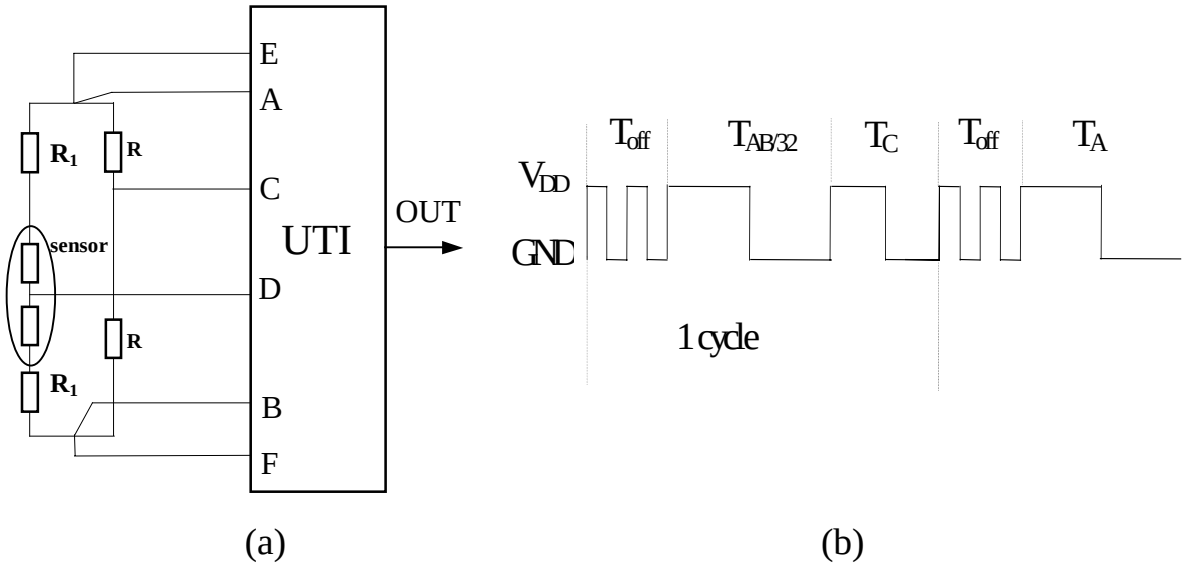


Figure 3 *(a) Circuit diagram of the connection of the electrolytic tilt-sensing element and the interface; (b) Output signal of the universal transducer interface [2].*

Figure 3 (a) shows the set-up for the electrolytic tilt-sensing element together with the universal interface circuit UTI. Also in this case a Wheatstone-bridge configuration has been used. In mode 9 of the UTI a maximum bridge imbalance of ±4% can accurately be measured. Bridge supply voltage is a square-wave AC signal, with a peak-to-peak value of $2V_{DD}$, without DC component. In order to prevent undesired electrolytic effects in the sensing element, the absence of any DC current is important. Using the principle of force and sense wires eliminates the influence of lead resistances.

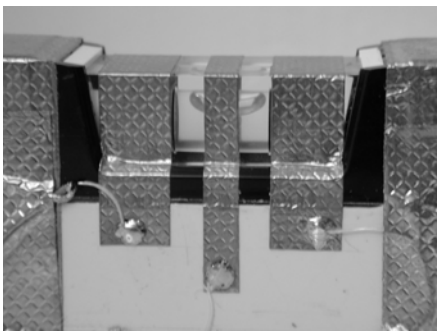
Figure 3(b) shows the period-modulated output signal of the UTI. During the time interval $T_{AB/32}$ the voltage V_{AB} is measured. The factor 32 accounts for the transfer function of a very accurate on-chip voltage divider for the measurement of the bridge voltage. The microcontroller measures the lengths of the various period times T_{off}, $T_{AB/32}$ and T_{CD} for the different phases. Afterwards, using the program LabView in a PC, the relative bridge unbalance is calculated, according to the equation:

$$M_r = \frac{1}{32}\frac{T_{CD} - T_{off}}{T_{AB} - T_{off}} = \frac{V_{CD}}{V_{AB}}$$

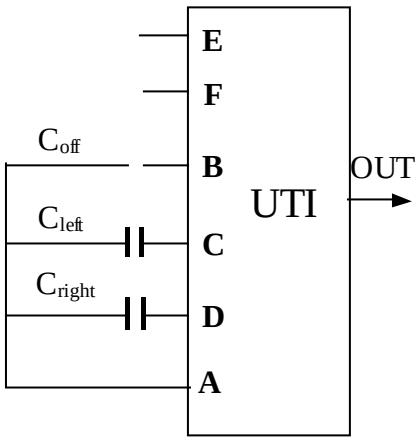
3. THE CAPACITIVE TILT SENSOR

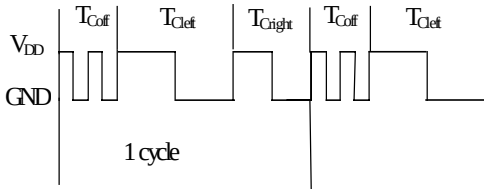
A drawback of the electrolytic sensing element is the need of inserted electrodes, which have to be in galvanic contact with the liquid. This makes the fabrication

expensive. Therefore, we also investigated the feasibility of an alternative approach in which an ordinary spirit level is used with noninvasive electrodes glued at the surface. The common electrode is placed in the center of the level, just above the gas bubble (Fig. 4(a)); two more electrodes are located on the left (E_{left}) and right (E_{right}) side of the common electrode.



(a)





(c) **(b)**

Figure 4 *A capacitive tilt sensor: (a) A set of electrodes have been sticked on the glass container of an ordinary spirit level; (b) The connection to the universal transducer interface; (c) output signal of the interface [2].*

In this way two capacitors C_{left} and C_{right} between the center electrode and the other two electrodes are formed. The value of these capacitors depends on the location of the gas bubble. The ratio C_{left}/C_{right} is an indirect measure for the tilt. When the air bubble is in the center both capacitors are equal to about 0.7 pF. For a tilt of 60 arcsec the differential capacitance $\Delta C = C_{left} - C_{right}$ =3.214 fF. With the universal sensor interface UTI such a small change can easily be detected, with a resolution as low as 50 aF. Figure 4(b) and (c) show the way of connection with the UTI set-up and the UTI output signal, respectively.

4. EXPERIMENTAL RESULTS

Electrolytic resistive tilt sensor: Using the setup presented in Section 2, tilt has been measured with the electrolytic resistive tilt sensor, over a range of ± 60 arcsec. Figure 5 shows the measured imbalance M_r for the total electrolytic sensor system. The results show that a good linearity has been achieved.

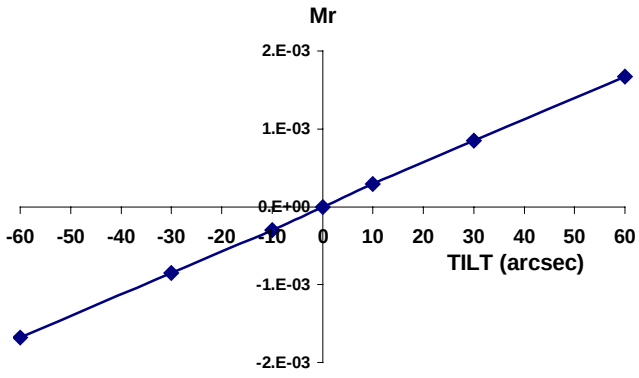


Figure 5 *The measured imbalance M_r for the electrolytic sensor system.*

Capacitive tilt sensor: Using the setup presented in Section 3, also with the capacitive sensor tilt has been measured over a range of ± 60 arcsec. Figure 6 shows the measured imbalance $(M_C - 1) = (C_{left}/ C_{right}) - 1$ for the total capacitive sensor system. The results show a strong nonlinearity, which probably is caused by mismatching in the electrode structure and a sub optimal electrode shape. However, in using an improved fabrication process it should be possible to reduce this problem and yet to have the advantage of low-cost non-invasive electrodes. The use of guarding and shielding electrodes will further improve the accuracy and reliability [4].
With a measurement time of 1 s a standard deviation of 4 arcsec has been found. For a measurement time of 10 s this standard deviation is reduced to 1.3 arcsec.

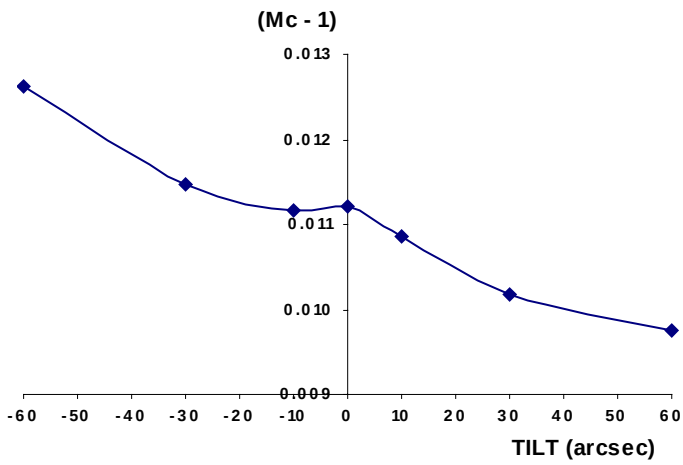


Figure 6 *The measured imbalance $(M_c$-1) for the capacitive sensor system.*

5. CONCLUSIONS

Investigations have been performed on tilt sensors implemented with a resistive sensing element and a capacitive sensing element, respectively. For both types of sensors the electronic signal processing has been performed with a universal sensor interface and a microcontroller. The best results have been obtained with the resistive type. A good linearity has been found with a resolution of 1 arcsec for a measurement time of 1s. The capacitive sensors have the advantage that no invasive electrodes are required. Using simple handmade electrodes and an ordinary spirit level for the capacitive sensor a proof of concept has been given. However, a strong nonlinearity of the output signal has been found. This nonlinearity is due to imperfections in the electrode geometry. In this simple setup the resolution amounts to 4 arcsec for a measurement time of 1 s.

5. REFERENCES

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