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MEMS TILT SENSOR FOR MICROROBOTS

The paper describes a miniature two-axes tilt sensor for microrobots built of a standard MEMS (Microelectromechanical Systems) accelerometer ADXL 202E. There is also presented the test station and exemplary results of the performed experimental studies. There are given technical data referring to the performance of the sensor that are not provided by the manufacturer.

1. INTRODUCTION

In the Institute of Micromechanics and Photonics, Warsaw University of Technology, there was carried out a work on building a snake-like microrobot [1]. One of members of the microrobot was a tilt sensor attached to its head. The sensor was to feature the following, miniature overall dimensions, two-axial tilt measurement (i.e. detection of the roll and the pitch) over the range of 360°, accuracy of about few degrees arc. On the market, there are no sensors that meet all the three requirements. It was succeeded to build a model of the microrobot (Fig. 1) and few models of the tilt sensor.

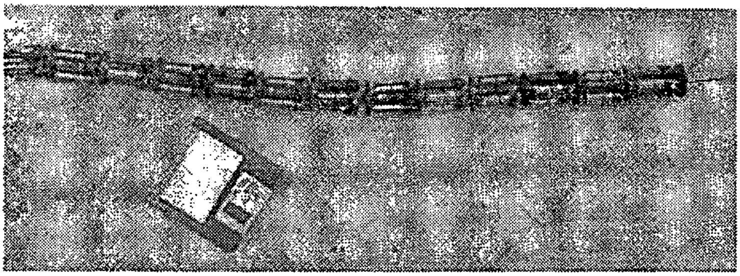

Fig. 1. The snake-like microrobot

Experimental studies performed on the models of the tilt sensor indicated that the most convenient kind of solution, as far as the above application is concerned, is a sensor based on accelerometers [2].

A requirement of miniature dimensions of the sensor is a factor that strongly limits the range of possible scope of technical solutions. While building a model of the sensor in a conventional technology (e.g. strain gauges bonded onto a flexible beam) dimension of the sensor exceed 20 mm [3].

It seems that MEMS technology provides the best opportunities in this case. It ensures to keep small dimensions and is very unique. While applied, it is easy to integrate electronic circuits with mechanical structure what results in a significant reduction of the noise level and thus, increasing the sensor resolution. It should be also noted that a MEMS sensor can be integrated with other systems manufactured in this technology. It is possible to integrate the sensor with a temperature sensor, and even a micro-oven providing a constant temperature of the sensor. Thus, the temperature error can be eliminated completely, while the overall dimensions are not enlarged.

As it was mentioned before, on the market there are no sensors that meet all the requirements introduced above. However, it is possible to use standard MEMS accelerometers for building the considered tilt sensor. The world's smallest (available on the market) MEMS accelerometer (having dimensions 5x5x2 mm) is ADXL 202E capacitive sensor by Analog Devices, Inc. [4]. It is presented in Fig. 2 (two pieces of the sensor are shown against a background of one-cent coin).

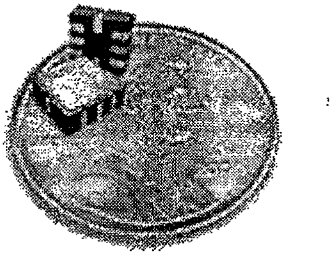

Fig. 2. ADXL 202E dual-axis MEMS accelerometer [4]

Because of its advantageous features (small dimensions, measurement of acceleration along two axes by two constituent acceleration transducers) one decided to apply it for building the dual-axis tilt sensor. Yet, while performing experimental studies instead of ADXL 202E one used ADXL 202 accelerometer [5]. These sensors are the same except for their package. The ADXL 202 has a package of bigger dimensions and thus, it is easier to fix it in a test station.

Because of the fact that the sensor is used in an untypical application (for dual-axis tilt measurement) the technical data provided by the manufacturer are not sufficient. Therefore, in order to obtain all the necessary information one had to carry out experimental studies.

2. THE TEST STATION

In order to carry out experimental studies of the sensor, there was constructed a special computer controlled test station presented in Fig. 3. It operates as follows. The computer *1* communicates (by means of a custom-designed software) with the electronic block *2* through an analog-digital data acquisition card Advantech PCL - 818 L. The electronic block controls the mechanical unit *3*.

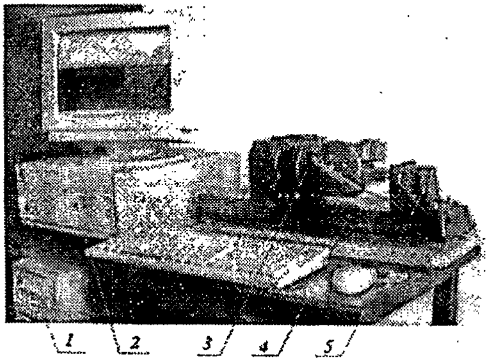

Fig. 3. View of the test station:
1 - computer; *2* - electronic module; *3* - mechanical unit; *4* - bed; *5* - footstock

The mechanical unit *3* is presented in Fig. 4. The main constituents of this unit are two rotary tables *1* and *2* powered by stepper motors. The vertical table *1* applies the roll angle while the moveable table *2* the pitch angle (in this configuration influenced by the roll also). The tested sensor *3* is fixed to the moveable table. The spirit level *4* enables to find an initial horizontal position (accepting the gravity vector as the reference).

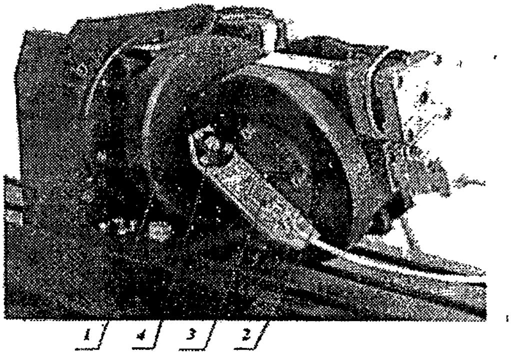

Fig. 4. Mechanical unit of the test station:
1 - vertical rotary table (to set the roll angle); *2* - moveable rotary table (to set the pitch angle); *3* - tested sensor; *4* - circular spirit level

The computer sets a certain angular position of each rotary table and then reads the output signals of the tested sensor (by means of the data acquisition card). This way, we can obtain indications of the tested sensor against the corresponding real angular positions. Comparison of these two provides information on the sensor accuracy.

2.1. Accuracy of applying the angular position

Accuracy of applying the roll and the pitch angle is different. Accuracy of the first angle equals kinematic accuracy of the vertical rotary table. But the pitch angle is dependent on the position of both tables [6]. Its maximal error is to be calculated according to the following formulae (by assuming that kinematic accuracy of both tables is of the same value):

$$\Delta\beta = \Delta\alpha\left(\left|\frac{1}{\left(1+\left(\frac{\mathrm{tg}\gamma}{\cos\alpha}\right)^2\right)\cdot\cos^2\gamma\cdot\cos\alpha}\right|+\left|\frac{\mathrm{tg}\gamma\cdot\sin\alpha}{\left(1+\left(\frac{\mathrm{tg}\gamma}{\cos\alpha}\right)^2\right)\cdot\cos^2\alpha}\right|\right) \qquad (1)$$

where:

$\Delta\beta$ - maximal error of the pitch;
$\Delta\alpha$ - kinematic accuracy of the rotary tables ($\Delta\alpha = \Delta\gamma = \pm 0.05^\circ$);
α - the roll;
γ - angular position of the moveable table.

Fig. 5 introduces a graphical interpretation of the formulae (1). There was considered one octant only because of an analogy in the case of the other seven octants. Values of $\Delta\beta$ are meant as multiples of $\Delta\alpha$ (e.g. for $\alpha = 90^\circ$ and $\gamma = 0^\circ$, $\Delta\beta = 5\ \Delta\alpha$).

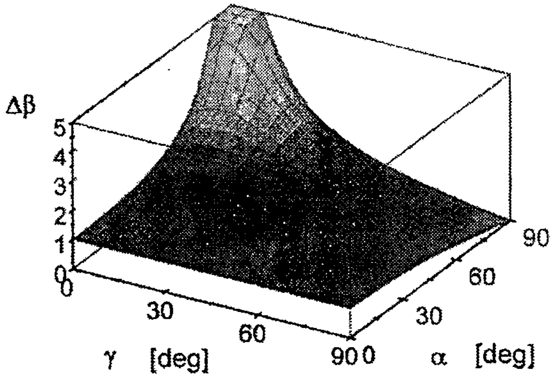

Fig. 5. Maximal error of applying the pitch angle

The highest values of the pitch error were decreased to 5, while in fact they are much bigger. However, this region of angular positions of the rotary tables cannot be used while performing experimental studies, since the error of applying the pitch angle is too big. It is usually assumed that accuracy of the measuring device is to be 10 times higher than the expected accuracy of the measured quantity.

2.2. Accuracy of reading the output signals from the accelerometer

Accuracy of measuring the output voltages form the sensor was resulted by the accuracy of the applied analog-digital data acquisition card (Advantech PCL - 818 L). On the basis of the technical data [7], one can derive a formulae for determining it:

$$\Delta V = 0{,}01\ V + 0{,}0002\ [\mathrm{V}] \qquad (2)$$

where:
V - the measured output voltage;
ΔV - accuracy of the measured voltage.

So, one can assume the following:

- Accuracy of applying the roll angle was of ±0.05°;
- Accuracy of applying the pitch angle was of ±0.1° (the regions characterised by higher errors of the pitch were not used while performing the experiments);
- Accuracy of measuring the output voltage form the sensor was no lower than 0,03 [V].

3. EXEMPLARY RESULTS OF THE TESTS

Because of a high number of the obtained results, the paper presents only some of them. The experimental studies were meant to obtain these data that are not provided by the manufacturer. They result mainly from the unusual application of the accelerometer as a dual-axis tilt sensor. Another goal was to determine factors influencing the accelerometer accuracy.

The tests were performed in the following way. First, a desired angular position was applied by means of the rotary tables. Then, after a time of few seconds (to make vibrations of the sensor damp) there were performed 30 readouts of the output signals (at the same angular position). The procedure was repeated until all the desired angular positions were reached.

In Fig.6 there is presented a characteristic of the sensor. It was obtained while rotating the vertical table, i.e. while applying the roll angle by a constant pitch angle. Course of the roll signal (voltage form the Y-output of the accelerometer), presented as a dashed line, is according to the expected one (see formulae (3) in section 4). However, course of the pitch signal (voltage form the X-output of the accelerometer), presented as a solid line, is expected in this case to be of a constant value. As can be observed, this course has also a shape of a sine curve with small amplitude.

This phenomenon is due to a so-called transverse sensitivity, or cross-axis effect. It is indicated in the manufacturer's data sheet and has value of about 2%. It causes a relatively high decrease of the sensor accuracy, yet it has a systematic character and therefore can be eliminated in a large measure (a full elimination is impossible in the case when both pitch and roll are being changed). This effect is a factor influencing accuracy of indications of the tested sensor the most.

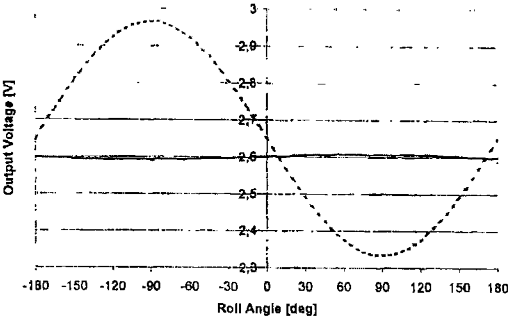

Fig. 6. Characteristic of the ADXL 202 sensor while rolled by the pitch angle of 0°: *dashed line* - roll signal; *solid line* - pitch signal

Fig. 7 presents the total error of the accelerometer indications (as referred to the roll angle) presented in Fig. 6. Indications of the pitch angle were not considered since their course in Fig. 6 is itself a course of indication error.

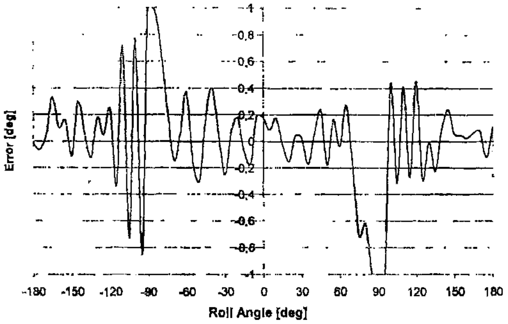

Fig. 7. Total indication error of the ADXL 202 sensor while rolled by the pitch angle of 0°

The error is meant as a difference between the real angular position of the sensor and the position calculated on the basis of its output signal.

As can be observed, the error is usually of few tenths of degree arc. This is why the test station had to be modified. The vertical table was coupled with an incremental angle transducer IDW 2/16384 manufactured by Jenoptik Carl Zeiss JENA, by means of a flexible coupling. Thus, the accuracy of applying the roll angle was of about 0.0006° and could be neglected in further considerations.

Fig. 8 presents a random error of the above indications. It is meant as a 3-sigma error. Again, a dashed line refers to the roll signal, while a solid one to the error of the pitch signal.

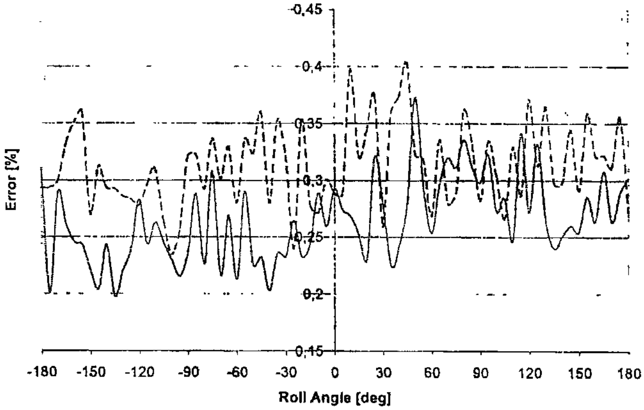

Fig. 8. Random error of indications of the ADXL 202 sensor

Random errors of both the roll and the pitch are of similar values and are independent on the sensor position. It should be noted that the random error is more than 10 times bigger compare to the resolution at the highest sensitivity (i.e. for a tilt of 0°). This value is not provided in the manufacturer's data sheet. .

4. DUAL-AXIS TILT MEASUREMENT OVER THE FULL ANGULAR RANGE

The considered accelerometer meets two of the three main requirements presented in the first section. It has miniature dimensions and enables dual-axis tilt measurement over the full range. Yet, it does not provide sufficient accuracy over the whole measuring range.

In Fig. 6, it can be observed that the total indication error dramatically increases around the roll (and analogically the pitch) angle of ±90°. It should be noted that the error in this position will be bigger than 1°, as it is on the chart. In other positions, where the pitch has a non-zero value, and there is performed only one readout of the sensor output signal, the error will be increased by the random component and additionally due to the cross-axis effect.

The main disadvantage of applying accelerometers for tilt measurement is the fact that their characteristic (see Fig. 6) is strongly non-linear. Let us consider the roll angle. It can be determined by means of the following formulae [2,8]:

$$\alpha = arc\sin\frac{g_y}{g} = arc\sin\frac{V_y - V_o}{V_{\max} - V_o} \qquad (3)$$

where:

g_y - the component gravitational acceleration (projection onto the y-axis);
g - the gravitational acceleration;
V_y - the actual output voltage;
V_o - the offset voltage (corresponding to the roll of 0°);
V_{max} - the maximal output voltage (corresponding to the roll of -90°).

On the basis of the above formulae, one can derive a dependency (i.e. derivative) describing the error function of determining the roll angle. It is even more strongly non-linear, and its value dramatically increases for α angles that are in the interval of 70°÷90° [2]. This can be observed also in Fig. 7 for roll angles around 90°.

So, when a higher accuracy of the sensor is required, indications in such regions cannot be used. In order to make it possible, one must introduce another accelerometer providing information in the regions of non-linearity. In the case of dual-axis tilt sensing, it is sufficient to introduce one additional accelerometer, provided all the three constitutional acceleration transducers (two in the first sensor and the third in the additional one) have appropriate spatial configuration. The best one forms 3 perpendicular axes: x, y, z [2] (the sensors can be located as e.g. in Fig. 2: one horizontally and the other vertically).

In that case, all the accelerations indicated by the constitutional acceleration transducers meet the following condition

$$g = \sqrt{g_x^2 + g_y^2 + g_z^2} \tag{4}$$

where:

g_x, g_y, g_z - component gravitational accelerations (projections onto x-, y- and z-axis);

g - the gravitational acceleration.

Then, in case one of the sensed angles (pitch or roll) is found in the interval 70°÷90°, instead of using formulae (3) one can use the following dependence

$$\alpha = arc\cos\frac{g_{xz}}{g} \tag{5}$$

where:

$$g_{xz} = \sqrt{g_x^2 + g_z^2} \tag{6}$$

Derivative of the formulae (5) (being the error function) is strongly non-linear for α angles around 0°, and at the same time almost linear for α angles around 90°, just the opposite compare to the formulae (3). So, by introduction of another accelerometer we improve accuracy of the tilt sensor by eliminating the necessity of using indications of the prime acceleration transducers within the region of their insensitivity.

It should be noted that the proposed spatial arrangement of acceleration transducers (forming x-, y-, z-axis) is advantageous because of the fact that in every angular position of the tilt sensor at least two constituent acceleration transducers operate outside of the region of insensitivity. Therefore, it is possible to avoid decrease of the sensor accuracy.

5. CONCLUSIONS

The works carried out proved that it is possible to use the ADXL 202 accelerometer as a dual-axis tilt sensor. However, there occur some limitations due to accuracy of the sensor indications.

There have been obtained values of many metrological features of the sensor, such as the total accuracy of tilt measurement, systematic errors, random errors. The manufacturer does not provide most of these features.

There are presented directions for achieving higher accuracy of tilt measurements thanks to introduction of another accelerometer. The best solution would be to apply a monolithic accelerometer containing three transducers indicating component acceleration on three separate axes (not necessarily perpendicular to each other). Currently, such accelerometers are not available on the market. However, such structures has already been designed, and even manufactured [9]. It should be expected that in the future such solutions will be widespread and commonly applied.

Dynamic properties of the sensor have been not studied because of the type of its application (i.e. as a tilt sensor operating only under static, or quasi-static, conditions).

If there is required a high relative accuracy (i.e. better then 1%) of tilt measurement, the following must be observed:

- One cannot use the whole measuring range of constituent transducers of the accelerometer (only ± 70°) what results in necessity of applying another accelerometer;
- One has to eliminate the systematic error (i.e. the transverse sensitivity);
- Instead of a single measurement, a series of measurements must be performed at each angular position;
- Appropriate data processing must be applied.

5.1. Future works

It is foreseen to continue in the nearest future further work on the tilt sensor built of MEMS accelerometers. The main goal is further increase of the sensor accuracy. The following tasks are considered:

- Elaborating algorithms of processing results of experimental studies (taking into consideration especially the statistical analysis);
- Determining other factors influencing accuracy of indications of the tested accelerometers;
- Carrying out further experimental studies.

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