SINGLE-AXIS TILT MEASUREMENTS REALIZED BY MEANS OF MEMS ACCELEROMETERS

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A problem of measuring tilt around a single axis is discussed in detail with regard to the resultant accuracy. Ways of improving the accuracy, based on application of various mathematical equations, are proposed. Presented results of related experimental studies, performed on a tilt sensor made of a standard MEMS accelerometer, have proven that it is possible to obtain accuracy of such measurements of ca. 0.2 degrees arc. Additionally, a problem of measuring tilt of an object, which rotates within a non-vertical plane, is addressed.

Keywords: *accelerometer, accuracy, measurements, microelectromechanical systems (MEMS), tilt sensor, orientation*

1. Introduction

The problem of measuring tilt occurs in many applications, which could be roughly divided into positioning, aligning, leveling, navigation and orientation. As far as mechatronics is concerned, tilt sensors are applied most often in mobile robots [1].

Measurements of tilt around one axis only are more common compare to their two- axial counterparts. Realization of such measurements by means of a miniature sensor built of accelerometers belonging to microelectromechanical systems (MEMS) is very advantageous, as these are characterized by miniature dimensions, satisfactory metrological parameters, and very low cost (less than $10) compare to the conventional solutions, like fluid sensors, magnetic sensors or systems based on gyroscopes (whose price usually exceeds $100). Here, the low cost is of great importance, as it opens new perspectives for application of the tilt sensor in devices, where a significant increase of the price would render them commercially unsuccessful (e.g. due to the competitors' offers).

An additional advantage of using accelerometers in tilt measurements is a possibility of employing various mathematical relations while determining the tilt, what will be addressed in detail later in the text.

In a general case, a tilt angle is usually expressed as two component angles: pitch α and roll β [2–4]. The component angles have been presented in Fig. 1 using an example of a military plane.

2. Determining the tilt

As it has been concluded, a very advantageous way of measuring tilt is to use a sensor made of commercial MEMS accelerometers, which employ measurements of Cartesian

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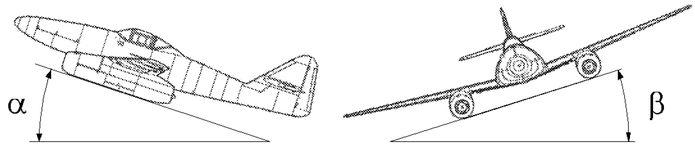

Fig.1: Component angles of the tilt

components of the vector of the gravitational acceleration. Let us then consider relations between the tilt angles and the components of the gravitational acceleration.

In Fig. 2 an arbitrary tilt angle φ has been distributed into two component angles α and β (pitch and roll), which are contained within vertical planes xz_0 and yz_0, where:

- g – gravitational acceleration;
- g_{x}, g_{y}, g_{z} – Cartesian components of acceleration g, which are its projections onto axes x, y, and z, respectively.

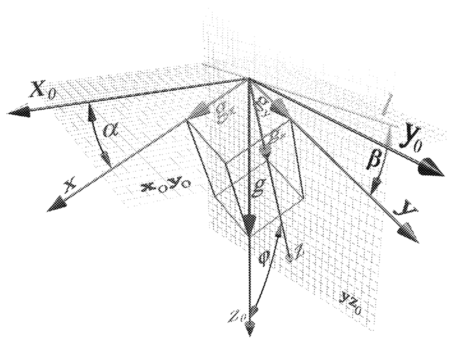

Fig.2: The tilt angles and distribution of the gravitational acceleration

The coordinate system $x_0y_0z_0$ is immobile, and its axis z_0 is vertical, whereas the coordinate system xyz is fixed to a mobile tilt sensor. Note that while the pitch angle α is included between axis x and x_0, the roll angle β is included between axis y and line l (which has been created as a result of the intersection of vertical plane yz_0 and horizontal plane x_0y_0), instead of axes y and y_0. This problem will be discussed later in the text.

While we consider the problem of measuring tilt over one axis only, let us choose for further consideration but one of the tilt angles – the roll, as presented in Fig. 3.

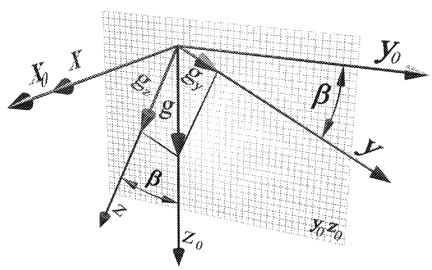

Fig.3: The roll angle against the components of the gravitational acceleration

As results from Fig. 3, the basic relations between the roll and the components of the gravitational acceleration can be expressed as follows:

$$\frac{g_\mathrm{y}}{g} = \sin\beta \ , \tag{1}$$

$$\frac{g_\mathrm{z}}{g} = \cos\beta \ , \tag{2}$$

$$\frac{g_\mathrm{y}}{g_\mathrm{z}} = \tan\beta \ , \tag{3}$$

where:

- g_y/g – output signal generated by an accelerometer-based tilt sensor assigned to its sensitive axis y,
- g_z/g – output signal generated by an accelerometer-based tilt sensor assigned to its sensitive axis z.

If the relevant tilt sensor is required to feature a measurement range of the roll wider than 180°, the sensor must consist of one or more accelerometers with a total number of the sensitive axes equal to at least 2 [since indications assigned to the sensitive axes of the tilt sensor reach all the possible values within the measurement range of 180° as it results from Eq. (1)–(3)]. While employing MEMS accelerometers, four options are reasonable: to use 2 single-axis accelerometers, 1 dual-axis, 1 tri-axial or 1 multi-axial – such as those presented e.g. in [5, 6]. Here, the simplest and preferable configuration is when the sensitive axes of the accelerometers are orthogonal with respect to one another, and thus form a Cartesian coordinate system yz, as depicted in Fig. 3 (any other spatial configuration of the sensitive axes, creating an affine coordinate system, is also acceptable provided the axes do not overlap each other nor the rotation axis x).

The problem of determining the roll over the full angle has been explained in Fig. 4 in the case of using Eq. (1). Its component g_y/g reaches all the possible values within the range of $\langle -90°, 90°\rangle$ – then component g_z/g of Eq. (2) has a positive value. Within the remaining range, i.e., $\langle -180°, -90°\rangle$ and $\langle 90°, 180°\rangle$ the indications reach recurrent values, yet g_z/g has a negative value. Thus, the sign of g_z/g makes it possible to unequivocally determine the angular position indicated by the tilt sensor. The same applies accordingly to Eq. (3).

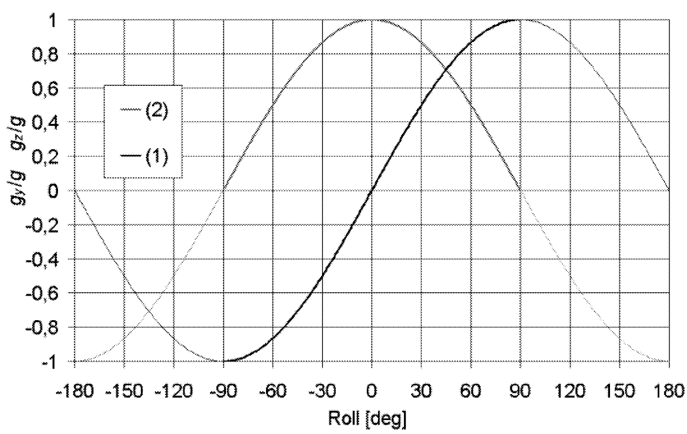

Fig.4: Illustration of Eq. (1) and (2)

In Fig. 4, we can also observe a symmetrical character of the sensor indications within the angular range of $\langle -90°, 90° \rangle$ for Eq. (1) and $\langle 0°, 180° \rangle$ for Eq. (2). Therefore, further considerations can be limited to a sub-range of $\langle 0°, 90° \rangle$ and will still fully represent all the possible cases [4]. A tangent function expressed by Eq. (3) is also symmetric within the range of $\langle -90°, 90° \rangle$.

As it results from the preceding considerations, we can determine value of the roll using various formulas [2], [4, 7] :

$$\beta_1 = \arcsin \frac{g_\mathrm{y}}{g} \ , \tag{4}$$

$$\beta_2 = \arccos \frac{g_\mathrm{z}}{g} \tag{5}$$

and additionally [8, 9]:

$$\beta_3 = \arctan \frac{g_\mathrm{y}}{g_\mathrm{z}} \ . \tag{6}$$

Let us note that angles β_1, β_2 and β_3 introduced above have the same nominal value; the additional subscripts have been introduced in order to allow us to unequivocally distinguish between the related formulas later in the text. Even though the nominal values of the roll determined according to the above equations are the same, yet their accuracy is different, as it is explained in the following section.

3. Accuracy of determining the roll

In order to evaluate accuracy of tilt measurements let us use a notion of uncertainty of the sensor indications, which refers to the involved random errors. According to the guidelines of the International Organization for Standardization, a combined standard uncertainty of a given quantity is to be estimated with the geometric sum of its partial derivatives with respect to all the input variables multiplied by the standard uncertainty of the respective variable [10]. Thus, while determining the combined standard uncertainty of the roll we can use the following equation :

$$u_\mathrm{c}(\beta) = \sqrt{\left[\frac{\partial\beta}{\partial g_\mathrm{y}}\, u(g_\mathrm{y})\right]^2 + \left[\frac{\partial\beta}{\partial g_\mathrm{z}}\, u(g_\mathrm{z})\right]^2 + \left[\frac{\partial\beta}{\partial g}\, u(g)\right]^2} \ . \tag{7}$$

In order to simplify considerations pertaining to the accuracy of determining the roll, let us accept the following relation justified by the author in [4, 7] :

$$u(g_\mathrm{y}) = u(g_\mathrm{z}) \gg u(g) \ . \tag{8}$$

Thus, the uncertainties resulting from Eq. (4)–(6) can be expressed respectively :

$$u_\mathrm{c}(\beta_1) = \frac{u(g_\mathrm{y})}{|g|} \frac{1}{\cos\beta_1} \ , \tag{9}$$

$$u_\mathrm{c}(\beta_2) = \frac{u(g_\mathrm{y})}{|g|} \frac{1}{\sin\beta_2} \ , \tag{10}$$

$$u_\mathrm{c}(\beta_3) = \frac{u(g_\mathrm{y})}{|g|} = \mathrm{const} \ . \tag{11}$$

Let us note that the component $u(g_\mathrm{y})/|g|$, i.e., the relative standard uncertainty of determining the components of the gravitational acceleration, characterizes performance of a given accelerometer and can be determined in an experimental way (e.g. while calibrating the tilt sensor). The related graphs have been presented in Fig. 5, having assumed that the relative standard uncertainty has a unitary value (note that since the terminal values of Eq. (9) and (10) grow to infinity, they have been omitted – in the first case the values for angles of $\langle 60°, 90° \rangle$ and in the second case, angles of $\langle 0°, 30° \rangle$).

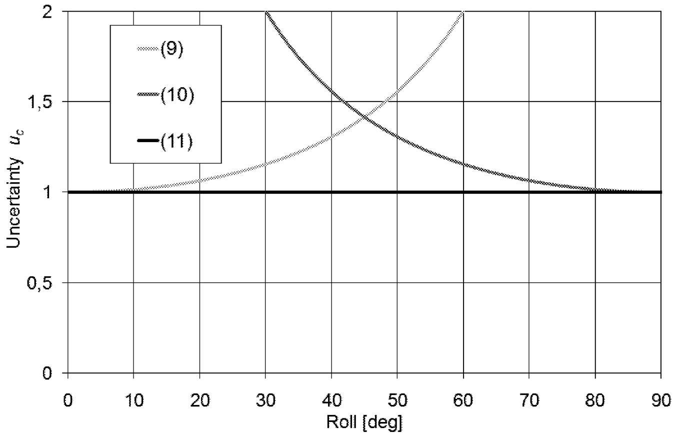

Fig.5: Graphical illustration of the uncertainties of determining the roll

4. Determining the roll with a pitch involved

It must be realized that if the pitch angle is not of zero value, Eq. (5) and (6) get more complicated, as the component acceleration g_x is then not of zero value [9, 11, 12], i.e.:

$$\beta_2 = \arccos \frac{g_\mathrm{xz}}{g} = \arccos \frac{\sqrt{g_\mathrm{x}^2 + g_\mathrm{z}^2}}{g} = \arccos \sqrt{\left(\frac{g_\mathrm{x}}{g}\right)^2 + \left(\frac{g_\mathrm{z}}{g}\right)^2} \;, \tag{12}$$

$$\beta_3 = \arctan \frac{g_\mathrm{y}}{g_\mathrm{xz}} = \arctan \frac{g_\mathrm{y}}{\sqrt{g_\mathrm{x}^2 + g_\mathrm{z}^2}} \;. \tag{13}$$

Moreover, this is not the only problem occurring while the tilt sensor is pitched. As already mentioned, the roll angle is not included between axis y and y_0 (see Fig. 2) as it is the case by pure roll measurements. Now, there is included another angle between axis y and y_0, denoted by γ and presented in Fig. 6, where:

$$\eta = \frac{\pi}{2} - \beta \;. \tag{14}$$

(It is worth mentioning that according to the standards accepted in aeronautics, the roll angle is not defined as angle β (see Fig. 2), but as an angle between axes y and y_0 [13], i.e. angle γ, as it is consistent with the real rotation angle experienced by the aircraft crew.)

As it results from Fig. 6 [14]:

$$g_\mathrm{y} = g_\alpha \sin\gamma = g \sin\gamma \cos\alpha \;. \tag{15}$$

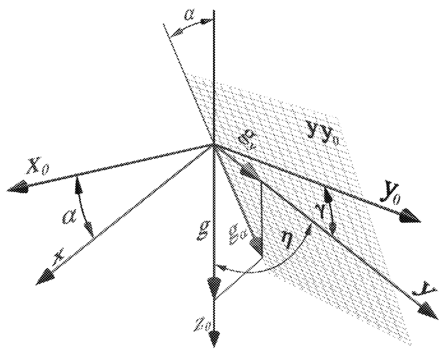

Fig.6: The component of the gravity vector against angles α and γ

By combining Eq. (4) with (15) we can obtain a relation between angle β and γ:

$$\beta = \arcsin(\sin\gamma\,\cos\alpha)\ . \tag{16}$$

If the pitch is of zero value, the considered angles are the same. However, if it has a significant value the angles are different (for instance, when pitch α is of 90° then γ becomes yaw instead of roll, and thus cannot be detected by tilt sensor). It is noteworthy that while the tilt sensors indicate the roll, in most of the cases it is easier to apply angle γ instead (e.g., while calibrating the sensor using a dual-axis test station presented in [4, 14]).

Yet another conclusion results from Eq. (16). The nonlinear relation between roll β and angle γ can be a source of an apparent nonlinearity of an accelerometer while calibrated using the gravity vector as the reference [15]. So, while calibrating accelerometers in such a way, one must take precautions to ensure that there is no pitch involved.

In some cases it is angle γ instead of β that we are interested in, as it reflects the real rotation of the sensor. An example can be here a model of a vehicle called segway [16, 17], where the control system actuates the vehicle position with respect to the vertical by means of rotary motors applying just angle γ while pitched. So, we can rearrange the preceding formula as:

$$\gamma = \arcsin\frac{\sin\beta}{\cos\alpha}\ . \tag{17}$$

Let us define a function e that represents an error of neglecting the pitch in Eq. (17) while determining angle γ:

$$e = |\gamma - \beta| = \left|\arcsin\frac{\sin\beta}{\cos\alpha} - \beta\right|\ . \tag{18}$$

A graph of the function is illustrated in Fig. 7. As can be observed, for small values of the pitch the error is small. Yet, for considerable pitch angles the error is significant.

At the same time, it must not be forgotten that the pitch and the roll are interdependent, what results from the basic equation (relevant in the case as in Fig. 2):

$$g = \sqrt{g_\mathrm{x}^2 + g_\mathrm{y}^2 + g_\mathrm{z}^2}\ . \tag{19}$$

Moreover, it can be proven that:

$$|\alpha| + |\beta| \le 90°\ . \tag{20}$$

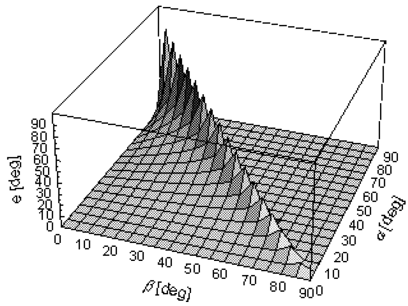

Fig.7: Graphical illustration of Eq. (18)

So, referring to the surface presented in Fig. 7, only the data on the left of the diagonal of the base of the cuboid are real. The irregular edge of the surface results from digitization errors involved in computer processing.

It must be realized that even in the case when the pitch is measured and taken into account (i.e., while using Eq. (17)), angle γ will be determined with some error, due to respective uncertainties of the roll and the pitch. Additionally, since Eq. (17) is not linear, the uncertainty of determining angle γ will be variable. Again, according to the guidelines of the International Organization for Standardization [10], the related combined standard uncertainty can be determined by the following equation :

$$u_c(\gamma) = \sqrt{\left[\frac{\partial\gamma}{\partial\alpha}\,u(\alpha)\right]^2 + \left[\frac{\partial\gamma}{\partial\beta}\,u(\beta)\right]^2} \tag{21}$$

where $u_c(\gamma)$ is the considered uncertainty; $u(\alpha)$, $u(\beta)$ – uncertainties of determining pitch and roll (by means of the tilt sensor).

By using appropriate formulas, we can obtain the following equation :

$$u_c(\gamma) = \sqrt{\left[\frac{\sin\alpha\,\sin\beta}{\sqrt{(\cos^2\alpha - \sin^2\beta)\,\cos^2\alpha}}\,u(\alpha)\right]^2 + \left[\frac{\cos\alpha\,\cos\beta}{\sqrt{(\cos^2\alpha - \sin^2\beta)\,\cos^2\alpha}}\,u(\beta)\right]^2}\ . \tag{22}$$

Since both angles are usually measured by the same accelerometer or accelerometers of the same type, for further analyses we can accept an assumption that

$$u(\alpha) = u(\beta) \tag{23}$$

and in this way, obtain a reduced form of Eq. (22) :

$$u_c(\gamma) = u(\alpha)\,\sqrt{\frac{\sin^2\alpha\,\sin^2\beta + \cos^2\alpha\,\cos^2\beta}{(\cos^2\alpha - \sin^2\beta)\,\cos^2\alpha}}\ . \tag{24}$$

A graphical illustration of Eq. (24) has been presented in Fig. 8, having assumed that uncertainty $u(\alpha)$ has a unitary value (note that since the terminal values of Eq. (24) grow to infinity, they have been limited to 5 on the figure).

As can be observed in Fig. 8, for small values of pitch (which is usually the case while performing single-axis tilt measurements) the considered uncertainty increases only slightly. Yet, in the case of higher values of pitch, it grows to infinity. However, such situation is related to the cases when the roll β is of about zero value, so it has no significant meaning in the case of measurements realized by means of MEMS accelerometers. Analogically to the case of Fig. 7, only the data on the left of the diagonal of the base of the cuboid are real; the irregular edge of the surface results from the digitization errors.

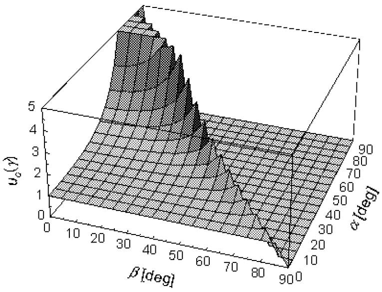

Fig.8: Graphical illustration of the uncertainty $u_c(\gamma)$

At this point, yet another shortcoming of measuring roll with a pitched sensor must be indicated. It is the cross-axis (or transverse) sensitivity of the tilt sensor. This parasitic sensitivity occurs in most of the tilt sensors (e.g., liquid sensors referred to in [18]), and is quite significant in MEMS accelerometers. In the related catalog data, e.g., [19, 20], it is estimated to be of 1 or 2 %. However, results of experimental studies carried out by the author [4] as well as other researchers [21] proved it to have a lower value. This can be explained by the fact that the value reported by the manufacturers is probably related to the highest accelerations detected, while in tilt measurements only a part of the measurement range of the accelerometer (i.e., 35 %) is used. Still another issue is a scatter of the metrological parameters within the production lot, which is quite significant in the case of MEMS devices, as it results from the data provided e.g. in [19, 20].

5. Experimental verification of the sensor accuracy

In order to evaluate accuracy of the roll measurements realized by MEMS accelerometers appropriate experimental studies have been carried out. In order to do it, a physical model of the tilt sensor was built. It consisted of dual-axis MEMS accelerometer ADXL 202E manufactured by Analog Devices, Inc. [20]. The experiments have been carried out using a simple rotary table applying the roll (with a resolution and 3-sigma uncertainty of $\pm 0.03°$) within the full range of the roll. The tested sensor was mounted in the movable table in such a way that its sensitive axes were precisely perpendicular to the rotation axis of the table (the precision has been achieved owing to a special aligning procedure minutely described in [22]). Various angular positions of the rotary table have been applied with a step of few degrees arc. Once a new angular position has been applied, the output signals from the tested sensor were read (by means of a computer data acquisition card, with a 3-sigma uncertainty of 0.0026 V) and then compared with the angular positions of the rotary table, providing thus information on the sensor accuracy. The methodologies of performing such experimental studies have been minutely described by the author in [22].

The obtained results are illustrated in Fig. 9. This time, the indication error expressed over axis y has been defined as follows:

$$e = |\beta_0 - \beta_{1..3}| \tag{25}$$

where β_0 is a value of the roll angle applied by means of the rotary table (the observed value) and $\beta_{1..3}$ is the value determined with respect to the average of respective indications of the tested sensor (i.e. the predicted value).

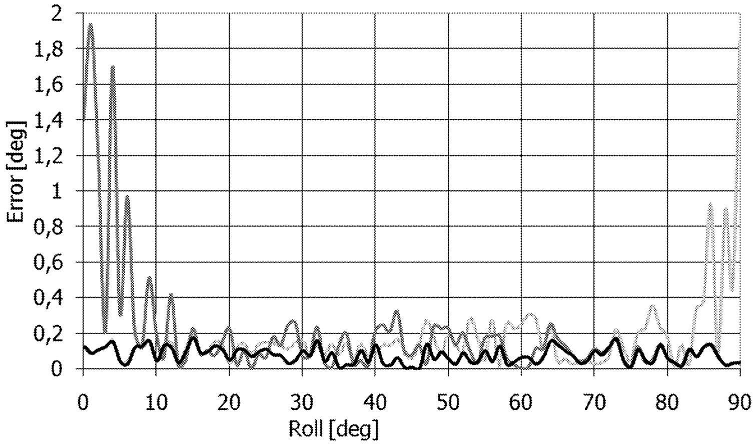

Fig.9: Error of determining the roll angle

With accordance to the color scheme used in Fig. 5, the light gray course in Fig. 9 corresponds to determining angle β_1 [calculated according to Eq. (4)], the dark gray course refers to determining angle β_2 [calculated according to Eq. (5)], whereas the black course is related to determining angle β_3 [calculated according to Eq. (6)]. As can be clearly observed, the highest accuracy of the measurements can be achieved in the case of using an arc tangent type of formula [i.e., Eq. (6)]. Moreover, slightly worse results can be obtained using a combination of the other two formulas, i.e.: an arc sine type of formula [i.e., Eq. (4)] for smaller values of the roll angle ($\beta < 45°$), and an arc cosine type of formula [i.e., Eq. (5)] for bigger values of this angle ($\beta > 45°$), as proposed in [4].

Over the whole measurement range of roll, the maximal values of the sensor errors related to different formulas reached:

- $0.18°$ for the arc tangent formula,
- $0.27°$ for the mentioned above combination of the arc sine and arc cosine formula,
- ca. $2°$ for both the arc sine and the arc cosine formula.

To summarize, it should be stated that the obtained results have proven the correctness of the proposed methods of determining tilt based on measuring three Cartesian components of the gravitational acceleration. Within the range of accelerometer sensitivity, the courses of the errors shown in Fig. 9 are consistent with the relevant theoretical curves presented in Fig. 5.

6. Conclusion

The author presented a theoretical approach to the metrological issues related to determining tilt over a single axis. The accepted idea of using for this purpose the components of the gravity vector allows a tilt sensor with miniature overall dimensions, made of MEMS accelerometers, to be applied. The proposed methods of determining tilt based on computing the Cartesian components of the gravitational acceleration ensure detection of tilt angles with the accuracy of ca. few tenths of a degree arc.

As it results from the presented theories and experiments, the most accurate measurements can be performed while using the arc tangent function. Yet, there are some cases when the arc sine function is more convenient, e.g. while calibrating the sensor or while measuring a small value of the roll using an accelerometer with a measuring range below ± 1 g [12].

However, it must be realized that the accuracy of a particular accelerometer is dependent on its design and quality, and is also influenced by many disturbances. In the case of MEMS accelerometers, the most important are their inherent instability and the ambient temperature, both causing drifts of the accelerometer bias and sensitivity [2, 19, 20]. Ways of dealing with these problems, as well as other considerations pertaining to improvement of the sensor performance, have been addressed by the author in [23].

The values of the errors reported in section 5 were not affected by the mentioned errors. Thus, when the influence of the disturbances is not limited, significant decrease of the best evaluated accuracy (to be of ca. $0.2°$) must be taken into account.

It is worthwhile mentioning that manufacturers of MEMS accelerometers have already dealt with some sources of indication errors, offering intelligent sensors. For instance, Analog Devices Inc. manufactures a Programmable Dual-Axis Inclinometer/Accelerometer ADIS 16201, which features, among other things: digitally controlled sample rate and frequency response, as well as sensitivity and bias calibration (including automatic zeroing and factory pre-calibration), embedded temperature sensor, digitally activated low power mode [24]. The only disadvantages of this sensor are its larger dimensions ($9.3 \times 9.3 \times 3.9$ mm) and significantly higher price (over $100).

Besides, an effective way of increasing accuracy of the roll measurements, due to redundancy of information, is to apply a tri-axial or a multi-axial accelerometer [7]. The spatial configuration of the sensitive axes of the accelerometer do not have to form a Cartesian coordinate system, however the sensor should be arranged in such a way, that none of them overlaps the axis, around which the sensor is rolled.

Even though single-axis measurements of tilt are much simpler than their dual-axis counterparts, there are some problems involved when the used tilt senor is being rolled under a pitch angle. If the pitch is overlooked, significant errors may occur. Unfortunately, even if it is respected, the accuracy of the considered measurements still decreases.

It must not be forgotten that a rapid progress in the main technologies used for fabrication of MEMS accelerometers will result in even better metrological parameters of the manufactured accelerometers, making these devices suitable for more and more demanding applications.

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