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Review Paper

Tilt Measurements in Mechatronic Devices and Mobile Microrobots

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A review of the author's own research on tilt measurements in mechatronic devices by means of micromachined accelerometers is presented. This comprehensive study addresses such issues as adjusting metrological properties of a tilt sensor for the application in a specific kind of a mechatronic device, systematizing problems pertaining to tilt measurements, applying various methods of decreasing uncertainty of tilt measurements, performing related experimental studies using custom test rigs, and building novel prototypes of tilt sensors. Due to the implementation of the proposed measurement techniques, considerations and novel ideas, it is possible to determine tilt either in a much simpler way, which translates to lower cost, or much more precisely, depending on particular requirements to be satisfied.

Key words: tilt; MEMS; accelerometer; mechatronics; accuracy.

1. Introduction

Tilt measurements have accompanied the mankind for a very long time – it may be even said that from the very beginning, as one of the human senses is equilibrioception. Definitely, the importance of this type of measurements increased along with the development of aviation, because of the spatial nature of the motion of flying objects. Nevertheless, this subject matter has been an important research topic, especially over the last years, when low-cost integrated micromachined sensors (micro-electro-mechanical systems – MEMS accelerometers, gyroscopes, magnetometers and altimeters) became commercially available, what enabled to build miniature inertial orientation systems based on these devices.

Author's own contribution to the development of research on problems pertaining to the construction of tilt sensors for mechatronic devices has begun while completing M.Sc. diploma [1] and Ph.D. dissertation [2]. Further research considered, first of all, the elaboration of appropriate techniques of related experimental studies and application of microsystems.

The subject matter pertaining to the application of microsystems is very interesting and topical, since sensors of this type have been applied in an increasing number of various kinds of electronic and mechatronic devices, of which many became sophisticated measurement systems. As far as developed countries are concerned, almost every human has become a user of MEMS sensors (smartwatches, devices with electronic compass – e.g., diving watches and computers, cellular phones, tablets, laptops, navigation systems, etc.). Moreover, MEMS sensors sometimes play a very important role, influencing directly human safety. A good example is the automotive industry employing MEMS inertial sensors in airbags or enhanced ABS-systems for motorcycles [3].

With regard to mechatronic devices, especially those of miniature dimensions of few tens of millimeters (e.g., small mobile robots) in which tilt measurements are to be performed, we deal with essentially different requirements regarding the features of the applied tilt sensor:

- operation conditions (static, quasi-static, dynamic),
- type of measurement (single-axis or dual-axis),
- measurement range (from few degrees of arc to full angle),
- measurement accuracy (usually of few tenths of a degree of arc),
- maximal overall dimensions (sometimes of few millimeters).

As a result of Author's own research, in most of the cases, mainly due to their advantages (i.e., miniature dimensions, low cost, easy integration with electronics, high shock-resistance, high reliability, satisfactory accuracy, and low power consumption), the most convenient solution is to employ MEMS sensors: an accelerometer, first of all, or additionally a gyroscope and a magnetometer. Because of dynamic technological development in the field of microsystems, these sensors are also the most interesting with respect to experimental studies. Application of a gyroscope, and possibly also a magnetometer, makes it possible to conduct tilt measurements under any conditions, including dynamic conditions, whereas the latest proposals connected with application of accelerometers operating in a differential measurement system [4] enable to achieve very high measurement accuracy, even of few seconds of arc [5]. Using more and more sophisticated techniques of data fusion (based on the application of various kinds of filters: complementary, Kalman, Madgwick) allows obtaining accuracy featured by accelerometers under static conditions over a wider bandwidth, as it was proposed, e.g., in [6].

Development of measurement systems based on MEMS sensors, also with respect to inertial measurement units (IMUs) composed of accelerometers, vibratory gyroscopes, magnetometers, and sometimes even temperature sensors and pressure sensors (altimeters) [7, 8], used for determining tilt will take place in the nearest future within the following areas:

- improving designs of MEMS accelerometers and gyroscopes, aimed at ensuring higher accuracy of measurements and wider bandwidth,
- improving measurement methods employing MEMS accelerometers,
- improving measurement methods employing MEMS gyroscopes,
- increasing range of dynamic operation of the accelerometers owing to the fusion of data generated by various types of sensors (sensor fusion).

The presented review refers to making a considerable contribution to the first two areas.

The conducted research work made it possible to systemize the problems pertaining to determination of tilt angles, to improve measurement methods connected with determination of this mechanical quantity by means of MEMS accelerometers, to elaborate a methodology of performing experimental studies of physical models of this type of sensors, and to create advanced algorithms for realization of tilt measurement. Additionally, these studies enabled to study MEMS accelerometers more thoroughly with respect to their metrological properties (effects of aging, mechanical hysteresis, and nonorthogonality of sensitive axes), which gained little attention in the relevant publications, and thus the related information is not provided in a satisfactory measure.

Owing to the realized studies, few original design solutions of tilt sensor based on the application of MEMS accelerometers were proposed, which made it possible (owing to the proposed design solutions) to obtain a high measurement accuracy (of ca. 0.2°). Prototypes of these solutions were built during the completion of M.Sc. diplomas projects under Author's supervision.

2. Measurements of tilt

This review mainly addresses tilt measurements. These measurements are commonly performed while realizing tasks such as [9]:

- leveling (low measurement range, very high accuracy),
- navigation and orientation systems (large or full measurement range, low accuracy),
- attitude-control systems for objects of large dimensions, e.g., heavy construction equipment (low measurement range, average accuracy).

As far as mechatronics is concerned, among the most popular applications of tilt sensors are various kinds of mobile robots [10], featuring often miniature overall dimensions, as in the case of designs proposed in [11, 12].

Various types of these sensors are employed in such measurements. These types can be divided into three basic groups: gravitational, gyroscopic and magnetic. Each group has its advantages and disadvantages. The most numerous group are gravitational sensors due to a possibility of obtaining a simple structure of the sensor. However, their main drawback is being incapable of operating under dynamic conditions. Some of these sensors can operate at most under quasi-static conditions – e.g., sensors based on MEMS accelerometers [13]. However, under such conditions one must take into account bigger errors such as unstable amplitude and phase characteristic over the frequency-domain [14], which result from imperfections of these sensors.

Liquid sensors are the most popular in this group, especially spirit levels, widely used, e.g., in shop scales. However, recently, it has become more and more common to use MEMS accelerometers in this type of measurements because of their extremely low price (as low as 5 Euros) and a rapidly increasing number of various PDA devices (smartphones, tablets, palmtops, etc.). However, the relevant publications presented much earlier (e.g., [15] in 2005) pointed out to tilt measurements as one of the primary applications of accelerometers.

At this point, it is worthwhile mentioning that one of the human senses is the vestibular sense located in the inner ear. In a technical sense, it may be said that it uses two pairs (left and right ear) of triaxial accelerometers (utricle and saccule) and two pairs of triaxial gyroscopes (semicircular canals). Due to this fact, it can be concluded that the application of accelerometers in tilt measurements is a reasonable solution, being a direct reference to the structure of such a perfectly created system as the human organism. An exact reference to this concept takes place when accelerometers work with gyroscopes, as it is in the case of the aforementioned IMUs – including their integrated versions.

An additional advantage of applying an accelerometer is a capability of measuring accelerations acting upon the mechatronic device in which the accelerometer is applied. Due to an appropriate technique of filtering, it is easy to determine a variable acceleration, whereas in the case when additional information on the orientation of the device is available (e.g., owing to application of gyroscopes), it is possible to determine also constant accelerations. Besides, it is worthwhile mentioning that the gravitational acceleration is one of the most stable reference sources available [16].

In a general case, tilt measurement consists in the determination of its two component angles [17, 18]: pitch and roll, as illustrated in Fig. 1 (the cuboid in the middle of the coordination system represents a MEMS accelerometer).

Relations between the component tilt angles themselves can be expressed as [25]

$$\gamma_1 = \arcsin\left(\frac{\sin\beta}{\cos\alpha}\right), \tag{2.1}$$

$$\alpha = 0 \Rightarrow \gamma_1 = \beta. \tag{2.2}$$

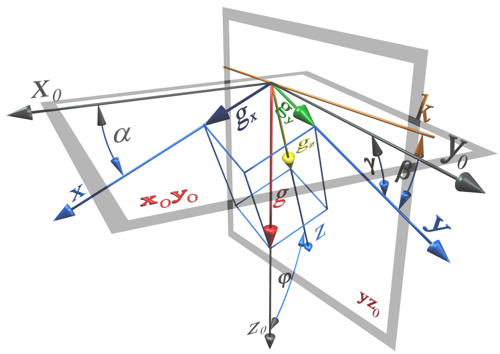

Fig. 1. Component tilt angles *versus* components of the gravitational acceleration: **g** – gravitational acceleration, g_x, g_y, g_z – Cartesian components of the gravitational acceleration **g**, α – pitch, β – alternative roll, γ – roll (defined according to the aeronautical standard [19]); φ – arbitrarily oriented tilt (axial tilt).

Basic relations between the component tilt angles and components of the gravity acceleration are as follows (the introduced subscripts correspond to the respective type of mathematical function) [30]:

$$\alpha_1 = \arcsin \frac{g_x}{g}, \tag{2.3}$$

$$\alpha_2 = \arccos \frac{\sqrt{g_y^2 + g_z^2}}{g}, \tag{2.4}$$

$$\alpha_3 = \arctan \frac{g_x}{\sqrt{g_y^2 + g_z^2}}, \tag{2.5}$$

$$\beta_1 = \arcsin \frac{g_y}{g}, \tag{2.6}$$

$$\beta_2 = \arccos \frac{\sqrt{g_x^2 + g_z^2}}{g}, \tag{2.7}$$

$$\beta_3 = \arctan \frac{g_y}{\sqrt{g_x^2 + g_z^2}}, \tag{2.8}$$

$$\varphi_1 = \arcsin \frac{\sqrt{g_x^2 + g_y^2}}{g}, \tag{2.9}$$

$$\varphi_2 = \arccos \frac{g_z}{g}, \tag{2.10}$$

$$\varphi_3 = \arctan \frac{\sqrt{g_x^2 + g_y^2}}{g_z}. \tag{2.11}$$

Moreover, additionally:

$$\gamma_3 = \arctan \frac{g_y}{g_z}. \tag{2.12}$$

More sophisticated relations between the component tilt angles and components of the gravity acceleration were proposed. The relations are a simple combination of Eqs. (2.3) and (2.4), (2.5) and (2.6) or (2.9) and (2.10), respectively, or a weighted average of these equations; they regard component angles α, β and φ in the same manner. So, let any of the angles α, β and φ be denoted ψ with a subscript corresponding to the respective equation. Then, the following additional formulas can be obtained [30]:

$$\left\{ \begin{array}{c} \psi_1, \psi_2 < 45^\circ \Rightarrow \psi_4 = \psi_1 \\ \psi_1, \psi_2 > 45^\circ \Rightarrow \psi_4 = \psi_2 \end{array} \right\}, \tag{2.13}$$

$$\psi_5 = \psi_1 \cdot \cos^2 \psi_4 + \psi_2 \cdot \sin^2 \psi_4. \tag{2.14}$$

However, in the case of axial tilt φ, Eq. (13) must be slightly rearranged, as follows:

$$\left\{ \begin{array}{c} \psi_1, \psi_2 > 45^\circ \Rightarrow \psi_4 = \psi_1 \\ \psi_1, \psi_2 < 45^\circ \Rightarrow \psi_4 = \psi_2 \end{array} \right\}. \tag{2.15}$$

The fact that the relevant literature is inconsistent with regard to defining the roll angle (angles β and γ presented in Fig. 1 are identical only in a specific case expressed by Eq. (2.2)) was indicated in [20]. There were analyzed errors that may result from such situation and a variable uncertainty of measurement resulting from the conversion of β angle into γ angle was also discussed.

In order to determine component tilt angles on the basis of values of Cartesian components of the gravitational acceleration, various inverse trigonometric functions can be used [21–23]. Analyzing variability of the uncertainty of tilt measurement while employing two such functions (Fig. 2a – assuming a theoretical value of the relative uncertainty of determining acceleration equal to 1%), in [24] there was proposed the use of a combination of arc sine and arc cosine function: in the angular range $\langle 0^\circ, 45^\circ \rangle$ arc sine function is employed, whereas in the angular range $\langle 45^\circ, 90^\circ \rangle$ arc cosine function is used (Fig. 2b – assuming a theoretical value of the relative uncertainty of determining acceleration equal to 1%). Application of this method is advantageous in three ways. First, the uncertainty of measurement considerably diminishes (both curves presented in Fig. 2a approach infinity). Second, the required measurement range of the accelerometers decreases by ca. 30%, what enables a further increase of measurement accuracy. In the case of determining tilt under such conditions when

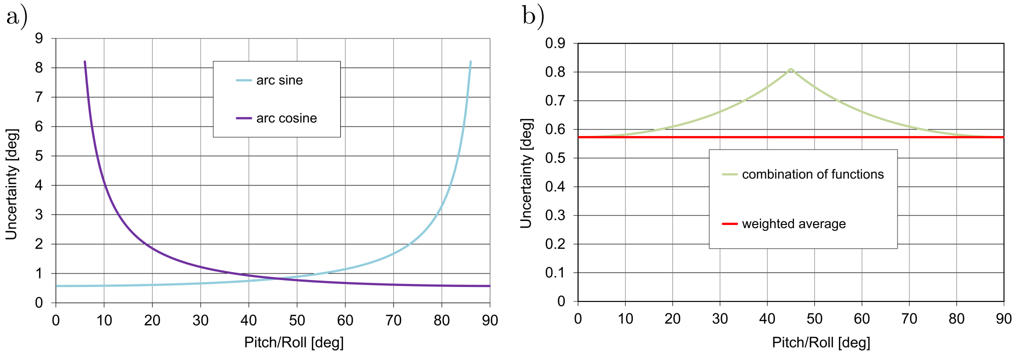

FIG. 2. The relative uncertainty of determining tilt (pitch, roll or axial tilt).

the accelerometer is subjected to vibration, the proposed method makes it possible to apply accelerometers featuring measurement range smaller than it results from the sum of the magnitude of gravitational acceleration and the amplitude of vibration. Third, by ensuring an appropriate spatial configuration of the accelerometer it is possible to obtain the full measurement range in dual-axis tilt measurements, having only two sensitive axes of the accelerometer (then arc sine function is assigned to pitch and arc cosine to roll, or vice versa) [25].

The combined uncertainty related to the particular type of mathematical formula can be expressed as [30]:

$$u_c(\psi_1) = \frac{u(g_{x...z})}{|g|}\frac{1}{\cos\psi_1}, \tag{2.16}$$

$$u_c(\psi_2) = \frac{u(g_{x...z})}{|g|}\frac{1}{\sin\psi_2}, \tag{2.17}$$

$$u_c(\psi_3) = \frac{u(g_{x...z})}{|g|} = \text{const} \approx u_c(\psi_5). \tag{2.18}$$

In the case of the combined uncertainty $u_c(\psi_4)$, a formula consistent with Eqs. (2.13) or (2.15) applies.

A further development of this idea, which consisted in combining arc sine and arc cosine functions on the basis of a weighted average with variable weight coefficients, was presented in [26]. As a result, a further decrease of the relative uncertainty of measurement by ca. 30% (Fig. 2b) can be achieved. Admittedly, the same effect can be obtained using another inverse trigonometric function. However, the application of the weighted average is especially justified in the case of employing triaxial MEMS accelerometers, which feature anisotropic metrological properties (their vertical sensitive axis is usually characterized by higher noise compared to the horizontal axes, and in some cases by bigger perpendicularity errors), what results from the fact that the manufacturing processes used for fabrication of MEMS accelerometers (usually surface or bulk technology [27] – although other methods are also applied, such as, e.g., LIGA or SLIGA technology [28]), are in fact pseudo-three-dimensional technologies [29]. Taking into account the aforementioned anisotropy by an appropriate selection of the weight coefficients, a further increase of accuracy of determining tilt is then possible.

All the possible methods of determining tilt, using this time the sensitivity of such measurement (Figs. 3a and 3b – analogous to Figs. 2a and 2b) were compared in [30]. This can be determined according to the following relations [30]:

$$k_1 = g\cos\psi_1, \tag{2.19}$$

$$k_2 = g\sin\psi_2, \tag{2.20}$$

$$k_3 = g = \text{const} \approx k_5. \tag{2.21}$$

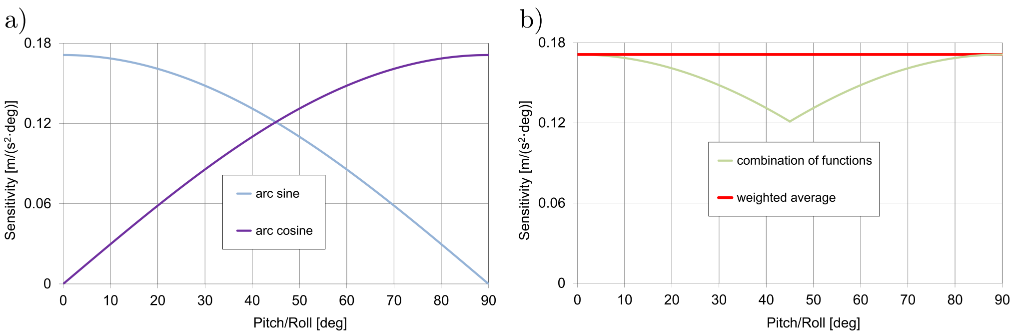

Fig. 3. The sensitivity of tilt measurements.

In the case of the sensitivity of determining ψ_4, a formula consistent with Eqs. (2.13) or (2.15) applies, whereas, in the case of determining roll γ, the following relations (derived from Eqs. (2.1) and (2.12), respectively) must be used [25]:

$$k_{\gamma 1} = g\cos\alpha\sqrt{\frac{\left(\cos^2\alpha - \sin^2\beta\right)}{\sin^2\alpha\cdot\sin^2\beta + \cos^2\alpha\cdot\cos^2\beta}}, \tag{2.22}$$

$$k_{\gamma 3} = g\cos\alpha. \tag{2.23}$$

In the case of theoretical considerations presented in [24, 30], their experimental verifications (Fig. 4), which clearly confirm the legitimacy of applying the proposed measurement methods, were demonstrated. The obtained results are fully consistent with the theoretical courses of the relative uncertainty of

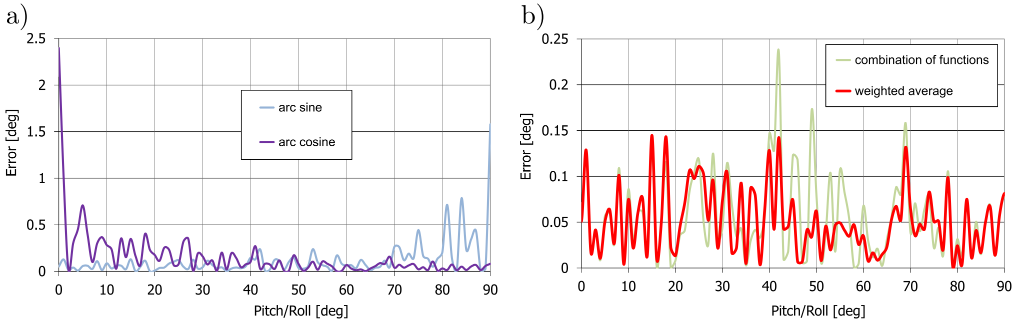

FIG. 4. Results of experimental studies.

measurement related to the tilt angles (pitch and roll) as well as the courses of the measurement sensitivity, illustrated in Figs. 2 and 3.

The error illustrated in Fig. 4 was determined as follows [30]:

$$e_n = |\delta - \psi_n| , \tag{2.24}$$

where δ is the component tilt angle applied by means of the test rig (see Fig. 5), and ψ is the corresponding component tilt angle computed on the basis of the output signals of the tested tilt sensor, according to respective formula (see Eqs. (2.3)–(2.15)).

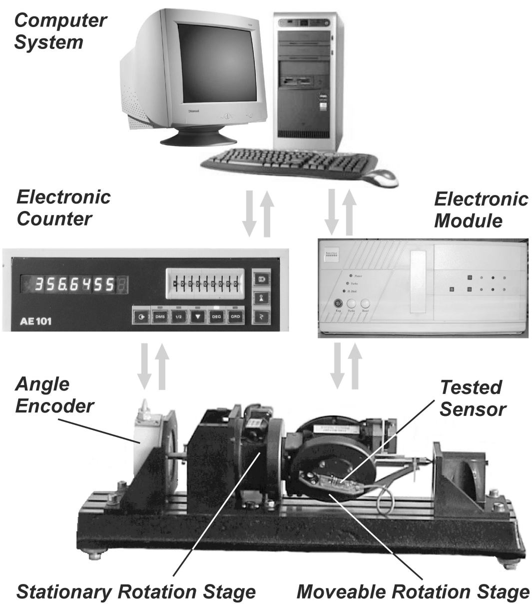

FIG. 5. Test rig employing standard rotation stages [50].

The most crucial properties of the considered measurement methods are listed in Table 1 (accepting that an approximated value of the gravitational acceleration $g = 10$ m/s^2).

Table 1. Properties of various measurement methods of determining tilt.

Function	A	B	C	D	E	F
arc sine: (2.3), (2.6), (2.9)	1–∞	10–0	1	2	$\geq \pm 10$	low
arc cosine: (2.4), (2.7), (2.10)	∞–1	0–10	1	2	$\geq \pm 10$	low
arc tangent: (2.5), (2.8), (2.11)	1	10	2	3	$\geq \pm 10$	low
combination of arc sine and arc cosine: (2.13), (2.15)	1–1.4	10–7	2	3	$\geq \pm 7.1$	medium
weighted average: (2.14)	~ 1	~ 10	2	3	$\geq \pm 10$	high

A – Relative uncertainty, B – Sensitivity [m/(s^2·rad)], C – Required no. of accelerometer sensitive axes in single-axis tilt measurement, D – Required no. of accelerometer sensitive axes in dual-axis tilt measurement, E – Required measuring range of the accelerometers [m/s^2], F – Complexity of the computational algorithm.

In [30] Author pointed out to a dependency between the number of accelerometer sensitive axes and the measurement range of the tilt sensor, as well as the resulting measurement sensitivity. The related data are listed in Table 2.

Table 2. Measurement ranges and values of the sensitivity of accelerometer-based tilt sensors.

Kind of measurement	Number of sensitive axes of the accelerometer							
	1		2		3		4	
	A	B	A	B	A	B	A	B
Single-axis	±90°	≤ 10	±180°	10	±180°	≥ 10	±180°	≥ 10
Axial tilt	⟨0°, 180°⟩	≤ 10	±180°	10	±180°	≥ 10	±180°	≥ 10
Dual-axis	–	–	±90°	≤ 10	±180°	10	±180°	≥ 10

A – Measurement range [deg.], B – Rounded value of measurement sensitivity [m/(s^2·rad)].

An additional case of determining tilt, which was called an axial tilt was defined in [31]. Accordingly to its definition, the measurement methods discussed above were modified. This case is interesting in such applications as, e.g., attitude control or directional drilling [32, 33]. Additionally, it can be applied as an alternative in single-axis tilt measurements. Then, owing to activation of all the sensitivity axes, by sensing the three Cartesian components of the gravitational acceleration, it is possible to diminish the measurement errors. However, as it results from Author's experiments, a very crucial issue, in this case, is compensation for the existing errors of perpendicularity between particular sensitivity axes. Even more important is the fact that employing such spatial configuration of the accelerometer reduces effects of misalignments of its particular sensitivity axes considerably, as minutely discussed in [34], which also results in an improvement of the sensor accuracy.

In [35] Author proposed to introduce some modifications in the mechanical structure as well as in the electronic circuits of MEMS accelerometers in order to improve their operational parameters. Some of the proposed improvements are currently implemented by some manufacturers of MEMS sensors (i.e., built-in temperature sensors [7, 8], built-in algorithms of converting the measured acceleration into values of the component tilt angles (pitch and roll) [4, 36]).

Other original proposed ideas have not been implemented in commercial MEMS accelerometers so far. However, since some of Author's proposals (e.g., application of integrated microwave ovens, integrated detectors of zero acceleration and acceleration corresponding to the measurement range) may considerably improve operation of MEMS accelerometers, it is probable that similar innovations will be introduced in future, in such sensors as, e.g., ADIS-type intelligent accelerometers manufactured, e.g., by Analog Devices Inc. [36]. It is worthwhile to mention that the aforementioned ideas can also be implemented while designing new MEMS gyroscopes.

Additionally, in [35] the application of immovable reference accelerometers in order to compensate for errors such as thermal and long-term-drifts of the offset and the scale factor was also proposed. A kind of variation of Author's idea was implemented in the aforementioned differential tilt sensor presented in [5]. Besides, a benefit resulting from the application of a multi-axial accelerometer in tilt measurements using an example of the original design of a MEMS accelerometer presented in [37], was discussed in [26]. The benefit is an increase of accuracy of determining tilt by approximately 13% (in this particular case).

An original algorithm of computing the component tilts angles based on the application of arc tangent-type of function was proposed in [38]. The algorithm employs accelerometer parameters determined in the process of its calibration (offsets, scale factors, angular phase shifts), and verifies the condition for operation under quasi-static conditions. At the same time, Author also pointed out to impossibility of verifying the aforementioned condition when no additional information is available. In addition, this algorithm enables the elimination of errors that may appear in some specific angular positions and the recalculation of the determined values of tilt angles into the full measurement range.

3. Experimental studies of tilt sensors

Despite the common use of MEMS accelerometers in many various devices, there still remain sensors that feature many shortcomings. However, the manufacturers have introduced more and more improvements to the physical structure of the accelerometer itself, as well as developed the electronic circuits processing its output signals. First of all, they have implemented a compensation for systematic errors (such as temperature drifts, misalignments, aging effects, etc.) owing to the performance of experimental works, making it possible to increase the accuracy of the tested accelerometers.

In this type of research, two kinds of test rigs are employed: test rigs composed of standard components, as, e.g., in [39–42], or custom equipment, as, e.g., in [43]. However, the second option is used much more rarely due to high costs.

In the case of using MEMS accelerometers in tilt measurements, it is quite difficult to determine the accuracy of such measurements on the basis of parameters provided in their datasheets. Therefore, two parameters determining the accuracy of indications of a tilt sensor: the difference between the observed and the predicted value [45] (i.e., a value applied by means of the test rig and a value calculated on the basis of the accelerometer output signals) as well as a value determined on the basis of prediction or confidence interval, obtained by means of a calibration model [46], were proposed in [24, 44].

Analyzing the related publications Author learned that the test rigs used in the reported research did not always satisfy relevant requirements and that the researchers usually did not pay enough attention to this issue. Application of an improper test rig results not only in obtaining erroneous numeric data but sometimes in a completely improper interpretation of the obtained results, as, e.g., in the case of the experimental study reported in [47]. Metrological parameters of this test rig built of standard rotation stages (Fig. 5) was described in detail [48] because of the aforementioned gap in the relevant literature. Capabilities of its reasonable development were indicated (aimed at improvement of its metrological properties). Such kinds of tests of tilt sensors and MEMS accelerometers, which can be realized by means of the test rig, were specified. Author also proposed few ways of increasing the accuracy of measurements of output voltages generated by analog MEMS accelerometers as well as measurements of the angular position applied by means of the test rig.

Authors of the related publications refer to various methods of calibrating MEMS accelerometers, which determine the resultant accuracy of their indications, including two methods being the most popular: using only extreme indications of the accelerometer or rotating the accelerometer about a horizontal axis. However, according to Author's knowledge, nobody tried to compare these methods, specifying their advantages, disadvantages and limitations. Therefore, in [49], a decision was made to fill that significant gap by comparing these two calibration methods, being the most popular, and proposing alternative solutions. It was proved that under appropriate conditions, both methods yield similar results. However, in the case of using only the extreme indications of the accelerometer, considerable limitations must be taken into account, especially in the case of tilt measurements.

In [44] Author pointed out to the fact that values of factory perpendicularity errors between the sensitive axes of MEMS accelerometers provided in their data sheets may be underestimated in some cases. Therefore, an original technique of their experimental determination was proposed. Based on Author's own research and the experimental results published by other researchers, e.g., in [43], Author observed that in the case of cross-axis sensitivity situation is quite opposite – the catalog values of this parameter are overestimated, what may result from a large scatter within a given production lot or perhaps its dependency on the used measurement range.

Since acceleration is a vectorial quantity, much attention was paid to the alignment of sensitive axes of accelerometers, as this is very crucial. It significantly influences not only the accuracy of tilt measurements [51] but also the results of the calibration process of accelerometers [52]. Effects of misalignment of the sensitive axis of the accelerometer with respect to axes, about which it is tilted were analyzed in [34]. Consequently, few design solutions of special aligning holders were proposed, whose prototypes and models were elaborated under Author's supervision. They are presented in [48, 34], and one of them is pictured in Fig. 6. It enables the realization of aligning movements by applying angular displacements about the three Cartesian axes. Author also proved that misalignment of accelerometer sensitive axes is a considerable source of errors [44] and that in the case of MEMS accelerometers it also results from nonorthogonality of their sensitive axes, whose value is usually of ca. few tenths of degree of arc (however, sometimes it exceeds even 1° – as it was found out on the basis of Author's own experimental studies of triaxial MEMS accelerometers).

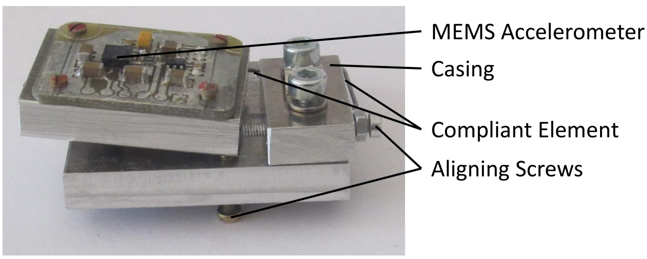

Fig. 6. Precise miniature aligning holder.

Even though the holder considerably simplifies the aligning procedure, it is still a toilsome task. Therefore, a fast and effective method for aligning sensitive axes of accelerometers was proposed [53].

4. Experimental studies of MEMS accelerometers

In [54] determination of mechanical hysteresis of MEMS accelerometers was disputed over. The reference point was the publication [47]. On the basis of Author's own experimental study as well as appropriate statistical analysis, it was proved that the problem of determining mechanical hysteresis was erroneously presented in [47].

First, it was proved that the applied test rig composed of standard rotation stages driven by stepper motors did not fit for this purpose due to the generated vibration (with amplitude exceeding 1.2 g), its own mechanical hysteresis and unsatisfactory accuracy of angular positioning. Nevertheless, some necessary modifications enabling application of this type of test rig in the considered study were also specified.

Secondly, it was demonstrated that the apparent hysteresis loop presented in [47] (illustrated in Fig. 7) did not result from the hysteresis phenomena at all, but from the accepted method of calibration of the tested MEMS accelerometer, which in this case was inadequate since it disregarded the existing angular phase shift between indications of the tested sensor and measurement scale of the test rig.

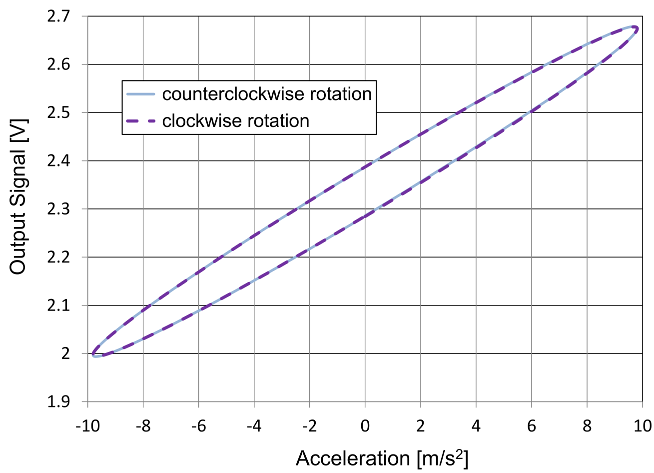

Fig. 7. Apparent hysteresis loop of a dual-axis MEMS accelerometer.

A test rig built under Author's supervision, which was free of the aforementioned shortcomings (Fig. 8), was presented. Owing to the experiments performed using this test rig, it turned out that mechanical hysteresis is a phenomenon of small significance in the case of MEMS accelerometers, both biaxial and triaxial ones.

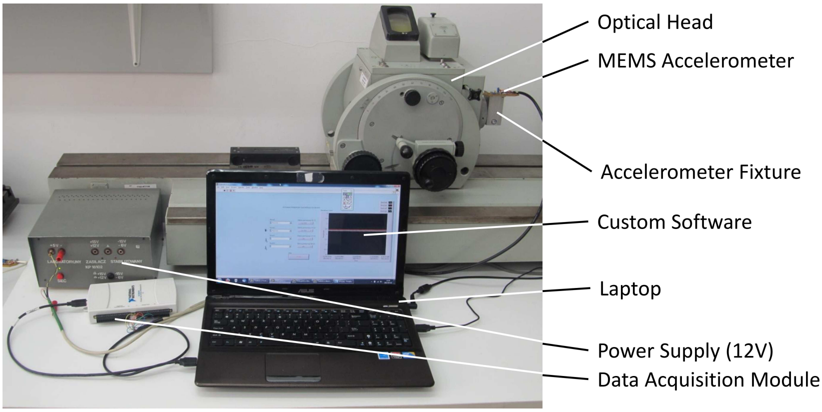

Fig. 8. Test rig for testing hysteresis of MEMS accelerometers.

Exemplary results obtained using a test rig shown in Fig. 5 are presented in Fig. 4, whereas the test rig shown in Fig. 8 made it possible to obtain results illustrated in Fig. 8.

5. Prototypes and designs of novel tilt sensors

Owing to results of Author's own research, it was observed that using only extreme indications of accelerometer could ensure the satisfactory accuracy of its calibration [49], and thus an original design of a tilt sensor having a cubical casing, whose walls are characterized by relatively high flatness and orthogonality was proposed. The casing is to be manufactured using a 3D printing technique.

Two prototypes of such sensor, having dimensions of $40 \times 48 \times 48$ mm (Fig. 9a) or $90 \times 68 \times 45$ mm (Fig. 9b), were built during the completion of two M.Sc.

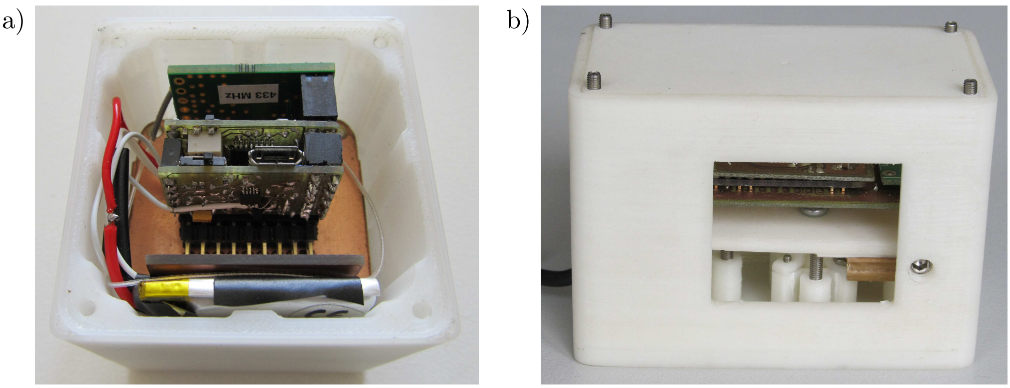

Fig. 9. Sensor prototypes with a cubical casing made of polymer using 3D printing: a) wireless version, b) wired version.

diploma projects [55, 56] personally supervised by Author. These prototypes enabled an easy and fast realization of this type of calibration. Owing to possibility of repeating on demand a fast and simple calibration procedure of the sensor, it is possible to obtain its high accuracy by eliminating (instead of only compensating for, as it is in the case of commercial sensors) the most significant errors of MEMS accelerometers, i.e., temperature and long-term drifts of the offset and the scale factor assigned to particular sensitive axes of the applied accelerometer.

The created prototypes of tilt sensor feature wireless or wired transmission of the measurement signals. A similar idea of a tilt sensor was presented in a recently published article [57]; however, few important issues were overlooked by the authors (e.g., additional machining of the casing base).

Based on the proposed concept, it is possible to build many various versions of the sensor adjusted to a certain application. They may differ in the following: kind of transmission of the signal from the measuring head, its casing (as aforementioned), number of the applied measuring heads, type of the applied MEMS accelerometers, and additionally type of a system processing the measurement data (PC, smartphone, custom microprocessor system, standard microcontroller).

At the present stage of research on the development of the sensor, application of a standard microcontroller system (Fig. 10a) for processing the data transmitted from the measuring head was recognized as the most advantageous solution. The system was additionally equipped with a Wi-Fi module (Fig. 10b), which enables wireless transmission of the processed data to PC, and an RF

a) b)

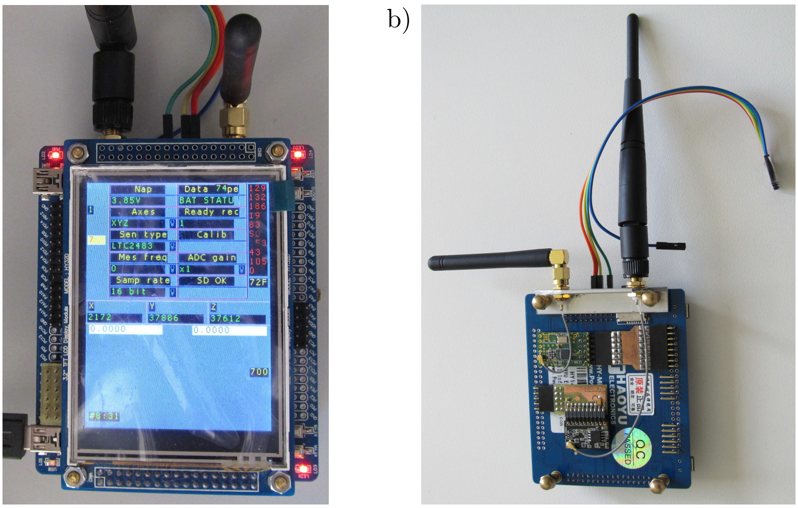

Fig. 10. Standard microcontroller system for processing data from the sensor: a) graphical touch-panel, b) additional Wi-Fi module and RF module.

module enabling communication with the measuring head. The cost of building the whole measurement system is relatively small, ca. 150 Euros.

In the final version of the sensor, the implemented algorithms for determination of tilt angles will comprise most of the ways of increasing accuracy of the related measurements proposed so far (employing various inverse trigonometric functions, aligning of the accelerometer, regarding anisotropy of triaxial MEMS accelerometers, determination of axial tilt in single-axis tilt measurements).

Besides the aforementioned problems, Author also dealt with tilt measurements within a small measurement range. As a result, two designs of a tilt sensor based on MEMS accelerometer were proposed, which make it possible to obtain an increased accuracy of indications in the case of such measurements [58]. A case of tilt measurement, where an accelerometer of smaller measurement range is employed was discussed [59], similarities between computing component tilt angles and interpolation of signals of incremental sensors within scale period were pointed out in [60]. A sophisticated algorithm for determining tilt using the proposed method based on the application of weighted average was presented in [61], and the combination of various mathematical relations was described in [62].

A dependency of properties of a tilt sensor on the spatial configuration of the applied accelerometers and on their initial angular position was analyzed in [25]. In the case when it is not required to obtain equal measurement accuracy for both pitch and roll, or in the case of single-axis tilt measurements, Author has defined appropriate spatial configurations of triaxial accelerometers, which make it possible to reduce the decrease of measurement accuracy due to their anisotropy [25]. Moreover, Author also proved that effects of the aging phenomena within the silicon structure of MEMS accelerometers are a source of considerable errors (up to 0.8–2.5%) [63, 64], and proposed an original method of limiting the errors [63].

As far as Author's early works are concerned, a novel design of a contact cuboid tilt sensor, employing a ball as the sensitive element [65] and a design of a flexible tilt sensor employing strain gauges [66] were elaborated.

6. Conclusions

The most important scientific achievements related to the presented research regarding tilt measurements by means of MEMS accelerometers are the following:

- proposal of tilt measurements employing data fusion [2, 24, 26, 30, 31, 59–62] – in this way, it is possible to regard anisotropic metrological properties of triaxial MEMS accelerometers and decrease their required measurement range, and thus to increase accuracy of determining tilt, up to few tens of percent in some cases;

- proposal of other original methods making it possible to increase the accuracy of determination of tilt by few percents or more [25, 26, 34, 35, 38, 44, 49, 62, 63];
- systemization of problems pertaining to the determination of tilt and optimization of the related measurements [2, 20, 24, 25, 30, 31, 34, 38, 62];
- elaboration of novel techniques of experimental studies (methodology, test rigs) of tilt sensors and MEMS accelerometers [34, 44, 48, 49, 53, 54];
- elaboration of a novel technique of testing mechanical hysteresis of MEMS accelerometers [54];
- novel designs of tilt sensors [1, 35, 58, 65, 66].

A considerable part of the above presented research is of the original character. The most innovative, in Author's opinion are: the proposal of computing tilt angles on the basis of data fusion (combination of functions or weighted average) and specifying application of these methods (tilt measurements under quasi-static conditions, compensation for anisotropic properties of triaxial MEMS accelerometers); that enables to increase accuracy of determining tilt even by few tens of percent. Another innovation is the proposal of a design of tilt sensor employing a casing that enables its fast calibration and precise initial alignment, keeping manufacturing costs low and ensuring high accuracy of indications at the same time.

Many original algorithms for autocalibration of MEMS accelerometers were proposed in recent years, e.g., in [57, 67–70]. It is planned to compare errors related to these algorithms. The earliest relevant publications evaluated errors related to this type of calibration at a quite high value of ca. 3% [70]. However, at present, it is often the case that such numerical data are not reported.

It should be emphasized that the results of the presented research are applied in practical usage of tilt measurements. Hopefully, in the nearest future, some of the effects of the discussed studies will be implemented. Then, a larger circle of technicians, engineers and R&D workers may be able to benefit from the presented achievements.

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