ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/01.3001.0010.2832

MULTIAXIAL TRANSDUCERS CALIBRATION

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Abstract

The aim of present article is investigating properties of accelerometer calibration method, called automatic calibration. The research of transducer's model was conducted and chosen optimization algorithms were rated by the simulation method and also using real transducer. The aim of tests was examination of the possibility to find parameters of the transducer model considering influence of temperature and deviation of axes. Described optimal calibration process without special calibration apparatus considers also influence of temperature on acceleration measurement. Afterward, described calibration method was tested on real transducer. Obtained results show that the hybrid two-step algorithm is suitable to the multiaxial transducers calibration.
In the research, accelerometer as triaxial transducer was chosen and subjected to tests and the results of simulation was recorded in the MATLAB workspace. From existing estimation, three algorithms were chosen: the quasi-Newton, simplex (Nelder-Mead), and Levenberg-Marquard. The experimental part of the calibration utilized the idea of using existing and known constant vector of the measured value like gravitational acceleration and magnetic field. Calibration with temperature compensation of real transducer was presented.

Keywords: *accelerometer, calibration, auto-calibration, nonlinear regression*

1. Introduction

Today many variables, which are vectors, can be measured by multiaxial transducers. The MEMS technology makes possible to design and use in the volume production triaxial transducers for the acceleration, angular rate and also magnetic field. It is also possible to integrate the various transducers in one SMT package with the micro-controller and one digital interface for all of them. The mentioned variables are components of the state of the various vehicles (flying, swimming, driving and walking) giving the data necessary to compute orientation and position of the vehicle. The devices, which produce the orientation and position data, are AHRS (attitude and heading reference system) and INS (inertial navigation system) and also hybrid systems where the mentioned measurements are supportive to another one like that obtained from receivers of navigation satellite systems.

Every measurement transducer should be calibrated to meet the measurement standards. In the case of triaxial transducers the measured value is a vector which tree components depends on the values perpendicular to the appropriate measurement axis (in the article the axis transducer will mean the part which responds on the one axis component). It should be considered that the output depends also on the disturbances. The temperature of transducer, which is not constant, is the most influencing disturbance. The transducers for the AHRS and INS should be thermally compensated or sometimes thermally stabilised. The thermal compensation is more challenging in the stage of calibration but it is more energetically effective in the operation [1, 2].

There are many various triaxial transducers calibration methods. The simplest one is the 6-states method, which is two-point calibration extension for triaxial transducers. It consists of placing each axis in line with and against direction of the measured vector field. Due to small amount of measurement data, such calibration is highly inaccurate.

Two most common precise methods use rotation platform and centrifuge. Both require specialistic lab equipment and user qualifications. In first, one transducer is attached to an arm rotating in 3-dimensional space. Angular orientation of measurement points is strictly determined and vector components on all axes are computed using trigonometric functions. However, the centrifuge method, used to calibrate accelerometers, is to rotate the transducer attached to the turntable with known angular velocity. Transducer measures centrifugal force, depending on acceleration. There is also less popular method, called automatic calibration. Its idea is that the transducer is set in numerous random positions in known vector field. As the vector magnitude is known, components on respective axes can be computed using optimization algorithms [3-7].

2. Triaxial transducer model

In the research provided, accelerometer as triaxial transducer was chosen and subjected to tests. For every its channel the response is given by the equation:

$$v = s \cdot a + o\,, \tag{1}$$

where:
v – measured voltage [V],
s – channel sensitivity [V/g],
o – channel offset [V],
a – acceleration [g].

Hence, mathematical model of triaxial accelerometer set randomly in gravitational field is [7-9]:

$$\sqrt{\left(\frac{v_x - o_x}{s_x}\right)^2 + \left(\frac{v_y - o_y}{s_y}\right)^2 + \left(\frac{v_z - o_z}{s_z}\right)^2} = 1\ [\mathrm{g}]. \tag{2}$$

The simulation model consists of (Fig. 1):

- Motion model with temperature – the output from this block there are two angles which change according to the simulated orientation of the transducer and actual transducer temperature,
- Vector g in the transducer frame – it is computation of the vector components on the nominal direction of the axes of the transducer,
- Model of transducer axes – it models the non-orthogonality of the transducer axes,
- Measurement model – model of characteristics of every axis including range, measurement resolution, noise level, scales and biases for every axis and temperature effect on them; in the Fig. 2 it is presented the GUI where these parameters are sets before simulation.

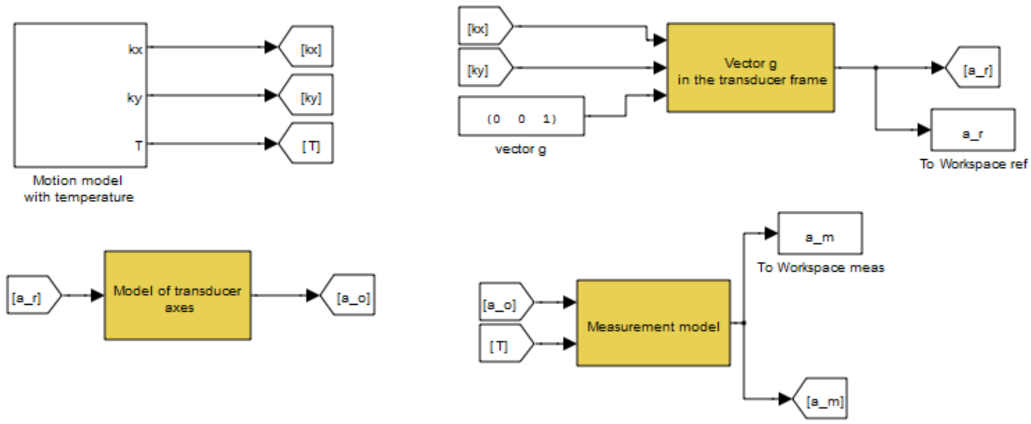

Fig. 1. Simulation model of 3 axial accelerometer

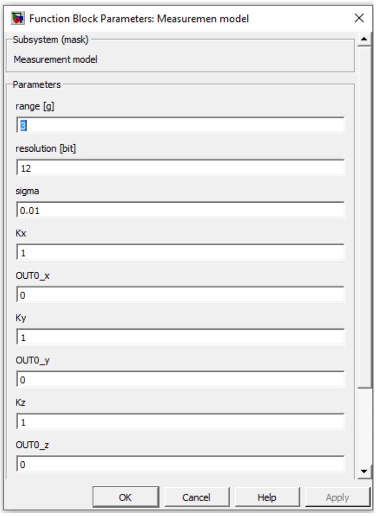

Fig. 2. Parameters of the measurement model

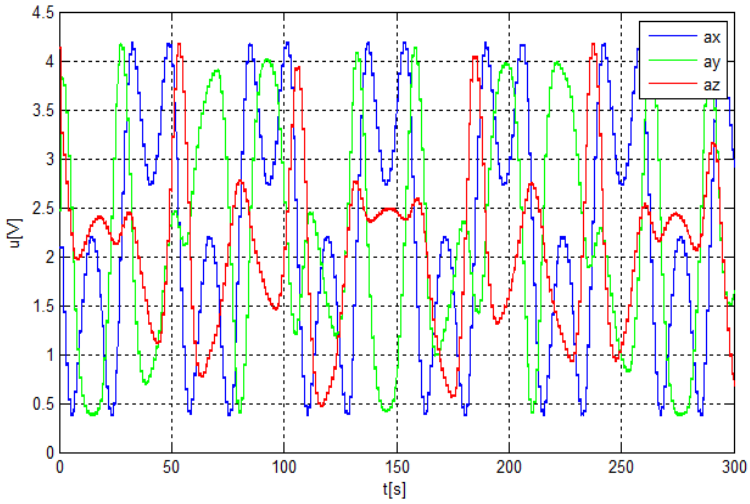

Fig. 3. Output a_m (three vector components) signal in time

The results of simulation are recorded in the MATLAB workspace (a_m – result of simulated measurements, a_r – real values of acceleration vector). In the Fig. 3, the simulated transducer responses are presented. The inputs are steady for every 1 s giving possibility to collect steady state data. The output data has noise component what makes the conditions of parameters estimation of simulated transducer similar to reality.

3. Estimation of the parameters of the model

According to equation (2), there are 6 parameters to estimate. Estimation is accomplished by non-linear least squares minimization of the formula (3):

$$\sum_{i=1}^{n}\sqrt{\left[\left(\frac{v_{(x,i)}-o_x}{s_x}\right)^2+\left(\frac{v_{(y,i)}-o_y}{s_y}\right)^2+\left(\frac{v_{(z,i)}-o_z}{s_z}\right)^2-1\right]^2}\rightarrow \min . \qquad (3)$$

From existing estimation, three algorithms were chosen:

- quasi-Newton,
- simplex (Nelder-Mead),
- Levenberg-Marquard.

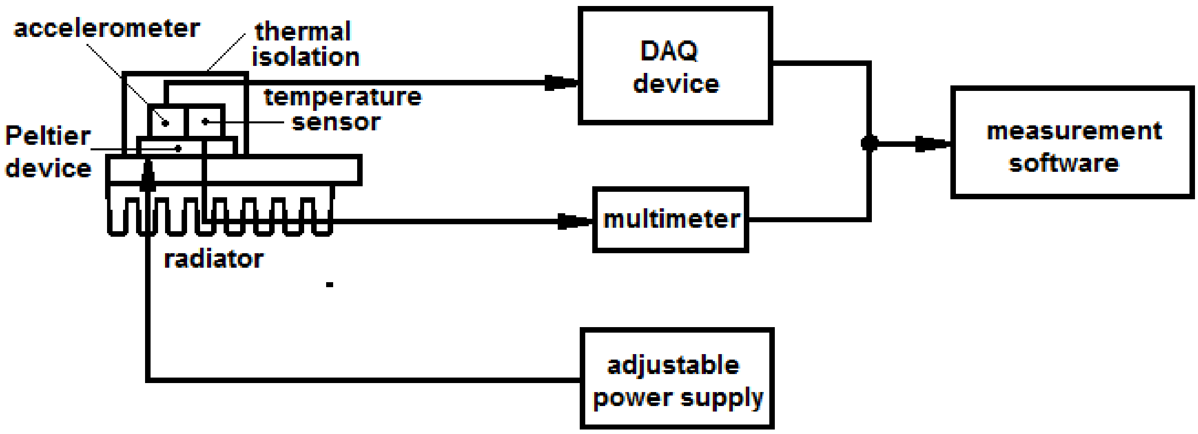

Fig. 4. Test-bench

Quasi-Newton method searches for extrema by finding zeros of gradient function. Unlike simple Newton algorithm, it does not require computing Hessian, which is estimated by successive gradient vectors.

Evolved by Nelder and Mead simplex method is mathematically simple but slow process. It is non-derivative and iterative algorithm based on transformations of simplex (a generalization of the notion of a triangle): reflection, expansion, contraction and shrink. Choice of next operation depends on comparison of successive values of minimized function.

Levenberg-Marquard algorithm uses gradient descent method when away from minimum and conjugate gradient method when close. In every step, movement towards fastest descent is made and deviation of value is checked.

Because of form of the equation (2), it appears that finding minimum of function is really fitting ellipsoid to measurement point's problem. Therefore, it is important to get many points of various distribution on ellipsoid surface [10, 11].

4. The calibration method

Considering the model of the transducer the calibration process consists of the experimental phase when the data is collected and computational phase. Second phase is estimation of the model parameters using recorded values.

The proposed experimental part of the calibration utilize the idea of using existing and known constant vector of the measured value like gravitational acceleration and magnetic field. Changing the orientation of the vector of the length v makes possible to stimulate every axis transducer in the range from $-v$ to v. In the case of the accelerometers in the orientation measurement, systems and also the magnetic field transducers intended to measure magnetic course the operation conditions are the same as in such experiment. Assuming that the transducer model given by (2) is valid, no reference measurement is necessary.

The temperature influence compensation makes necessity to use the equipment to control and stabilize the temperature of the transducer. The thermal chamber in which the calibrated transducer is set on the 3D rotational plate is one possibility but besides the cost of such apparatus the size and mass of the chamber means large time inertia. The small size of the transducer makes possible to use the small chamber prepared for every transducer with Peltier module as the heater and cooler. This solution has been effectively used in pressure transducer calibration [12].

The particular stand is presented in the Fig. 4. Small size of the whole makes possible to change freely orientation of it so the necessary set of points is easily achievable.

Tested calibration procedure is as follows:

1. setting the transducer in a random position,
2. quasi-static state detection,
3. repeating first two steps n times to get data,
4. parameters optimization,
5. transformation of the output u [V] to the measured value a [g] using equation (1).

5. Simulation tests

The evaluation of the calibration method was done using simulation method. Using the model described in part 2, it is possible to set parameters of every axis transducer and after estimation of these parameters evaluate errors. These tests give also information about the convergence and influence of the number and location of calibration points.

Table 1 shows how number of samples influence on results. It is also proved that this calibration method is reliable. With 15 samples, maximal error equals 1.68%, while with 50 samples errors of all parameters are less than 0.1%.

Tab. 1. Results of calibration for various number of samples

Survey type			Parameters					
Data type	Number of samples	Method	o_x	o_y	o_z	s_x	s_y	s_z
estimated	15	Marquard	2.1017	2.1006	2.0871	2.0030	2.0021	1.9664
		Nelder	2.1004	2.1014	2.1000	1.9999	2.0016	2.0010
		Newton	2.1002	2.1000	2.0994	1.9997	2.0002	1.9995
estimated	50	Marquard	2.0994	2.1001	2.0977	2.0004	2.0000	1.9954
		Nelder	2.1001	2.1000	2.1001	2.0001	2.0000	2.0001
		Newton	2.1001	2.1000	2.1001	2.0001	2.0000	2.0002
estimated	200	Marquard	2.0998	2.0997	2.0998	2.0003	2.0004	1.9989
		Nelder	2.1000	2.1000	2.1000	2.0000	2.0000	2.0000
		Newton	2.1000	2.1000	2.1000	2.0000	2.0000	2.0000
expected	N/A	N/A	2.1000	2.1000	2.1000	2.0000	2.0000	2.0000

Next, temperature influence on transducer's model was studied. Linear relationship between temperature and sensitivity and offset for each channel was implemented by equation

$$v_i = a_i\, s_i\,[1 + \mathrm{d}K_{si}(T - T_0)] + [o_i + K_{oi}(T - T_0)]\,, \tag{4}$$

where:

$i \in \{x, y, z\}$,

K_{oi}, $\mathrm{d}K_{si}$ – temperature parameters.

It causes six new parameters to estimate. During test it appeared that with this method, it is impossible to achieve proper results in this form [14]. The additive temperature parameters were not expected values. To avoid this problem, replacement parameters were provided

$$\begin{aligned} K_i &= o_i + K_{oi}(T - T_0), \\ \mathrm{d}K_i &= s_i\,[1 + \mathrm{d}K_{si}(T - T_0)] \end{aligned} \tag{5}$$

and calibration process was divided into 2 parts. In first, replacement parameters are estimated and in second, approximation of correct parameters is applied. Tab. 2 and 3 shows results of such calibration process for 5 temperatures. Every survey contains 50 samples.

Last simulation test was temperature and axes orthogonality deviation compensation. Transducer axes may be non-orthogonal due the repeatability of the transducer production process. To avoid measurement errors due the non-orthogonality, transducer coordinate system (B) and gravitational coordinate system (A) were discriminated. Acceleration vector components are projected into transducer axes using transformation matrix:

$$L_{BA} = \begin{bmatrix} \cos(k12)\cos(k13) & \cos(k12)\sin(k13) & -\sin(k12) \\ -\cos(k21)\sin(k23) & \cos(k21)\cos(k23) & \sin(k21) \\ \cos(k31)\sin(k32) & \sin(k31) & \cos(k31)\cos(k32) \end{bmatrix}, \tag{6}$$

where angles *kij* designation: *i* – rotated axis, *j* – axis of rotation.

Then an assumption was made that at least one axis is mounted correctly, which simplify matrix (6) to form (7).

$$L_{BA} = \begin{bmatrix} 1 & 0 & 0 \\ -\sin(k23) & \cos(k23) & 0 \\ \cos(k31)\sin(k32) & \sin(k31) & \cos(k31)\cos(k32) \end{bmatrix}. \tag{7}$$

To estimate parameters, measurement matrix must be multiplied by inverted and transposed matrix $L_{AB} = (L_{BA})'$.

Tab. 2. Results of first part of calibration

Survey type			Replacement Parameters					
Data type	T [ºC]	Method	K_x	K_y	K_z	dK_x	dK_y	dK_z
estimated	5	Marquard	1.9998	2.0001	1.9997	0.5001	0.5003	0.4990
		Nelder	2.0000	2.0001	2.0000	0.5000	0.5002	0.4997
		Newton	2.0002	2.0001	1.9997	0.5001	0.5001	0.4995
expected		N/A	2.0000	2.0000	2.0000	0.5000	0.5000	0.5000
estimated	12	Marquard	2.1400	2.1399	2.1400	1.1999	1.2000	1.2000
		Nelder	2.1400	2.1399	2.1400	1.1999	1.2000	1.2001
		Newton	2.1401	2.1399	2.1400	1.1999	1.2000	1.2001
expected		N/A	2.1400	2.1400	2.1400	1.2000	1.2000	1.2000
estimated	19	Marquard	2.2799	2.2796	2.2793	1.9006	1.9002	1.8979
		Nelder	2.2800	2.2801	2.2800	1.9001	1.8998	1.9001
		Newton	2.2800	2.2801	2.2800	1.9002	1.8999	1.9001
expected		N/A	2.2800	2.2800	2.2800	1.9000	1.9000	1.9000
estimated	24	Marquard	2.3800	2.3800	2.3799	2.3998	2.4002	2.3995
		Nelder	2.3800	2.3800	2.3801	2.3998	2.4001	2.4001
		Newton	2.3800	2.3800	2.3801	2.3999	2.4000	2.4001
expected		N/A	2.3800	2.3800	2.3800	2.4000	2.4000	2.4000
estimated	32	Marquard	2.5400	2.5400	2.5400	3.2000	3.2004	3.1993
		Nelder	2.5401	2.5400	2.5400	3.1999	3.2000	3.2001
		Newton	2.5401	2.5400	2.5400	3.2000	3.2000	3.2001
expected		N/A	2.5400	2.5400	2.5400	3.2000	3.2000	3.2000

Tab. 3. Results of approximation

Method	Marquard	Nelder	Newton	Expected
o_x	2.2999	2.3000	2.3001	2.3000
o_y	2.2999	2.3000	2.3000	2.3000
o_z	2.2998	2.3000	2.3000	2.3000
K_{ox}	0.0200	0.0200	0.0200	0.0200
K_{oy}	0.0200	0.0200	0.0200	0.0200
K_{oz}	0.0200	0.0200	0.0200	0.0200
s_x	2.0001	1.9999	2.0000	2.0000
s_y	2.0002	2.0000	2.0000	2.0000
s_z	1.9991	2.0000	2.0000	2.0000
dK_{sx}	0.0500	0.0500	0.0500	0.0500
dK_{sy}	0.0500	0.0500	0.0500	0.0500
dK_{sz}	0.0500	0.0500	0.0500	0.0500

During research, it appeared that only quasi-Newton algorithm could compute deviation angles [14]. Results of calibration with temperature and axes deviation compensation are shown in Tab. 4 (parameters of ellipsoid in every temperature), Tab. 5 (axes angles parameters) and Tab. 6 (approximated parameters). Every survey contains 100 samples.

The results show that the method of estimation is effective in the presented application.

Tab. 4. Results of first part of calibration

Survey type		Replacement parameters					
Data type	*T* [°C]	K_x	K_y	K_z	dK_x	dK_y	dK_z
estimated	5	2.0000	2.0000	2.0001	0.5000	0.5000	0.5001
expected		2.0000	2.0000	2.0000	0.5000	0.5000	0.5000
estimated	12	2.1400	2.1400	2.1400	1.2000	1.2000	1.2001
expected		2.1400	2.1400	2.1400	1.2000	1.2000	1.2000
estimated	19	2.2800	2.2800	2.2801	1.9001	1.8999	1.9001
expected		2.2800	2.2800	2.2800	1.9000	1.9000	1.9000
estimated	24	2.3800	2.3800	2.3802	2.4000	2.4001	2.4000
expected		2.3800	2.3800	2.3800	2.4000	2.4000	2.4000
estimated	32	2.5400	2.5400	2.5399	3.2000	3.2000	3.2001
expected		2.5400	2.5400	2.5400	3.2000	3.2000	3.2000

Tab. 5. Results – estimated deviation angles

Survey type		Angles		
Data type	*T* [°C]	*k23*	*k31*	*k32*
estimated	5	1.0041	0.4760	0.1968
expected		1.0000	0.5000	0.2000
estimated	12	0.9979	0.5080	0.2088
expected		1.0000	0.5000	0.2000
estimated	19	1.0053	0.4978	0.2011
expected		1.0000	0.5000	0.2000
estimated	24	0.9992	0.5002	0.1906
expected		1.0000	0.5000	0.2000
estimated	32	1.0027	0.4964	0.2025
expected		1.0000	0.5000	0.2000

Tab. 6. Results of approximation

Parameter	Estimated	Expected
o_x	2.3000	2.3000
o_y	2.3000	2.3000
o_z	2.3001	2.3000
K_{ox}	0.0200	0.0200
K_{oy}	0.0200	0.0200
K_{oz}	0.0200	0.0200
s_x	2.0000	2.0000
s_y	2.0000	2.0000
s_z	2.0001	2.0000
dK_{sx}	0.0500	0.0500
dK_{sy}	0.0500	0.0500
dK_{sz}	0.0500	0.0500

Finally, the methods’ rating was performed taking many simulations [14]. Its results are presented in Tab. 7. Methods were classified from the worst (3) to the best (1) in 5 categories as:

- quickness – meaning how many iteration is necessary to obtain steady result,
- accuracy – how large is difference between result and expected value,
- reliability – sometimes in particular condition the method led to improper results, the most reliable is robust to that,

– initial point – indicates robustness to the initial conditions,
– axes deviation – possibility to compute the axes deviation parameters.

Tab. 7. Methods' rating

Feature (description)	1	2	3
Quickness	Newton	Marquard	Nelder
Accuracy	Newton	Nelder	Marquard
Reliability	Marquard	Newton	Nelder
Initial point	Marquard	Newton	Nelder
Axes deviation	Newton	–	–

Tab. 8. Results of first part of calibration

Survey type		Replacement parameters					
T [°C]	Method	K_x	K_y	K_z	dK_x	dK_y	dK_z
6	Marquard	1.2648	1.2748	1.3345	0.2079	0.2081	0.2108
	Nelder	1.2660	1.2732	1.3429	0.2049	0.2080	0.2021
	Newton	1.2660	1.2732	1.3428	0.2049	0.2080	0.2022
8	Marquard	1.2679	1.2738	1.3427	0.2063	0.2067	0.2015
	Nelder	1.2678	1.2738	1.3427	0.2063	0.2067	0.2015
	Newton	1.2679	1.2738	1.3427	0.2063	0.2066	0.2015
10	Marquard	1.2663	1.2728	1.3415	0.2034	0.2063	0.2025
	Nelder	1.2664	1.2728	1.3415	0.2034	0.2063	0.2025
	Newton	1.2663	1.2728	1.3415	0.2035	0.2063	0.2025
13	Marquard	1.2684	1.2692	1.3409	0.2053	0.2127	0.2020
	Nelder	1.2687	1.2743	1.3410	0.2053	0.2062	0.2017
	Newton	1.2685	1.2722	1.3410	0.2053	0.2089	0.2017
18	Marquard	1.2714	1.2717	1.3392	0.2028	0.2086	0.2016
	Nelder	1.2714	1.2717	1.3392	0.2027	0.2086	0.2016
	Newton	1.2714	1.2717	1.3392	0.2028	0.2086	0.2016
20	Marquard	1.2703	1.2726	1.3393	0.2049	0.2071	0.2011
	Nelder	1.2703	1.2726	1.3392	0.2049	0.2071	0.2011
	Newton	1.2703	1.2726	1.3393	0.2049	0.2071	0.2011
26	Marquard	1.2714	1.2724	1.3379	0.2045	0.2076	0.2008
	Nelder	1.2712	1.2734	1.3379	0.2049	0.2059	0.2008
	Newton	1.2712	1.2734	1.3379	0.2049	0.2060	0.2008
33	Marquard	1.2722	1.2732	1.3375	0.2041	0.2066	0.2004
	Nelder	1.2722	1.2733	1.3375	0.2041	0.2066	0.2004
	Newton	1.2722	1.2732	1.3375	0.2041	0.2066	0.2004
38	Marquard	1.2747	1.2726	1.3360	0.2054	0.2064	0.2002
	Nelder	1.2748	1.2725	1.3360	0.2053	0.2064	0.2003
	Newton	1.2748	1.2726	1.3360	0.2053	0.2064	0.2002
46	Marquard	1.2758	1.2738	1.3360	0.2036	0.2051	0.1992
	Nelder	1.2758	1.2739	1.3361	0.2037	0.2051	0.1992
	Newton	1.2758	1.2738	1.3361	0.2037	0.2051	0.1992

6. Real transducer calibration

After getting knowledge of observed processes in simulation tests, calibration with temperature compensation of real transducer was performed. Deviation angles determination appeared to be hard to perform. Axes were deviated so slightly, that trigonometric functions of such small values led to wrong results. Therefore, that step was abandoned at this moment.

Using test-bench described in chapter 4, measurements in 10 different temperatures were made. Accelerometer used in research is ADXL 330, characterised by features [13] (at 3V supply):

- sensitivity – 0.27-0.33 V/g,
- offset – 1.2-1.8 V.

Parameters estimation is the same as in simulation test. Results are presented in Tab. 8 and 9. Every survey contains 50 samples. It should be noticed that the sensitivity and offset are in another range because the supply was 2.5 V. Taking into consideration the rating presented in the Tab. 7 some results by Marquard algorithm different than the others in the same conditions should be rejected.

To prove that the temperature influence compensation is required comparison of results gained with real temperature parameters and results gained with constant temperature T_0 = 20ºC have been done using error indicator (8) using mean error (9) given at every measurement point by formula (10).

Tab. 9. Approximation results

Method	Marquard	Nelder	Newton
o_x	1.2699	1.2700	1.2700
o_y	1.2727	1.2731	1.2729
o_z	1.3387	1.3397	1.3397
K_x	0.0002	0.0002	0.0002
K_y	0.0000	0.0000	0.0000
K_z	–0.0001	–0.0002	–0.0002
s_x	0.2049	0.2046	0.2046
s_y	0.2076	0.2068	0.2071
s_z	0.2023	0.2012	0.2012
dK_x	0.0000	0.0000	0.0000
dK_y	0.0000	0.0000	0.0000
dK_z	0.0000	0.0000	0.0000

To prove that the temperature influence compensation is required comparison of results gained with real temperature parameters and results gained with constant temperature T_0 = 20ºC have been done using error indicator (8) using mean error (9) given at every measurement point by formula (10).

$$\overline{\Delta a} = \sqrt{\Delta a_x^2 + \Delta a_y^2 + \Delta a_z^2}\ , \tag{8}$$

$$\Delta a_i = \frac{1}{n}\sum_{j=1}^{n} |\,\Delta a_{(i,j)}\,|, \tag{9}$$

$$\Delta a_{(i,j)} = \frac{v_{(i,j)} - o_i(T)}{s_i(T)} - \frac{v_{(i,j)} - o_i(T_0)}{s_i(T_0)}, \tag{10}$$

where $i \in \{x, y, z\}, j \in [1, n]$.

In Tab. 10 mean error values (absolute and relative) are shown. The axes sensitivities vary but in the tested range of temperatures (40ºC) the temperature coefficient is about 0.05%/ºC.

7. Conclusion

First of all, automatic calibration was proved as reliable. It can be an alternative for more expensive and complicated methods. Obtained results are satisfying, furthermore highly-qualified staff is not required if the algorithm is a part of measurement system.

Tab. 10. Temperature influence error

Method	$\overline{\Delta a}$ [g] ($\overline{\delta a}$ [%])			
	a_x	a_y	a_z	a
Marquard	0.0148 (1.17)	0.0047 (0.37)	0.0118 (0.89)	0.0194 (1.94)
Nelder	0.0142 (1.12)	0.0040 (0.31)	0.0122 (0.92)	0.0191 (1.91)
Newton	0.0143 (1.13)	0.0035 (0.28)	0.0121 (0.91)	0.0191 (1.91)

Estimation algorithms rating, made during research, reveals that simplex method is the worst of used ones but two remaining have some deficiencies. The best calibration procedure is hybrid method where two steps are used:

1) finding preliminary parameters using Marquard algorithm (no need for accurate initial point),
2) finding correct parameters using Quasi-Newton algorithm, starting with parameters achieved in step 1 as initial point.

Temperature compensation is highly recommended. Without it, the errors are of range 2% comparing to the possible accuracy of about 0.1%.

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