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Inertial Sensors in the Stabilization System of the Balancing Vehicle

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***Abstract*—The article presents the possibilities of using popular MEMS inertial sensors in the object tilt angle estimation system and in the system for stabilizing the vertical position of the balancing robot. Two research models were built to conduct the experiment. The models use microcontroller development board of the STM32F3 series with the Cortex-M4 core, equipped with a three-axis accelerometer, magnetometer and gyroscope. To determine the accuracy of the angle estimation, comparative tests with a pulse encoder were performed.**

***Keywords*—inverted pendulum, MEMS, sensor fusion, Kalman filter, control, applications**

I. Introduction

FOR over 20 years, many manufacturers of electronic components have been developing the technology of Micro Electro-Mechanical System - MEMS. Along with its rapid development, there are also new possibilities of using them. Manufacturers offer many types of sensors, the most important of which are accelerometers, gyroscopes, pressure sensors. The use of these elements is very wide, from mobile phones, game controllers, GPS navigation, car systems to medical or industrial equipment [1-10].

Currently, the price of these sensors used in consumer equipment is relatively low and usually does not exceed a few dollars [5,6]. However, it should be noted that MEMS sensors designed for professional applications are offered at prices over a hundred times higher [7-9]. An example of this is the ADIS16480 component of the complete inertial measurement unit (IMU) by Analog Devices, quite popular in scientific publications, which in its structure includes a three-axis accelerometer, magnetometer and gyroscope, and a pressure sensor. Additionally, an extended Kalman filter (EFK) has been implemented in this system to fuse measurement data from an accelerometer, magnetometer and gyroscope. The manufacturer declares that the sensors in the production process have been pre-calibrated, and in the documentation you can find values determining the uncertainty of measurements [9]. In the case of cheap MEMS sensors produced in large numbers for consumer equipment, such as mobile phones or game controllers, worse metrological parameters can be expected, which may limit the possibilities of their use.

In the literature on the stabilization of balancing vehicles, it is rare to find solutions using the cheapest inertial sensors. Typically, such projects were implemented as part of a master's thesis. The descriptions of these projects often show that their creators had some problems with ensuring the stability of the vehicles they build. The stability of the designed balancing vehicles depends on many factors, including the PID regulator settings and the dynamics of the drive system. Therefore, research was carried out on the possibility of using cheap inertial MEMS sensors in the stabilization system of the vertical position and the direction of movement of the balancing vehicle model.

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II. Data Fusion

In the case of a balancing vehicle vertical stabilization control system, it is required to measure the instantaneous value of the vehicle inclination angle in real time. If the vehicle is to behave stably, an uncertainty in measuring the vehicle inclination angle of less than 1 degree is required.

Using only the accelerometer, it is possible to theoretically determine the angle of inclination of the sensor. However, in this case, the measured acceleration values obtained from the accelerometer have additional errors of a random nature: noise of the converters and the measuring circuit, and undesirable vibrations from the vehicle drive. The use of low-pass filtering, especially with higher-order filters, causes a delay of the signal and the occurrence of a dynamic error in the measurement of the tilt angle. This error adversely affects the vertical stability of the vehicle by the controller.

The gyroscope measures the angular velocity with respect to the axis, however, it has a zero error (bias) and random errors such as noise. You can integrate the angular velocity over time to find the tilt angle. This process will eliminate noise, but the zero error causes the tilt angle error to increase over time - drift. To eliminate the zero error, the angular velocity signal should be subjected to high-pass filtration.

As a result, both the angle values determined from the measurements with the gyroscope and the accelerometer have errors characteristic of these measuring systems. In the described case, the concept of sensory fusion is used in practice to estimate the vehicle tilt angle, in which one algorithm integrates measurement data from various sensors [1,11,12].

One of the methods of correcting the determined value of the tilt angle is the use of complementary filters. Often, in practice, data fusion is also carried out with the use of the Kalman filter, which allows the estimation of non-measurable quantities based on the available signals and the process model [11]. The usefulness of the simple complementary filter and the Kalman filter are presented in the measurement results below.

A. Complementary filter

In the data fusion experiment, as the simplest tool, a first-order discrete complementary filter was used, described by the following expression:

$$\theta_f[k] = a(\theta_f[k-1] + \omega_g[k] \cdot \Delta t) + (1-a)(\theta_a[k]) \tag{1}$$

the filter time constant:

$$\tau = \frac{a}{1-a}\Delta t \tag{2}$$

where: Δt - sampling period, k - selected moment of time. The operation of the complementary filter described by the expression (1) can be presented in a block diagram – Fig. 1.

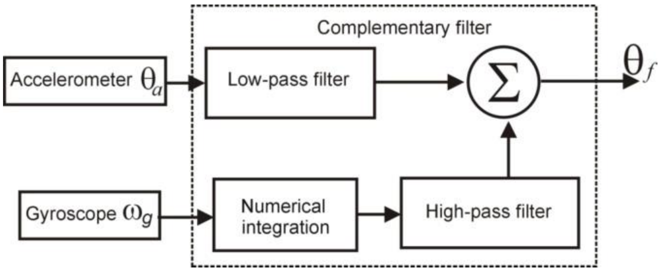

Fig. 1. Complementary filter operation scheme

B. Kalman filter

The Kalman filter is a type of recursive optimal filtering, i.e. information is processed in each step, and the filter does not store the states from previous measurement cycles. The filtration is optimized by taking into account all available measurements of a given physical quantity, regardless of their accuracy As a result of filtration, we obtain an estimate of the state of the measured system – Fig. 2. A great advantage of the Kalman filter is the ability to determine unmeasured values from the input data.

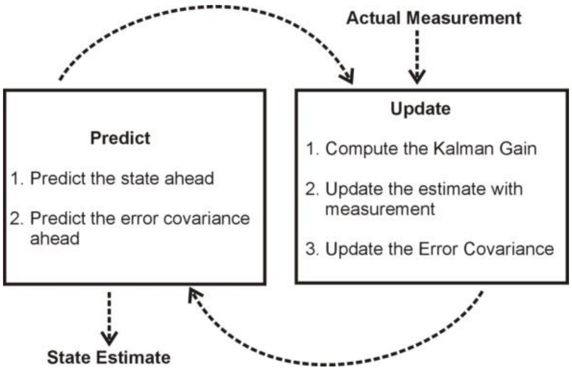

Fig. 2. Kalman filter operation scheme

The filter is designed for linear processes [11]. In the case of nonlinear processes there are some extensions of the Kalman filter - EKF, UHF [1]. In order to determine the estimated value, the process and the measurement system should be described with the appropriate equations:

$$x_k = A \cdot x_{k-1} + B \cdot u_{k-1} + w_{k-1} \tag{3}$$

$$z_k = H \cdot x_k + \upsilon_k \tag{4}$$

where:
A - state matrix,
B - state force matrix,
w_{k-1} - process noise,
H - matrix linking measurement with state,
υ_k - measurement disturbances.

The calculation of the Kalman filter is a continuous process consisting in the cyclic calculation of the state vector and its covariance and has two stages (phases): - prediction, - correction. In the prediction stage, a priori values of the state model and the covariance model are determined, hence it is often called a time update [11], while in the correction stage, a posteriori values of the process state and covariance are calculated and it is called measurement updating. The prediction phase uses the data calculated in the previous step in the correction phase.

The Kalman filtration process is represented by formulas.
Prediction phase:
Predicted a priori state values:

$$\hat{x}_k^- = A \cdot \hat{x}_{k-1} + B \cdot u_{k-1} \tag{5}$$

where:
$\hat{x}_{k-1}$ - state vector in the previous step,
u_{k-1} - forcing vector,
A - control matrix,
B - forcing matrix.
Predicted a priori values of the filter error covariance matrix:

$$P_k^- = A \cdot P_{k-1} \cdot A^T + Q \tag{6}$$

where:
$\boldsymbol{P}_{k-1}$ - filter error covariance matrix in the previous step,
Q - process variance matrix.
Correction phase:
Calculation of the Kalman gain:

$$K_k = P_k^- \cdot H^T \cdot \left(H \cdot P_k^- \cdot H^T + R\right)^{-1} \tag{7}$$

where:
H - matrix linking the input vector with the output vector,
R - measurement variance matrix.
State vector correction taking into account the measurement vector:

$$\hat{x} = \hat{x}_k^- + K_{k\cdot}\left(z_k - H \cdot \hat{x}_k^-\right) \tag{8}$$

Correction of the covariance matrix of filtration errors:

$$P_k = \left(I - K_k \cdot H\right)P_k^- \tag{9}$$

where: *I* - identity matrix.
For the discussed case of estimating the tilt angle of a balancing vehicle, the system equation was defined as follows:

$$\theta_k = \theta_{k-1} + \left(\omega_{k-1} - g_{bias}\right) \cdot \Delta t \tag{10}$$

where:
θ - angular tilt,
ω - angular velocity,
g_{bias} - gyro drift.
The angular velocity ω will be the control u (3).

III. Models for research

A. *Microcontroller board*

To test these sensors, a 32-bit STM32F303CTV6 microcontroller development board with an ARM Cortex-4M core with the trade name STM32F3DISCOVERY by STMicroelectronics was selected – Fig. 3. The microcontroller central unit has capabilities similar to signal processors in digital signal processing (DSP) and is equipped with a floating-point arithmetic unit, which ensures its high efficiency. On the board, apart from the microcontroller, there are two MEMS converters integrated circuits. The first one, marked with the symbol L3GD20, is a three-axis gyroscope with digital signal output realized by means of a serial interface SPI or I2C. The gyroscope includes a 16-bit A / C converter and an additional 8-bit A / C converter of the temperature sensor. The second chip LSM303DLH contains a three-axis accelerometer and a three-axis magnetometer. The integrated circuit has a 16-bit A / C converter and an additional temperature sensor. The digital output of the signal was realized by means of the I2C serial interface. The manufacturer informs that the accelerometer converter has been pre-calibrated at the production stage. In the case of a magnetometer, you need to calibrate yourself, even roughly, because the experiments show that the XYZ axes of the transducer are not orthogonal. The manufacturer provides typical parameters in the technical specifications of the elements, but does not guarantee them.

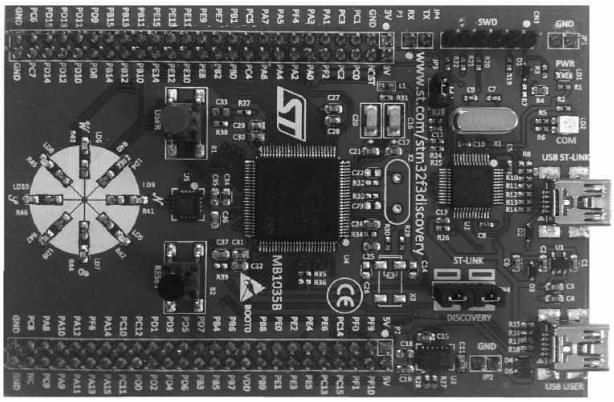

Fig. 3. View of the 32-bit development board of the STM32F303CTV6 ARM Cortex-4M microcontroller

B. *Model for verification of tilt angle estimation*

Descriptions of the constructed balancing vehicles or walking robots usually present the results of measurements in the form of time graphs: the determined angle of tilt obtained from the accelerometer, the integrated value of the angular velocity of the gyro and the estimated value of the angle based on data fusion. Unfortunately, these graphs do not show the actual value of the tilt angle. It is difficult to compare the estimated value of the tilt angle to a noisy signal from an accelerometer or the integral value of a gyro signal with a drift. In the case of starting these vehicles, their creators at the same time tune the parameters of the filter and the vertical stabilization regulator. These attempts are not always successful. Without the actual sensor angle, it is more difficult to tune the filter parameters. Pre-tuning the filter parameters based solely on an estimate of the standard deviation of the observed disturbances or the observation of "smoothing" in the time plot of the estimated angle may not be sufficient. Incorrect selection of the filter parameters may lead to a significant delay of the estimated angle signal, so that the PID controller tuning will not ensure the stability of the control system. Therefore, a model was built to experimentally verify the estimated tilt angle. The model allows you to observe the effectiveness of the measurement and data fusion process.

Figure 4 shows the view of the model for the experimental verification of the estimated angle of inclination of the development board. The model consists of a vertical plate rigidly attached to the second plate, which is a stable base. A hub removed from the hard disk is embedded in the vertical plate. There is a rod in the hub, which is the axis of rotation. On the shorter end of the axis there is an optical rotary-pulse encoder, which can be found in popular inkjet printers. The optical sensors of the encoder are placed on the vertical plate of the model. The encoder resolution is 7200 imp / rev, i.e. 0.05 angular degree (deg). It was assumed that the measurement uncertainty is not greater than the resolution. The encoder is protected against dust and mechanical damage with a tight cover. At the end of the axis, behind the encoder, a wheel with an additional load on the arm ensuring a stable "0" position, similar to a pendulum. The longer part of the axis is intended to attach the test board. The microcontroller development board can either be powered via soft wires or from a battery attached to the board. Communication with the master computer can take place via the RS232 interface cable and USB converter, or you can use the wireless connection via the Bluetooth BTM222 module, which is "transparent" from the point of view of the RS232 interface.

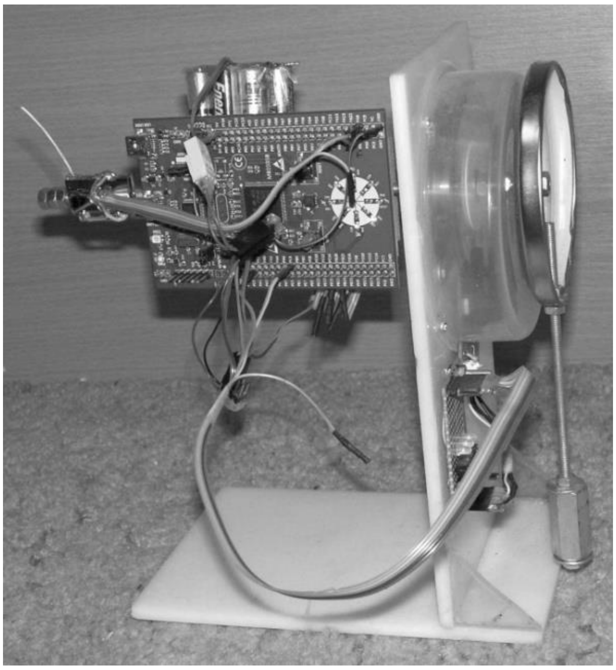

Fig. 4. Model view for experimental verification of the estimated slope angle

C. *A balancing vehicle prototype*

The In order to conduct an experiment that could confirm the usefulness of cheap inertial sensors in balancing vehicles, a simple prototype of a two-wheeled vehicle was built, shown in Fig. 5.

The mechanical structure of the vehicle consists of a vertical plate with a plate transversely glued on top, which constitutes a loading platform. Attached to the vertical plate are: 4x1.2 V NiCd battery pack, microcontroller development board, IR receiver enabling remote control, BTM-222 Bluetooth radio module, two H-bridge plate for DC drive motors, potentiometer plate for filter tuning and PID regulators, plate conditioning of signals from impulse encoders mounted on the wheels of the vehicle. The vehicle uses individual drive for each wheel, equipping them with impulse encoders to measure the distance traveled. Miniature modeling servos were used to drive the wheels. The control system was removed from them and the mechanism of limiting the rotation of the drive axle was eliminated. The drive remains a miniature high-speed brush motor and a multi-stage toothed gear acting as a gear motor.

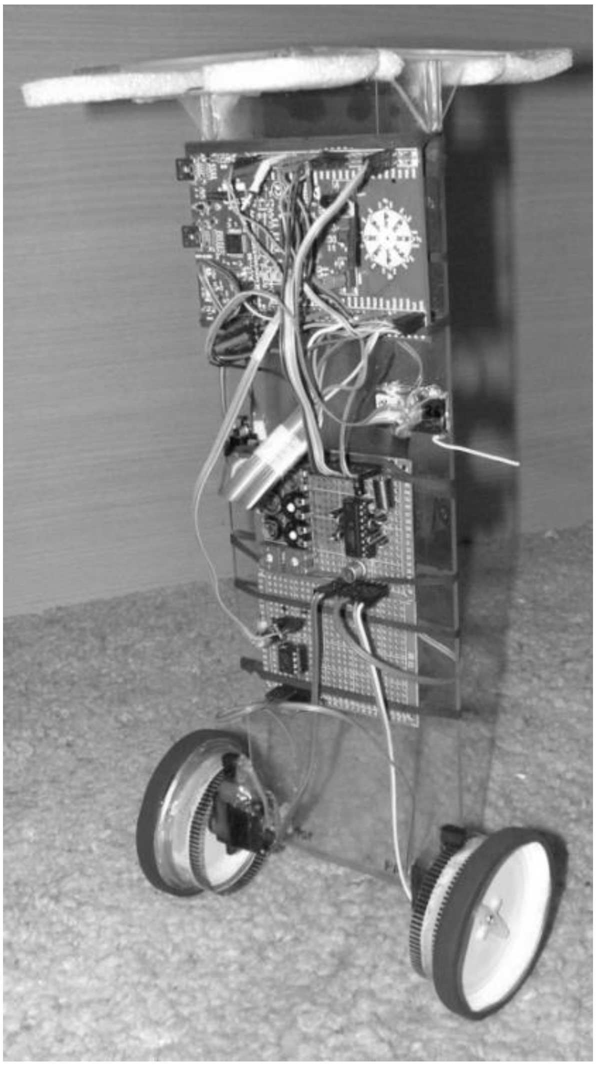

Fig 5. A balancing vehicle prototype

A frequently observed mistake made by novice designers of this type of vehicle is placing heavy elements in the transmission systems with a large moment of inertia, and this also applies to the selection of vehicle wheels. To ensure high linear acceleration of the base of the vehicle, the drive components should be as light as possible. In the model, metal covers made of thin sheet metal were used to build wheels. The heart of the vehicle control system is the aforementioned STM32F3 microcontroller development board. Vehicle software was made using C language. The frequency of the main loop of the program is 100 Hz. In the main loop, the values measured by the accelerometer, magnetometer and gyroscope are read. Then, the appropriate values of the measured signals are processed in the implemented algorithms of the complementary filter or Kalman. The estimated values of the vehicle inclination angle after subtraction from the set value go to the input of the classic discrete PID controller. The trapezoidal method was used in the integration algorithm. The rectangle method gave worse stability in the operation of the controller (redundant integration). In addition to the tilt angle regulator, the software has implemented a discrete PID regulator of the vehicle speed, which controls the value of the vehicle tilt angle. The output of the pitch angle controller is the duty cycle of the PWM waveform. The PWM output signal is obtained with the use of two microcontroller timers that individually control each wheel drive. It is worth mentioning that the aforementioned microcontroller, in addition to high computing performance, is very richly equipped with additional peripheral systems, which predispose it to applications in the control of electric drives - the possibility of implementing two 3f inverters for induction or BLDC motors.abstract should concisely state the purpose of the investigation and summarize the important conclusions.

IV. Results and discussions

A. *The results of the verification of the tilt angle estimation*

Immediately As a preliminary experiment, the tilt angle of a motionless microcontroller board at the "0" position was measured. Figure 6 shows time charts for the tilt angle, determined respectively: on the basis of the accelerometer signal - 1, the reference value determined from the encoder - 2, the value estimated by the complementary filter - 3, the value estimated by the Kalman filter - 4, and the determined value of the standard deviation for the obtained signal from the accelerometer - 5. Due to the bias of the gyroscope gbias ≈ 0.7 deg / s, the plot of the integral over time for the gyro signal has not been presented.

In order to investigate the influence of disturbances generated by the vehicle drive on the signals from the sensors, a miniature model servo drive operating in a reversible mode was attached to the microcontroller board. The previously mentioned time courses of the tilt angle were registered. Figure 7 shows time charts for the tilt angle, determined respectively: on the basis of the accelerometer signal - 1, the reference value determined from the encoder - 2, the value estimated by the complementary filter - 3, the value estimated by the Kalman filter - 4, and the determined value of the standard deviation = 1,25 deg for the obtained signal from the accelerometer - 5.

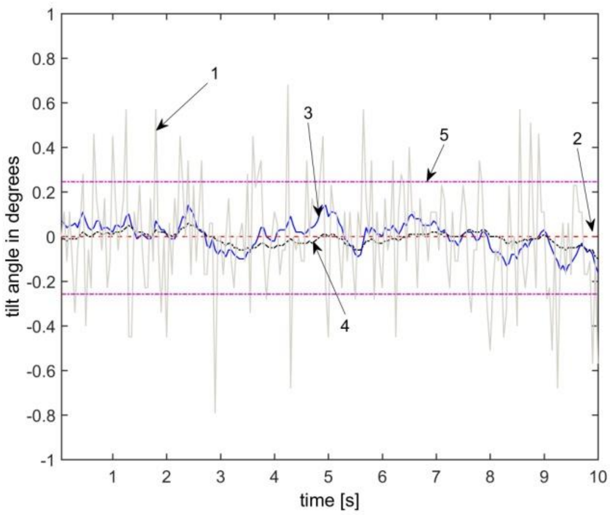

Fig 6. Time charts of the tilt angle - measurements for the static state

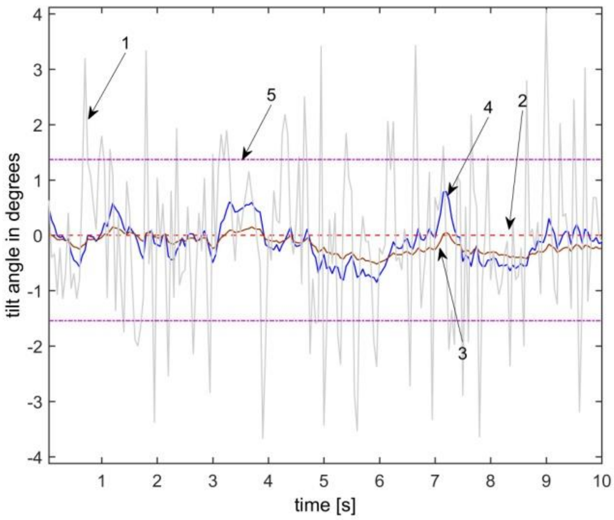

Fig. 7. Time charts of the tilt angle - measurements for the static state with additional disturbance

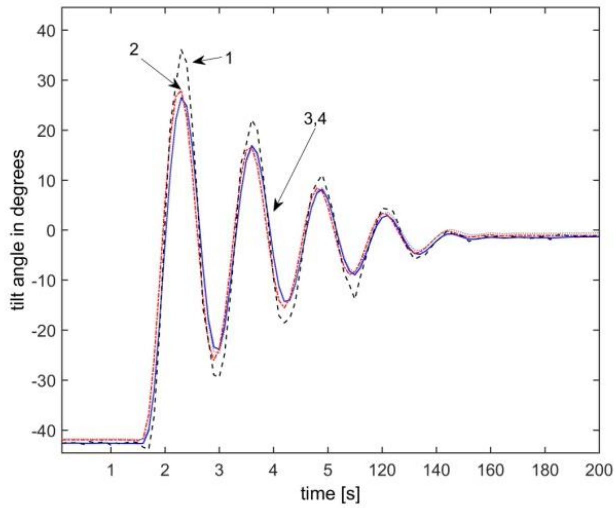

Fig. 8. Time charts of the tilt angle - measurements for the dynamic state, pendulum motion

Based on the estimated values of the standard deviation and the observed amplitude spectrum from the accelerometer signal, initial fine-tuning of the complementary and Kalman filters was made. Then, the results of the tilt angle estimation for the case of tilting the microcontroller board were tested. The load attached to the axis of rotation made swing movements. The aforementioned, determined time courses of the tilt angle were registered – Fig. 8.

Next, the results of the tilt angle estimation for the case of tilting the microcontroller board were examined. The load attached to the axis of rotation has limited swing movements - the effect of "jerking". The aforementioned, determined time courses of the tilt angle were registered – Fig. 9.

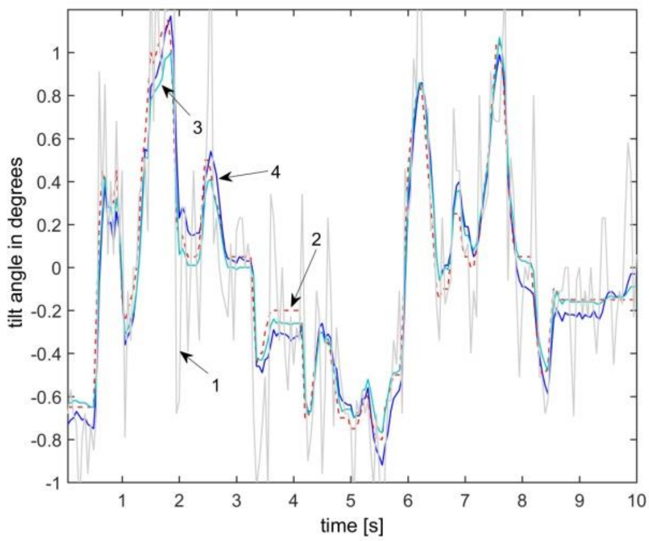

Fig. 9. Time charts of the tilt angle - measurements for the dynamic state, jerking

Figure 10 shows an example of the recorded time charts of the tilt angle of board for detuned filters.

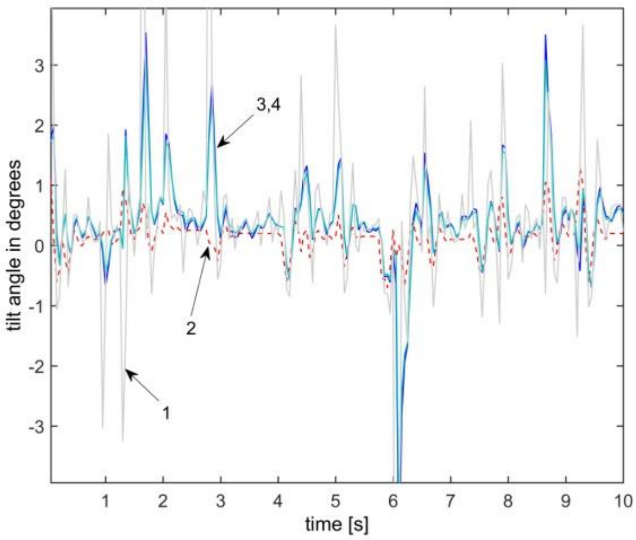

Fig. 10. Time charts of the tilt angle - measurements for the dynamic state for detuned filters

B. The results of the vertical stability of the vehicle

In the presented experiment, the vertical stability of the vehicle was examined for a set speed equal to zero. The research was carried out for the cases of hard and even ground as well as soft and uneven floor – carpet In addition, during the stability test, an asymmetrically additional load was placed on the vehicle's loading platform, and the vehicle's behavior was also tested for attempts to unbalance it by pushing the loading platform. Satisfactory results of vehicle vertical stability tests were obtained for all considered cases. Figure 11 shows the vehicle tilt angle charts: 1 - estimated using the complementary filter, 2 - determined on the basis of data from the accelerometer, 3 - the set value of the tilt angle at the vehicle tilt controller input.

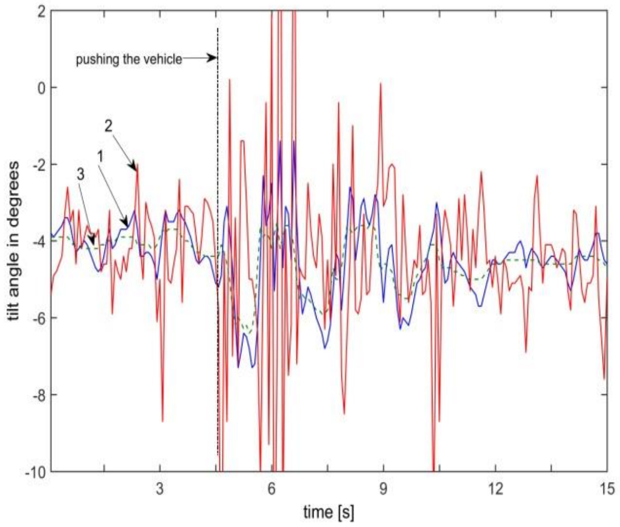

Fig 11. Time charts of the vehicle tilt angle - complementary filter

Figure 12 shows the vehicle tilt angle charts: 1 - estimated using the Kalman filter, 2 - determined on the basis of data from the accelerometer, 3 - the set value of the tilt angle at the vehicle tilt controller input.

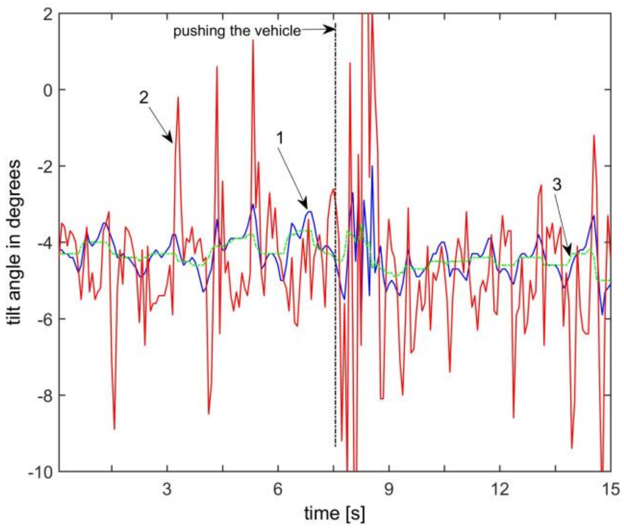

Fig 12. Time charts of the vehicle tilt angle - Kalman filter

CONCLUSION

Based on the obtained results of verification of the estimated tilt angle and observation of the vertical stability of the balancing vehicle, it can be concluded that the tested cheap accelerometer and gyroscope converters can be applied in the vertical stabilization control systems of vehicles or balancing robots. Due to the small tilt angles occurring in this case, there is no significant nonlinearity in the model, so it is sufficient to use a complementary or linear Kalman filter in the sensory fusion. In further tests, the traction capabilities of the balancing vehicle will be tested and an attempt will be made to use artificial intelligence methods [13] in the control system and direct drives with BLDC motors will be used (no gear motor).

REFERENCES

[1] P. Groves, “Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems”, Norwood, MA: Artech House, 2008.

[2] J. Collin, P. Davidson, M. Kirkko-Jaakkola, H. Leppäkoski “Inertial Sensors and Their Applications” S. Bhattacharyya, E. Deprettere, R. Leupers, J.Takala “Handbook of Signal Processing Systems”. Springer, 2019, pp.51-85. DOI 10.1007/978-3-319-91734-4_2

[3] M. Labowski, P. Kaniewski, P. Serafin, "Inertial Navigation System for Radar Terrain Imaging," *Proceedings of IEEE/ION PLANS 2016*, Savannah, GA, pp. 942-948, April 2016.

[4] M. Elhoushi, J. Georgy, A. Noureldin and M. J. Korenberg, "A Survey on Approaches of Motion Mode Recognition Using Sensors," in *IEEE Transactions on Intelligent Transportation Systems*, vol. 18, no. 7, pp. 1662-1686, July 2017, DOI: 10.1109/TITS.2016.2617200.

[5] B. Aguiar, T. Rocha, J. Silva and I. Sousa, "Accelerometer-based fall detection for smartphones," *2014 IEEE International Symposium on Medical Measurements and Applications (MeMeA)*, Lisboa, 2014, pp. 1-6, DOI: 10.1109/MeMeA.2014.6860110.

[6] J. M. Darmanin *et al.*, "Development of a High-G Shock Sensor Based on MEMS Technology for Mass-Market Applications," *2019 IEEE International Symposium on Inertial Sensors and Systems (INERTIAL)*, Naples, FL, USA, 2019, pp. 1-4, DOI: 10.1109/ISISS.2019.8739763.

[7] M. Mansoor, I. Haneef, S. Akhtar, M. A. Rafiq, S. Z. Ali and F. Udrea, "SOI CMOS multi-sensors MEMS chip for aerospace applications," *SENSORS, 2014 IEEE*, Valencia, Spain, 2014, pp. 1204-1207, DOI: 10.1109/ICSENS.2014.6985225.

[8] A. Mikov, A. Panyov, V. Kosyanchuk and I. Prikhodko, "Sensor Fusion For Land Vehicle Localization Using Inertial MEMS and Odometry," *2019 IEEE International Symposium on Inertial Sensors and Systems (INERTIAL)*, Naples, FL, USA, 2019, pp. 1-2, DOI: 10.1109/ISISS.2019.8739427.

[9] C. Acar, "High-performance 6-Axis MEMS inertial sensor based on Through-Silicon Via technology," *2016 IEEE International Symposium on Inertial Sensors and Systems*, Laguna Beach, CA, 2016, pp. 62-65, DOI: 10.1109/ISISS.2016.7435545.

[10] I. P. Prikhodko, B. Bearss, C. Merritt, J. Bergeron and C. Blackmer, "Towards self-navigating cars using MEMS IMU: Challenges and opportunities," *2018 IEEE International Symposium on Inertial Sensors and Systems (INERTIAL)*, Moltrasio, 2018, pp. 1-4, DOI: 10.1109/ISISS.2018.8358141.

[11] R. E. Kalman, "A New Approach to Linear Filtering and Prediction Problems." ASME. *J. Basic Eng*. March 1960; vol. 82, no1, pp. 35–45. DOI 10.1115/1.3662552

[12] J. Gajda, R. Sroka, M. Stencel, T. Żegleń, “Data fusion applications in the traffic parameters measurement”, *Metrology and Measurement Systems*, vol. 2, no. 3, pp. 249–262, 2005.

[13] S.Chudzik, “The idea of using artificial neural network in measurement system with hot probe for testing parameters of heat-insulating materials”, *Measurement*, vol. 42 pp. 764–770, 2009.