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INVESTIGATIONS TO DIGITIZING OF THE GYRO OSCILLATION SWING BY A LINE CAMERA

The **purpose** of this work is to develop a technology for an automatic measurement process for determining the azimuth by the "Gyromax AK-2M" gyroscope. The accuracy of determining the principal values should be higher than by manual procedure. A method for digitizing the gyro oscillations using a camera with a linear sensor and programming code is proposed in this work. The working possibility of the line camera from Coptonix™ company was investigated, as well as the possibility of its connection to a single board computer Raspberry Pi 3B for data transmission and processing. The possibility of using the Python 3.0 programming language for these tasks was tested. **Methodology**. To implement this project, an integrated approach was used, using devices such as a camera with a linear sensor, a single board computer and facility, that simulates gyroscope oscillations. This research includes investigations in digitizing of data, computing the azimuth values and automatizing these processes. For automatized data computation were used the same two methods as in the regular manual measurements – Turning point method (TPM) and Pass-Through method (PTM). **Results**. The result of this work is an automated oscillation measurement system, that can be applied in gyroscopes. The system includes developed software, which connects the user to the linear camera and processing computer, records the necessary data, transfers them to the client-computer and calculates the necessary values. For the convenience of using the program by other users, the program is provided with a graphical user interface. The result of the program is a file with the extension XML, which contains data about measurements. **Scientific novelty and practical significance**. The new method of digitizing the gyroscope oscillations is proposed in this work. Application of a line camera and a single board computer for the digitization of measurements opens a lot of possibilities for improving the automation processes of the geodetic devices, which could increase the accuracy of measurement and decrease its duration. By developing this method of digitization, it is possible to start production of an improved version of gyro add-on GYROMAX AK-2M.

Key words: gyroscope, line camera, digitizing, automation of measurements.

Introduction

As was noted in [V. Kovtun, 2010], the development of gyroscopic technology has led to the fact that a very wide class of instruments has been called that way, and now the term "gyroscope" is used to refer to devices containing a material object that performs rapid periodic rotations.

As in any industry, the inventors suffered many setbacks before creating a reliable and convenient device. Immediately to design the ideal gyroscope was not possible. In addition, the problem of the historical development of gyroscopic equipment is that initially when creating gyroscopes other purposes were pursued. These were instruments primarily for the fleet and for the army (mainly artillery). But thanks to the sailors, the surveyors got a gyrocompass and gyro-sextant, and thanks to the artillerymen – a gyro-boussole. Elmer Sperry from the US visited Europe many times in the early 1900s. He was taking ideas from German and other European companies, especially from Anschütz for his own gyroscope inventions. His company was founded in 1910 and today still on the market. In 1914 he won a price in Paris for a stabilized airplane flight. The WW I made him a lot of contracts for torpedo, ship and airplane navigation/steering [S. Shestov, 1989].

At the same time, in the USSR in the 1930s were also held researches on the creation of gyrocompasses, and in 1936, the Leningrad Institute of Fine Mechanics (LITMO) in the Faculty of Fine Mechanics and Optics has opened two new branches: navigation instruments and calculating devices. There were developed prototypes of gyrocompass and gyro-boussole, but they proved to be completely inapplicable in geodesy and mine surveying. And only after the Second World War, both countries – the USSR and Germany – returned to the idea of creating a "ground" gyro. According to [V. Golovanov, 2004], in the USSR, all the works were concentrated in the All-Union Scientific Research Mine Survey Institute (VNIMI) under the direction of P. L. Ilyin, and in FRG similar work was carried out at the Clausthal Mining Academy under the direction of Professor O. Rellensman [H. Ziegler, 1962].

In 1957, the development of a model of a surveying gyro compass with torsion suspension TV4 was completed. In 1958 the firm Fennel released torsion gyrotheodolite KT-1 (Kreiseltheodolit), and further – the advanced models of KT-2, MW10, MW7, MW50, MW77, and gyro add-on TK-4, TK-5 [N. Voronkov, 1980].

Nowadays, many types of gyroscopes require the user to read data manually, which can cause the appearance of observer errors and increases the duration of measurements. If we consider modern models of gyroscopes, in which there is the possibility of automatic measurements, then all of them are in the highest price category and purchase of which is beyond the means of many customers. Today, the main manufacturers of gyroscopic instruments are Germany and Japan. In Japan, SOKKIA produces gyro add-ons of GP-series. The determination of the direction to the north is made with the standard deviation ±20" at latitudes up to 75°. The weight of the set-top box, which is mounted on top of the electronic theodolite or total station, is only 3.8 kg. A German company DMT, engaged in the production of gyro appliances, is known for the creation of GYROMAT-2000 (and its advanced versions GYROMAT-3000&5000) the “gold standard” for geodetic-mining measurements during tunnel cross-cuts. Since entering the market to this day, engineers around the world have called GYROMAT the best gyro, fully automated and possessing excellent characteristics. None of the existing gyros created before did not provide such accuracy and rapidity of measurements. The only disadvantage of this system is its price. The GYROMAT 2000 of the company DMT GmbH was built in 1993. Its azimuth accuracy is 1 mgon (20") at 10 min measurement time. The gyroscope consists of gyroscope (directional part) and a mounted, mechanically fixed connected theodolite type WILD/T2 (directional part). The T2 was modified, adapted to the gyroscope, mechanically fixed and temperature-dependent calibrated (–20 to 50 °C). In the rotor part there is a motor with extremely well balanced rotor, optical-electronic speed control and special suspension tape. The gyroscope consists of the measuring cell with motor, the suspension system with suspension tape and the autocollimation device with CCD camera (line camera). Unfortunately, there is no information about its automatic azimuth detection system in the public domain. Depending on modification, the GYROMAT-3000 can cost up to 150000 €. Many companies cannot afford to purchase such an expensive device. A great solution would be to convert the old model of the gyroscope, making the measurements automatic.

The main purpose of this work is the development of an automatic data reading system with a gyro using a camera with a linear sensor with the ability to wirelessly transmit data. The cost of developing this system should not greatly impact on increasing the cost of a gyro. In the modern world, all processes are trying to be automated. Manual work is a secondary concern and in many areas of the economy, manual procedures are forgotten. Therefore, for modern users, it will be much more profitable to use an automatic device.

Purpose

The main goal of this work is to develop a technology for automatically determining the azimuth and further computation of the necessary data with the possibility of application in a gyroscope. The accuracy of determining principal values should be higher than by manual procedure. It is necessary to check the working possibility of the line camera as well as the possibility of its connection to a single board computer for data transmission and processing.

Methodology

This project includes several approaches and methods related to the mathematical calculation of the desired quantities, programming the program interface, the selection of the necessary devices. The general scheme of the developed system is shown in Fig. 3.

According to [T. Thomas, 1982], there are six methods of finding north using a suspended gyroscope. But since this project is done for the Gyromax AK-2M model only the Pass-Through method is possible to perform with the line camera. Therefore, this method will be considered below. The oscillation curve of the moving bar is shown in Fig. 1 as a function of time. This observation of transit times was first proposed by [H. Schwender, 1964]. In this method, the gyroscope has to be oriented to the north during the measurement process, which is provided by the pre-orientation procedure. Pre-orientation could be done by compass or by quick defining of two turning points, one on the east from the north, another on the west [W. Caspary, 1987]. Before and after Pass-Through measurement the tape-zero procedure has to be done. The device should be turned off. With the released gyro, using the air brakes operator has to make the light bar stay in the observation field. After dumping the speed of the light bar, the operator records the position of all turning points three times for each direction. After each procedure, aiming at the target should be done twice. The main measurement procedure is performed with the turned on gyro. After acceleration, the gyro has to be released. The speed and position of the light bar can be regulated with air brakes. As a rule, measurements are taken with the initial light bar moving from the left to the right. Each passing of the light bar through the zero-point of the scale is marked with the timer. The positions of the turning points are also recorded. After the measurement procedure gyro must be arrested and then turned off.

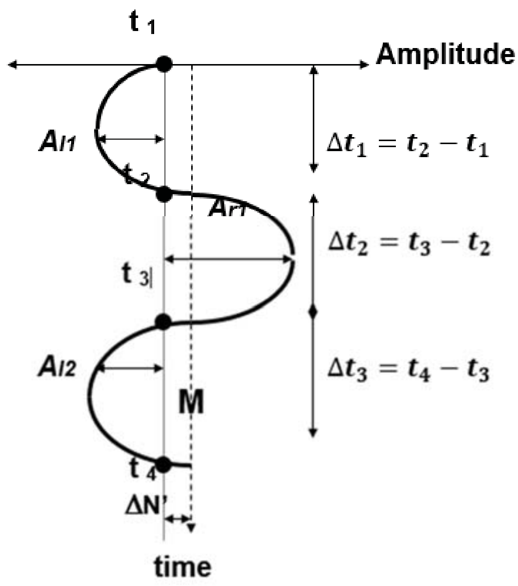

Fig. 1. Oscillation curve [Fabeck, 1980]

$\Delta N'$ is a line segment between the line N' that corresponds to zero on observation scale and the middle line M of the oscillation curve. *a*, the amplitude of turning points, is equal to:

$$a = \frac{(A_l + A_r)}{2}, \quad (1)$$

where A_l and A_r are left and right turning points respectively. Δ*t* is the oscillation time difference between two passings through the zero-point:

$$\Delta t = t_r - t_l. \quad (2)$$

After this the correction factor of the pass-through method Δ*N* is calculated:

$$\Delta N = \Delta t * a * c, \quad (3)$$

where ***c*** is a proportionality factor, that expresses the relationship between the directional moment of the gyro and directional moment of the tape. Since the directional moment of the gyro changes with geographic latitude, ***c*** is determined for the site where measurements will be taken.

$$c = \frac{(N_1' - N_2')}{(\Delta t_2 * a_2 - \Delta t_1 * a_1)}, \quad (4)$$

As has been shown by [W. Caspary, P. Schwintzer, 1981], the final formula for azimuth A_i determination is the following:

$$A_i = Z_i - (N' + \Delta N) - C - E, \quad (5)$$

where Z_i is the direction to the target, N' is direction of preliminary orientation, ΔN is correction factor of the Pass-Through method from formula (3), *C* is the tape zero correction, *E* is the calibration constant of the device.

Tape zero correction *C* can be calculated like this:

$$C = dW * t_m, \quad (6)$$

where dW is tape zero factor for latitude φ and t_m is mean tape zero.

$$dW = \frac{dW_e}{\cos(\varphi)}, \quad (7)$$

where dW_e is the tape zero factor for latitude φ = 0° i. e. equator.

$$t_m = \frac{tz_b + tz_a}{2}, \quad (8)$$

where tz_b and tz_a are tape zero before and after measurements respectively.

The calibration value ***E*** is a constant for the instrument. This value shows the difference between the azimuth that is determined by the gyro (raw value ***U***) and the true value ***X***, both measured on a special calibration station.

$$E = X - U. \quad (9)$$

The schema for an explanation of the *E*-value is displayed on Fig. 2.

E-value to geographical Azimuth:

$$E_g = Azi - Azi_g. \quad (10)$$

E-value to local Azimuth:

$$E_l = Azi - Azi_l. \quad (11)$$

Other methods of determination are discussed in [Vanicek, 1972].

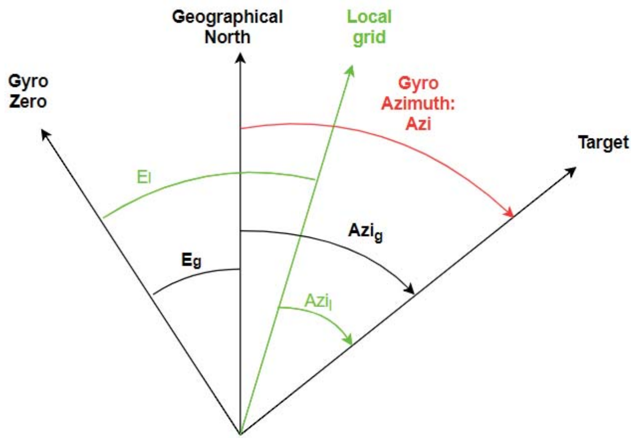

Fig. 2. E-Value schema

To establish the relationship between the scale of the measuring tape in the gyro and the scale of the sensor panel in the linear camera, it is necessary to know the parameters of both scales. The length of the measuring tape in Gyromax AK-2M is 26 mm from –20 to 20 increments. Altogether it is 40 increments. Therefore, one increment of scale will have:

$$i_m = \frac{26mm}{40} = 0{,}65\ mm$$

It is generally accepted that the human eye can divide the visible segment into 10 parts without special devices. Then the accuracy of measurement in the scale tape system will be $m_{man} = 0{,}065\ mm$. According to the information on the website of the manufacturer of the line camera [https://www.coptonix.com/_en/html/usblinecamera.html], the size of one pixel is 7×7 µm. Based on this information, it can be stated that the measurements with a line camera are approx. 9 times more accurate than manual measurements:

$$\frac{0{,}065mm}{0{,}007mm} \approx 9{,}2$$

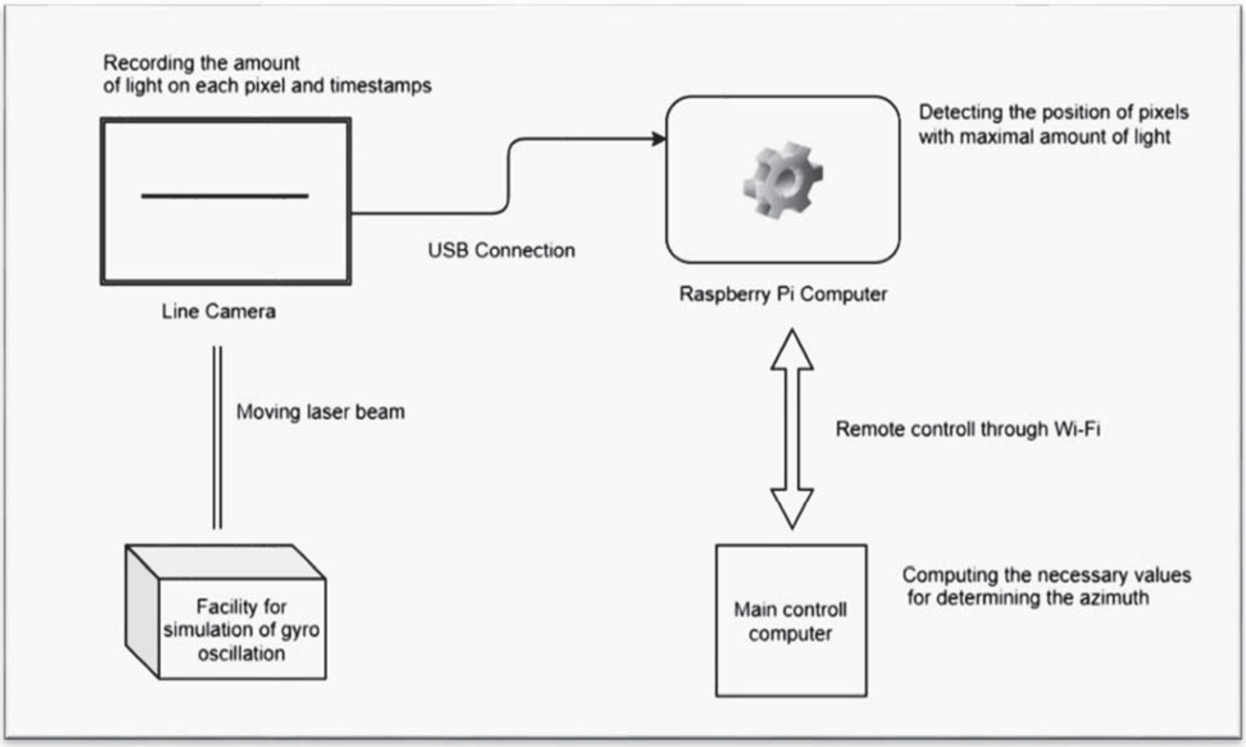

Fig. 3. General schema of developed system

It also will depend on measurement frequency and the speed of light source movement. As for measuring time, the operator can measure time with an accuracy of 0.1–0.2 seconds using a stopwatch. In an automated system, this depends on the frequency of the measurements. At a frequency above 10 Hz, the frequency of the time measurement will also increase. According to the performed tests with a line camera, it is possible to achieve a frequency of about 100 Hz. The accuracy of the time measurement, in this case, will be 0.01 sec that is 10 times more accurately than manual operations.

Line camera. A linear photosensitive matrix is a semiconductor device that line-by-line converts the optical image into an analogue signal. There are two types of linear photosensitive matrices with separate circuit configurations: CMOS and CCD matrices. Linear photosensitive matrices are suitable for devices such as scan components for photocopiers, image and barcode scanners, single-line scanning cameras used for visual studies (film, prints, textiles, etc.), grain sorters for color and banknote recognition systems in bank terminals [https://toshiba.semicon-storage.com/eu/product/sensor/linear-sensor.html].

For this project, a line camera “Coptonix USB Line Camera” from Coptonix™ was used (see fig.4). USB Line Camera consists of two circuit boards, the main circuit board, and the sensor circuit board. The main board contains the high-speed USB controller, the line sensor controller, and Memory. The sensor board contains a CCD or a CMOS line sensor and a complete 16-Bit imaging signal processor, which consists of an input clamp, Correlated Double Sampler, offset DAC, Programmable Gain Amplifier and high-performance 16-bit A/D converter. The main board supports multiple sensor boards for various sensors with a different number of pixels. The USB Line Camera is USB Bus-powered, therefore no separate power packs for voltage supply are needed. The maximum power consumption is less than 500 mA.

Furthermore, the main board has an I2C interface, which allows the control of external hardware such as IO Expander, stepper motor, ADC, DAC, temperature sensors, etc [https://www.coptonix.com/_en/html/usblinecamera.html].

A computer model Raspberry Pi 3B (see Fig. 5) was chosen for this research. It is possible to connect a line camera to a computer using a USB interface. Also, there is an operating system with a graphical interface on the computer, on which it is convenient to create the necessary programming code. It is a single-board computer with wireless LAN and Bluetooth connections.

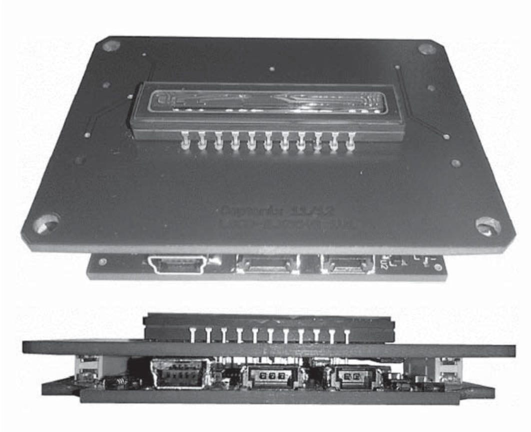

Fig. 4. USB Line Camera from Coptonix

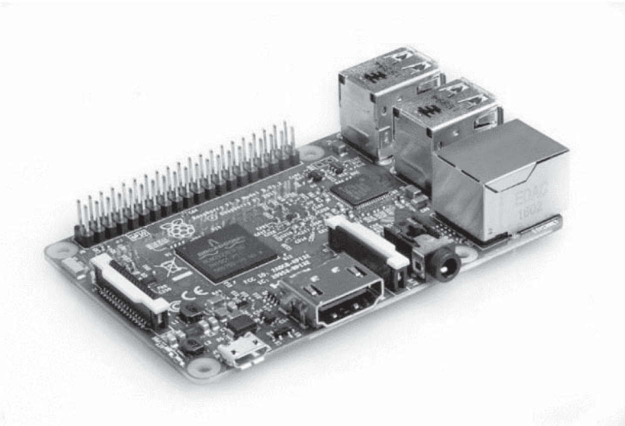

Fig. 5. Raspberry PI 3 Model B

Implementation

The project began with the testing of the camera. It was necessary to check whether this camera is suitable for the project task, and also whether it has damaged pixels

The main idea of checking pixels for damage is to find pixels with an abnormality or zero value of light sensitivity in the output file. For eliminating the influence of the daylight the black carton box was used. On Fig. 6 the graphics of output files without and with the black box are presented. The noise with using the black box is in the interval 0–500 counts of intensity (amount of light in each pixel) and 4500–8000 counts of intensity with the influence of the daylight. The minimum value for integration time – 27 μs was set up. The integration time is the time during which processor holds the voltage signal as it maximizes and stabilizes so it's possible to measure it. At the end of the integration time, the processor "resets" the voltage back down to zero so the sensor is ready for the next pulse.

With the black box, the difference between the maximum and minimum noise for every pixel was on the average 200–300 counts of intensity (for 100 measurements in different time moments). The value of counts of intensity varies from 0 to 65535 units, so the value of 229 is only 0.35 %. Every pixel had a non-zero value for 100 measurements. So there are no damaged pixels. Because each pixel on a CMOS sensor has several transistors located next to it, every 4096 pixels cannot has the same characteristics. Many of the photons that hitting the chip, hit the transistors instead of the photodiode.

For this project were used the programming language Python 3.0 and a part of the code in C-language, which was written by camera producer. The important thing was to provide access to line-camera using python code. Interaction with the camera is carried out using certain functions that are in a special library file. The library is a collection of subroutines or classes used to develop software. Libraries expose interfaces that clients of the library use to execute library routines. But since there was only the library for C-languages, a wrapper library was created. Wrapper libraries consist of a thin layer of code that translates a library's existing interface into a compatible interface. There is a foreign function library in Python which allows using C compatible data types and gives a possibility to call functions in DLLs or shared libraries. The class which has been used is a wrapper that allows the user to call the usblc32.dll Delphi library from a Python code. All parameters passed into functions and classes in this module can be regular pythonic types, and all return values are pythonic types as well. All type conversions are carried out within the wrapper, for which the "ctypes" module is internally used. The next step is to develop the graphic user interface (GUI) for convenient working with the device. For this was used PyQt toolkit. PyQt is a set of "bindings" of the Qt graphics framework for the Python programming language, implemented as a Python extension. PyQt developed by the British company Riverbank Computing (https://riverbankcomputing.com/software/pyqt/intro). PyQt also includes Qt Designer (Qt Creator), a graphical user interface designer. The special interface compiling program "pyuic" generates Python code from files created in Qt Designer. This makes PyQt a very useful tool for rapid prototyping. In addition, it's possible to add new graphical controls written in Python to Qt Designer. The loop function is nested in the code for continuous data retrieving. The function in the loop will work until the stop button interrupts it.

Particular attention should be given to obtaining data. The computer gets the value of light intensity for each pixel. The camera has 4096 pixels, the light value in each pixel needs 2 bytes for storage, that is, for the entire line camera – 8192 bytes. Since the data reading speed is very high, about 500 reads per second, all recorded data will take up a lot of memory. The output file of measurement data for one minute will contain about 245 megabytes of data. To reduce the amount of data and better information reading, the following steps have been taken: since such a high measurement speed is redundant, the program was set up to read-only every fiftieth measurement. This number made it possible to reach a frequency of approximately 10 Hz.

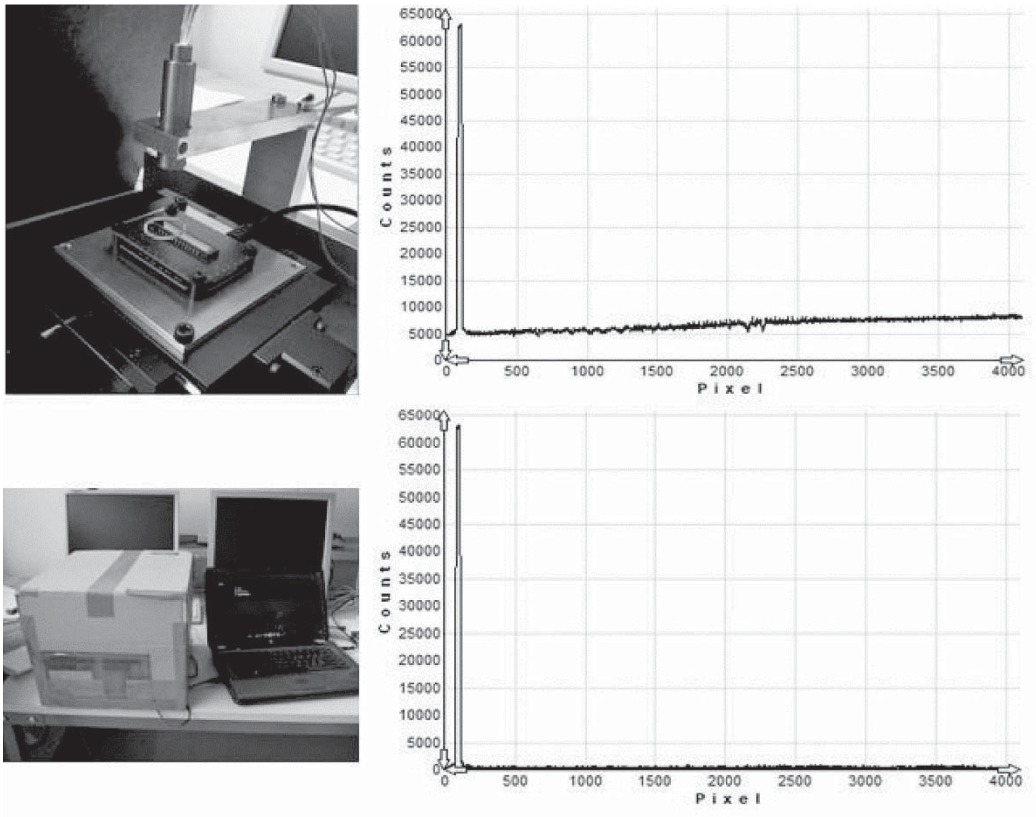

Fig. 6. Graphics of output files without and with the black box

For the purposes of the project, there is no need to write values from all 4096 pixels. It only needs to know the pixel with the highest value of light intensity. And if there are several pixels with the highest value, then the middle one is required. For this, an "if" statement was set inside the retrieving loop function with a conditional threshold of 50000. This statement implies that the intensity peak will always be above the 50.000 marks. Parallel to the recording of the intensity value of the program, computer records the time of each measurement. In the future, it will be necessary for the Pass-Through method. At the output, we have two arrays, one of which stores the number of the pixel that had the highest intensity value, and the second one stores the time in which the measurement was made. Since the number of elements in these arrays is the same, the positions of the corresponding elements in them are the same as well. This makes possible to combine these data by iterating over all elements of the array. The data structure is represented in such format: the pixel number, which had the maximum intensity value, was first specified. Then, after the colon, the date and time of the measurement are specified, in which this pixel was defined. After closing the device, the last action of the program is launching the script on the Raspberry, which loads the file with the selected data on the webserver. At the end of the program, the web.py script is launching for uploading the data on the webserver. Web.py is a framework, for supporting the development of web applications including web services, web resources, and web APIs. But for this project, only one function of this framework is required: to upload data to a local address, with the ability to download data from other devices. To run the external script from the main program a subprocess module is required. The subprocess module allows the developer to run program processes from Python. In other words, it's possible to run applications and pass arguments to them using the subprocess module.

The second program was written for client-device since the computing power of the raspberry processor is not enough for quick data processing. The GUI for this program was also developed on the PyQt framework. To test the program, it was necessary to simulate oscillations of the gyroscope suspension tape. For this purpose, a special installation was designed, on which a line camera was placed (see Fig. 7).

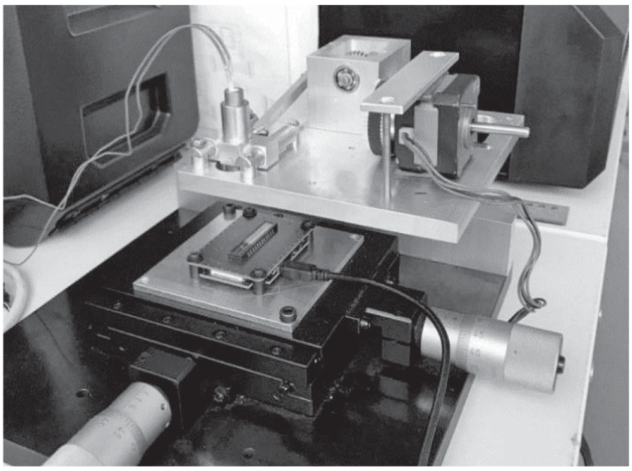

Fig. 7. Special facility for testing the camera

The purpose of this installation is that above the camera there is a light source that is pointed to the camera's pixel panel. With the help of a system of gears and a motor connected to the chip, the laser moves along the pixel panel of the camera reaching the edge and returning back. Thus, the motion of the light bar in the gyroscope is simulated. The chip programmed two modes of the speed of the motor corresponding to the approximate speed of the light bar motion when the gyro mode is on and off. So it is possible to simulate tape zero measurements with one-speed mode and Pass-Through method measurement with another.

To test the program, 5 complete measurements have been made. Measurement results are displayed in Fig. 8. The maximal difference between turning points position in one measurement was 2 pixels, that equals to 0.014 mm. The maximal difference between turning points position in different measurements was 10 pixels, that equals to 0.070 mm. Such a big difference between turning points pixels is due to the fact, that the laser moving system is not very precise. The maximal difference between the timestamps of a zero-crossing pixel in different measurements is around 0.5 seconds. This is due to the same drawback of the facility.

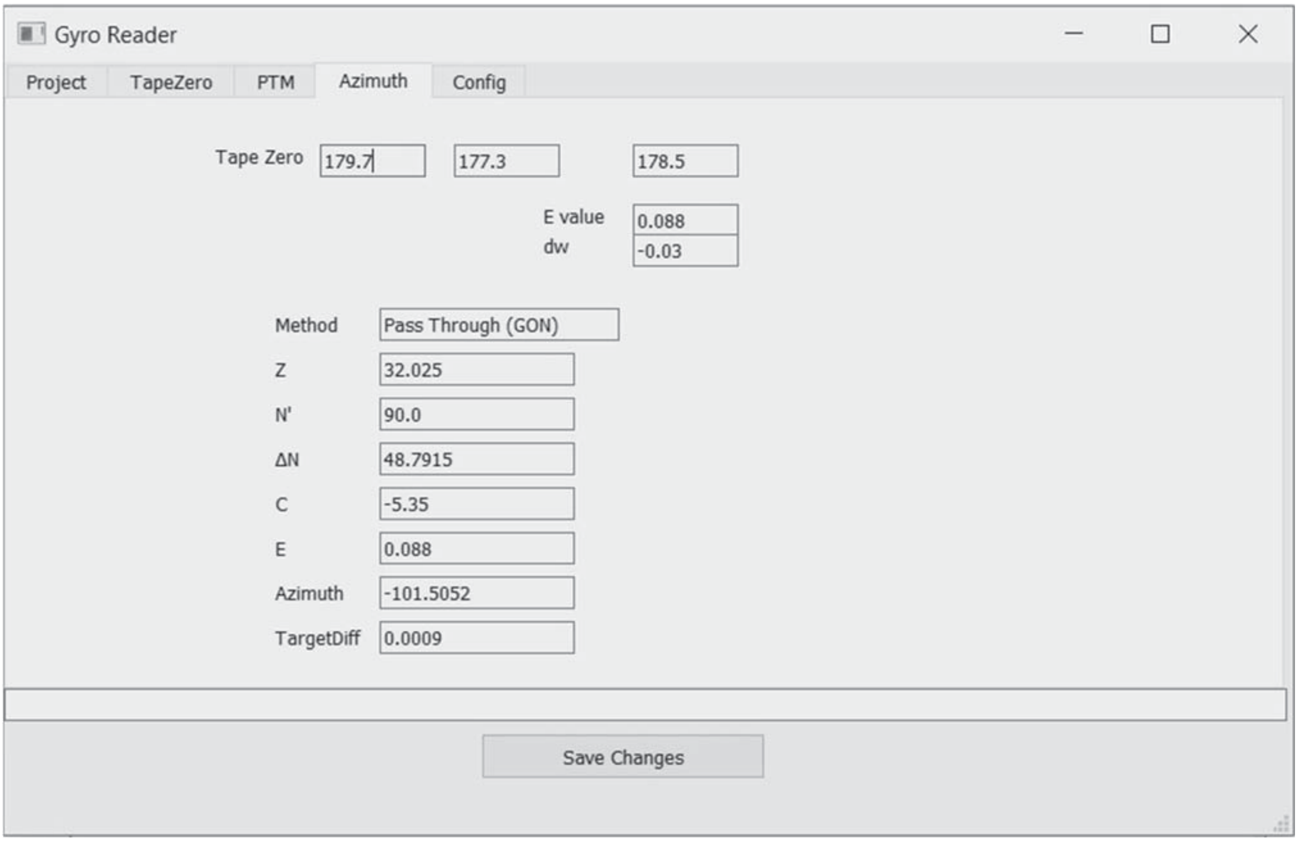

Fig. 8. Results of running the test program

Results

The designed system was tested using a special installation that simulates gyroscope oscillations. The results of its work showed that the accuracy of determining the position of oscillations is approximately 10 times more accurate than with manual measurements. The accuracy of measurements in automatic mode will depend on the frequency of the measurements and the size of the pixels. For example, if manual measurements have the accuracy of the amplitude determination around 0.1–0.2 scale increments, then for automatic measurement this value is less than 0.1 scale increment. For manual measurement of time accuracy is around 0.1–0.2 sec., so for automatic mode, it is less than 0.1 sec., i. e. frequency of measurement should be greater than 10 Hz. In practice, it's possible to reach 100 Hz frequency. It should also be noted that in automatic measurements, an observer error is excluded. It is worth saying that it was not possible to implement the actual testing of the developed system on the AK-2M gyroscope due to the inability to mount the designed system into the gyroscope housing. Future research should include solutions to place this system inside the gyro housing.

Scientific novelty and practical significance

The completely new method of digitizing the measuring process in the GYROMAX AK-2M gyro add-on was presented in this work. The results of this investigation open the possibilities to improve the Gyromax AK-2M gyroscopic add-ons by implementing the automated measuring procedure, therefore, for the modern users it will be much more profitable to use an automatic device. Doing manual measurements, there is always an observer error. The automated measurement process allows excluding this error, thereby increasing the accuracy of measurements. Also, it allows using ready-made templates and measurement programs that come with the product.

Conclusions

A linear camera from Coptonix has been tested for use in Gyromax AK-2M gyro add-ons. The camera pixels interpret the light that enters them as quantity units from 0 to 65535. Testing showed that the camera is working properly, no damaged pixels were detected. Camera parameters meet project requirements. The software has been created for communicating with the camera, processing the data received from it, and calculating the necessary values.

Python programming language was used for this task. The software is represented by two programs with a graphical interface. One of them developed on the single-board computer Raspberry 3B and responsible for data acquisition, the other one, on the client computer, that processes the data and makes computations. The software has a user-friendly graphic user interface that allows a user to make all necessary operations. The end result of the program is the XML-file with the results of measurements. Special installation for the simulation of gyro oscillation was created. The reproduction of the oscillation process is carried out by means of a moving light source driven by a system of gears connected to the motor. The system has two-speed modes for different measurement methods. It can be used in further research.

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ДОСЛІДЖЕННЯ ОЦИФРУВАННЯ КОЛИВАНЬ ГІРОСКОПА ЗА ДОПОМОГОЮ ЛІНІЙНОЇ КАМЕРИ

Метою цієї роботи є розроблення технології автоматизованого процесу вимірювання гіроскопом “Gyromax AK-2M” для визначення азимута. Точність визначення основних величин має бути вищою, ніж за механічної процедури вимірювання. У цій роботі описано метод оцифрування коливань гіроскопа з використанням камери із лінійним сенсором. Досліджено можливість роботи з лінійною камерою фірми

Coptonix™, а також можливість її підключення до одноплатного комп'ютера Raspberry Pi 3B для передавання даних та їх оброблення. Перевірено можливість використання програмної мови Python 3.0 для реалізації проєкту. **Методика**. Для реалізації цього проєкту застосовано комплексний підхід з використанням таких пристроїв, як камера із лінійним сенсором, одноплатний комп'ютер і пристрій, що імітує коливання гіроскопа. У роботі досліджено оцифрування даних вимірювання, обчислення значення азимута й автома. Для автоматизованого обчислення даних використано ті самі два методи, що використовують у звичайних вимірюваннях – метод поворотної точки (TPM) та метод проходження (PTM). **Результати**. Результат роботи – автоматизована система вимірювання коливань, яка може бути застосована в гіроскопах. У систему входить розроблене програмне забезпечення, яке з'єднує користувача із лінійною камерою і комп'ютером, який обробляє вимірювання, записує необхідні дані, передає їх на комп'ютер-клієнт і обчислює необхідні значення. Щоб забезпечити зручність використання програми для інших користувачів, програма оснащена графічним інтерфейсом. Результатом роботи програми є файл із розширенням XML, який містить дані про вимірювання. **Наукова новизна та практична значущість**. У роботі запропоновано новий метод оцифрування коливань гіроскопа. Застосування камери із лінійним сенсором та одноплатного комп'ютера для цього завдання відкриває багато можливостей для вдосконалення процесів автоматизації геодезичних приладів, що може підвищити точність вимірювань та зменшити їх тривалість. Розробляючи цей метод оцифрування вимірювань, можна розпочати виробництво вдосконаленої версії гіроскопічної насадки GYROMAX AK-2M.

Ключові слова: гіроскоп, лінійна камера, оцифрування, автоматизація вимірювань.