Розроблено алгоритм процесу моніторингу внутрішнього контуру гірської виробки, що дозволяє визначити геометрію виробки з врахуванням особливостей геотехнічного моніторингу. В основі алгоритму побудови профілю лежать залежності перетворювання координат точки в просторі при переході від різних систем координат, які дозволять врахувати відхилення геомехатронного комплексу від прямолінійного руху

Ключові слова: геомехатронний комплекс, система координат, профіль виробки, датчик відстані, мікроконтролер

Разработан алгоритм процесса мониторинга внутреннего контура горной выработки, позволяющий определить геометрию выработки с учетом особенностей геотехнического мониторинга. В основе алгоритма построения профиля лежат зависимости преобразования координат точки в пространстве при переходе от различных систем координат, которые позволяют учесть отклонение геомехатронного комплекса от первоначального направления

Ключевые слова: геомехатронный комплекс, система координат, профиль выработки, датчик расстояния, микроконтроллер

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DEVELOPMENT OF A GEOMECHATRONIC COMPLEX FOR THE GEOTECHNICAL MONITORING OF THE CONTOUR OF A MINE WORKING

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1. Introduction

Present stage of development of the means for determining the properties and diagnosing the condition of geotechnical facilities is characterized by the use of the latest achievements of mechanics, information technology, electrical engineering and control theory. Engaging such fields of science and technology in combination with geography and geology enabled to create qualitatively new directions of technical progress: geoinformatics (geoinformation systems), well telemetry, internal pipe inspection and others. These systems are integrated computer systems that are managed by specialists-analysts who collect, save, manipulate, analyze, simulate and map spatially correlated data [1]. Given the existence of characteristic attributes, such as IT-technologies, electronic systems, control systems, different types of sensors, mechanical, optical and other systems of data collection, such systems can be categorized as mechatronic [2]. For the purpose of creating automated systems of geomechanical monitoring [3], there is a need to create domestic profilometer for underground workings based on a multi-purpose geomechatronic complex. Similar robotic geoinformation complexes have been successfully implemented in research where the presence of a human is complicated: exploring the volcanoes, wells, deserts, seabed, oil-gas fields, etc. [4–7].

The principle of work of a profilometer for underground workings is similar to the means of diagnosis of oil pipelines, the internal pipe profilometers, which unclude odometer, spider, power supply, pipe turn sensor and sealing cuffs. Direct application of the internal-pipe profilometer is impossible for a number of reasons. Displacement of diagnostic complexes in most cases takes place due to the energy of the flow of transported product. Positioning the sensors relative to the axis of a pipeline is achieved through a direct contact between conical sealing cuffs and inner periphery of the contour [8]. Moving a diagnostic complex along the axis of the underground facility is enabled by employing a pneumatic drive of the trolley that carries a set of sensors with registering equipment. Because of this, a change in position relative to the initial coordinate system is very likely, as well as the distortion of data. In order to retrieve actual data on the relative geometry of an excavation profile, it is necessary to convert data taking into account the actual position of sensors relative to the initial frame of reference. To carry out conversion, which would align free spatial motion of a diagnostic complex with an initial reference system, it is necessary to develop a sequence of transformations. They are executed based on the existing positioning patterns of the elements of mechatronic systems. This will make it possible to determine the actual profile of an excavation contour taking into account special features in the geotechnical monitoring of a mining excavation. That is why devising an algorithm for the operation of a geomechatronic complex for monitoring the inner surface of an underground working based on analytical dependences that take into account a change in the position of the system relative to the initial coordinate system is an important scientific task.

2. Literature review and problem statement

One of the main factors that define the proper stability of workings is the actual profile of a working. Establishing the difference between a projected initial state of mounting and the operational data makes it possible to control, diagnose and predict the stressed-strained state of a geomechanical space [9]. Depending on the tasks, which are solved, there are two methods commonly used in mining engineering: the method of contour benchmarks and the serif method (the triangle method) [10]. In both cases, they measure the distances between benchmarks or between serifs and railhead, which makes it possible to determine the convergence of benchmarks and serifs by comparison. To determine the absolute value of displacement of a working profile, it is necessary to level one of the benchmarks or two railheads. Both in the first and the second case, the processes of obtaining data are labor intensive and allow retrieving data only for a particular cross section that predetermines low productivity of geotechnical monitoring.

Another technique to receive information about a change in the profile deformation is to install in the connected nodes the cuffs, which deform at change in a working profile [11]. This method enables obtaining information continuously about condition of a working in a particular intersection, but it is applicable for use under conditions of frame fastening.

To obtain data lengthwise the structures, mobile robots are employed with laser distance sensors that allow receiving data at high speed [3]. In order to displace a hardware complex along a working, among various options, caterpillar and pneumo-wheeled platforms, the most widely used are those four-wheeled and six-wheeled [12]. Application of pneumo-wheeled platforms minimizes energy costs when moving the equipment. In order to determine a complicated stressed state of the massifs adjacent to the contour, it is required to define geometric parameters of the system. For this purpose, it is possible to use a 3-D map [13]. Creating 2-D and 3-D maps is carried out by using the pairwise registration method [14]. This will make it possible to determine a position by comparing data from several sensors under conditions where it is impossible to use the global navigation system. Using the given systems requires applying hardware redundancy and employment of complicated mathematical transformations for the environments that contain cyclic structures.

Simplifying the system for collecting and processing information with the improved accuracy of received data is carried out by using modern microelectronic systems. This is possible by applying dependences of conversion of a point coordinates in space during transition from different coordinate systems: the original and the current.

3. The aim and tasks of research

The aim of present study is to define the algorithm of operation and to create an industrial-experimental sample of a geomechatronic complex to determine the actual profile of an underground working that would make it possible to analyze the state of fixture or processing.

To accomplish the set aim, the following tasks were formulated:

– to analyze existing methods for determining the geometry and shift in a profile of mine workings;

– to analyze techniques for the positioning of elements of mechatronic systems;

– to develop a base of functioning of a geomechatronic complex, which would make it possible to define the tasks and the area of application of the devices of this class;

– to test experimentally the devised theoretical developments by constructing a profile of a working contour.

4. Development of basic approaches and an algorithm of operation of a geomechatronic complex for monitoring the inner surface of an underground working

An analysis of situations for the main types of underground facilities and communications, possible damage to fastening and processing, a change in design position of structures allows us to define the main tasks that need to be addressed during geotechnical monitoring:

– analysis of the stressed-strained state of a nearby contour of underground workings;

– analysis of change in geometric parameters of an underground working (the contour, the profile, the plan);

– analysis of damage to structural elements.

As additional parameters that make it possible to safely conduct the underground development of mineral resources, we can use parameters of gas and dust concentration.

These operations are particularly important and complicated given the need to receive specified data from emergency areas.

The scope of application of a geomechatronic complex:

– underground structures of enterprises that employ underground technology of exploration of mineral resources;

– transportation tunnels for various purposes;

– urban engineering facilities.

If need be, a geomechatronic complex can be adapted to tackle related problems, such as diagnosing the state of dust and gas concentration in the underground workings, etc.

Considering the set tasks and the scope of application, the basic criteria when creating an algorithm for the operation of mechatronic complexes for monitoring the geotechnical structures are:

– probability of a characteristic to detect damage to the fastening of underground workings;

– probability of a characteristic to detect critical strained states of the mountain massifs adjacent to an underground working;

– speed and range of motion of a geomechatronic complex for the geotechnical monitoring of the contour of a mine working;

– reliability in the operation of a geomechatronic complex.

Among the main requirements that need to be considered when creating geomechatronic complexes, it is necessary to note the following:

– low cost of the creation and maintenance of the complex;

– safety during monitoring;

– simple design, no need for adjusting and complex regulation on the site;

– resistance to high humidity and dust concentration;

– explosion safety;

– ease of training for staff and easy management;

– mobility;

– transportability.

When a geomechatronic complex moves along an underground working, position of the sensor is constantly changing as a result of surface irregularities of the working soleplate. A platform that carries distance sensors, accelerometer and gyroscope and which moves at velocity V is displaced relative to the initial position and is turned at angles around the axes of the original coordinate system OX, OY, OZ (Fig. 1). This leads to the distortion of received data on the profile of the working. When the complex stops, the sensors of distance and of the turning angle of distance sensor form the primary data array $[\alpha', R']$ that describes in the polar coordinates the working contour relative to the new position:

In order to obtain coordinates of the profile relative to the initial coordinates, received data are converted to the Cartesian coordinates, they are then recalculated taking into account the new position of the platform, next it is possible to convert to the polar coordinates

$$[\alpha', R'] \rightarrow [X', Y', Z'] \rightarrow [X_0, Y_0, Z_0] \rightarrow [\alpha, R].$$

To describe position of the complex platform, one requires 6 parameters in a three-dimensional space. We selected displacements Δx, Δy, Δz and the Euler angles Δφ, Δψ, Δθ (Fig. 2) as parameters that describe position of the platform.

Among various systems of the Euler angles that describe orientation of a body relative to the initial coordinate system, we selected a system whose rotation vectors are collinear to the axes OX_0, OY_0, OZ_0. These directions of rotation are called the angles of pitch φ, roll θ and yaw ψ. The advantage of this system is in the application of modern microelectronic systems to control the motion of devices [6, 7].

Because the sensor of distance R' is in point O' and rotates around its axis that is parallel to the $O'X'$ axis, all values are within plane $O'Y'Z'$:

$$x' = 0. \tag{1}$$

Conversion from the polar coordinate system to the Cartesian $[\alpha', R'] \rightarrow [X', Y', Z']$, taking into account (1):

$$\begin{cases} x' = 0; \\ y' = R' \cos\alpha'; \\ z' = R' \sin\alpha', \end{cases} \tag{2}$$

where R' is the distance from the sensor rotation axis to the internal contour; α is the sensor rotation angle.

A transition between the coordinate systems

$$[X', Y', Z'] \rightarrow [X, Y, Z]$$

can be executed by making use of the system of dependences, which takes into account the gradual displacement and rotation [15]:

$$\begin{cases} x_0 = (\cos\Delta\varphi \, \cos\Delta\theta)x' + \\ +(\cos\Delta\varphi \sin\Delta\psi \sin\Delta\theta - \sin\Delta\varphi \cos\Delta\psi)y' + \\ +(\cos\Delta\varphi \sin\Delta\theta \cos\Delta\psi - \sin\Delta\varphi \sin\Delta\psi)z' + \Delta x; \\ y_0 = (\sin\Delta\varphi \cos\Delta\theta)x' + \\ +(\sin\Delta\varphi \sin\Delta\psi \sin\Delta\theta + \cos\Delta\varphi \cos\Delta\psi)y' + \\ +(\sin\Delta\varphi \sin\Delta\theta \cos\Delta\psi - \cos\Delta\varphi \sin\Delta\psi)z' + \Delta y; \\ z_0 = -\sin\Delta\theta x' + (\cos\Delta\theta \sin\Delta\psi)y' + \\ +(\cos\Delta\theta \cos\Delta\psi)z' + \Delta z. \end{cases} \tag{3}$$

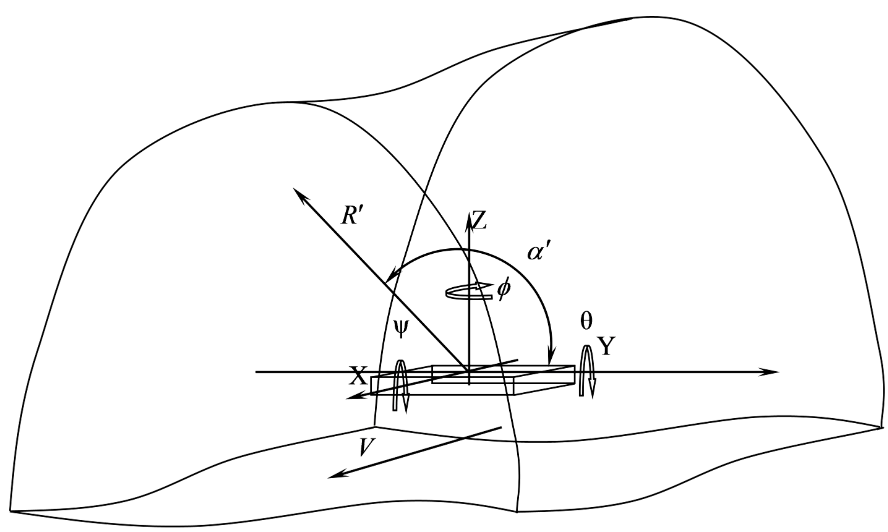

Fig. 1. Schematic of motion and data collection of a geomechatronic complex

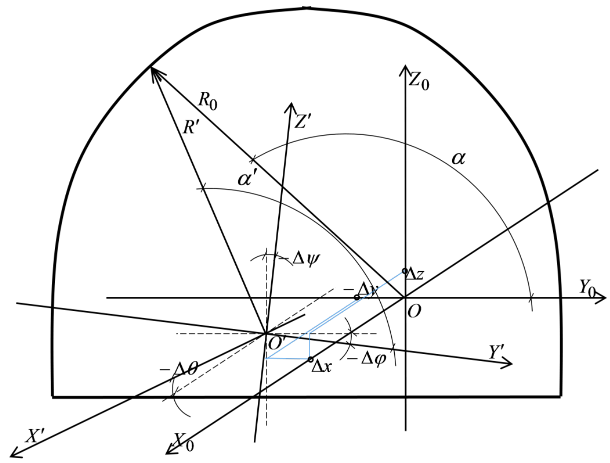

Fig. 2. Schematic of conversion between the coordinate systems $\left[X',Y',Z'\right]\to\left[X,Y,Z\right]$

Considering system (2), system (3) takes the following form:

$$\begin{cases} x_0=(\cos\Delta\phi\sin\Delta\psi\sin\Delta\theta-\sin\Delta\phi\cos\Delta\psi)R'\cos\alpha'+ \\ +(\cos\Delta\phi\sin\Delta\theta\cos\Delta\psi-\sin\Delta\phi\sin\Delta\psi)R'\sin\alpha'+\Delta x; \\ y_0=(\sin\Delta\phi\sin\Delta\psi\sin\Delta\theta+\cos\Delta\phi\cos\Delta\psi)R'\cos\alpha'+ \\ +(\sin\Delta\phi\sin\Delta\theta\cos\Delta\psi-\cos\Delta\phi\sin\Delta\psi)R'\sin\alpha'+\Delta y; \\ z_0=(\cos\Delta\theta\sin\Delta\psi)R'\cos\alpha'+(\cos\Delta\theta\cos\Delta\psi)R'\sin\alpha'+\Delta z, \end{cases}$$

where Δx is the displacement lengthwise the working, Δy is the displacement in the horizontal plane, Δz is the displacement in the vertical plane.

If need be, to build a separate profile along the working with coordinate x_0, it is possible to pass to the polar system $\left[X_0,Y_0,Z_0\right]\to\left[\alpha,R\right]$

$$\begin{cases} \alpha=\arccos\dfrac{x_0}{\sqrt{x_0^2+z_0^2}}; \\ R=\sqrt{x_0^2+z_0^2}. \end{cases}$$

A particular difficulty when determining a position of the mechatronic systems is determining the position of the centre of reference system $O'X'Y'Z'$ (Δx, Δy, Δz) by the readings of accelerometer through double integration of the obtained values of acceleration by time [16–18]. The result of noise and distortion of data associated with vibration, a change in the position and calibration of the sensor, is a significant measurement error (up to 20 m). That is why, to determine the position O'(Δx, Δy, Δz), it is proposed to use data of the gyroscope and the length of the path (trajectory) L (Fig. 3).

Coordinates of the centre of reference system (Δx, Δy, Δz) with a certain accuracy can be represented as the sym of projection of elementary displacements Δl along the axes OX, OY, OZ:

$$\begin{cases} \Delta x=\sum_{i=1}^{n}\Delta l\cos\Delta\theta_i\cos\Delta\phi_i, \\ \Delta y=\sum_{i=1}^{n}\Delta l\cos\Delta\phi_i\cos\Delta\psi_i, \\ \Delta y=\sum_{i=1}^{n}\Delta l\cos\Delta\theta_i\cos\Delta\psi_i, \end{cases}$$

where n is the number of steps.

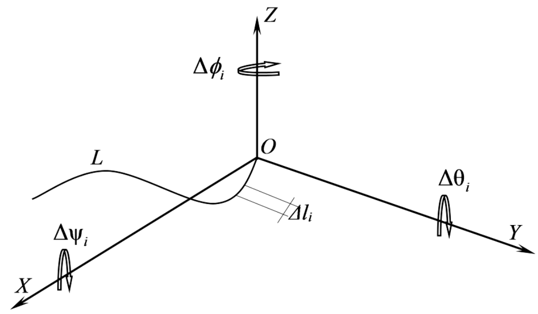

Fig. 3. Schematic of determining a position of the reference system

Data for building the profile of an underground working represent an array of data. It contains distances from the inner contour of the working to the axis of rotation, the sensor rotation angle, sensor incidence relative the initial position and the path that the complex traveled. Obtained data are accumulated in the device memory and undergo subsequent analysis by recalculating the distance from the sensor to the periphery of the working with the correction of its position and the simulation of a spatial model of the working.

The algorithm of program operation (Fig. 4) is a cyclical structure, which successively performs data registration from different sensors, data conversion, and records data on a memory card. Each cycle of the program is executed when a geomechatronic complex covers distance Δl. At a certain position of the distance sensor α', data are retrieved about incidence of the complex relative to the initial position δφ, Δψ, Δθ and the distance from the point of the contour of working to the axis of distance sensor R'. The number of points of one intersection depends on the design of the turning drive of the sensor. When using a step engine, the number of points is determined by the angular displacement Δα, which is 1.8° per one step. Thus, the total number of points n_α without the use of a gear can be within 200 values, which is sufficient to diagnose the condition of a working.

A basis of the complex for geotechnical monitoring of the profile of a mine working, similar to any mechatronic device, is a microcontroller. In the present work we used the Arduino corporation microcontroller based on the ATmega328 processor (ATmega16U2) (Italy), which enables high speed processing (clock speed is 16 MHz) of obtained data and setting controlling influences on the complex's power electronics, which in turn supplies power to the final controlling elements (Fig. 5).

A special feature of this type of a microcontroller is an open source code of the programming environment that implements the algorithm Processing/Wiring by the programming language C and includes a series of libraries that make it possible to integrate the device with periphery. The microcontroller has 20 digital output contacts for entering, six of which under certain conditions (lack of control over servomotor) can be used as PWM outputs while six can be used as analog inputs. The given microcontroller, due to a built-in voltage stabilizer, can be powered by three schemes: from USB and the DC sources of 5 and 9–12 V. Embedded USB connection can be used for simple FLASH ROM programming or to communicate with other devices. The advantages of this type of controller when creating new mechatronic systems is the ease of programming and the ease of connecting different types of sensors and modules. The disadvantages include a small volume of memory (32 KB) and low reliability.

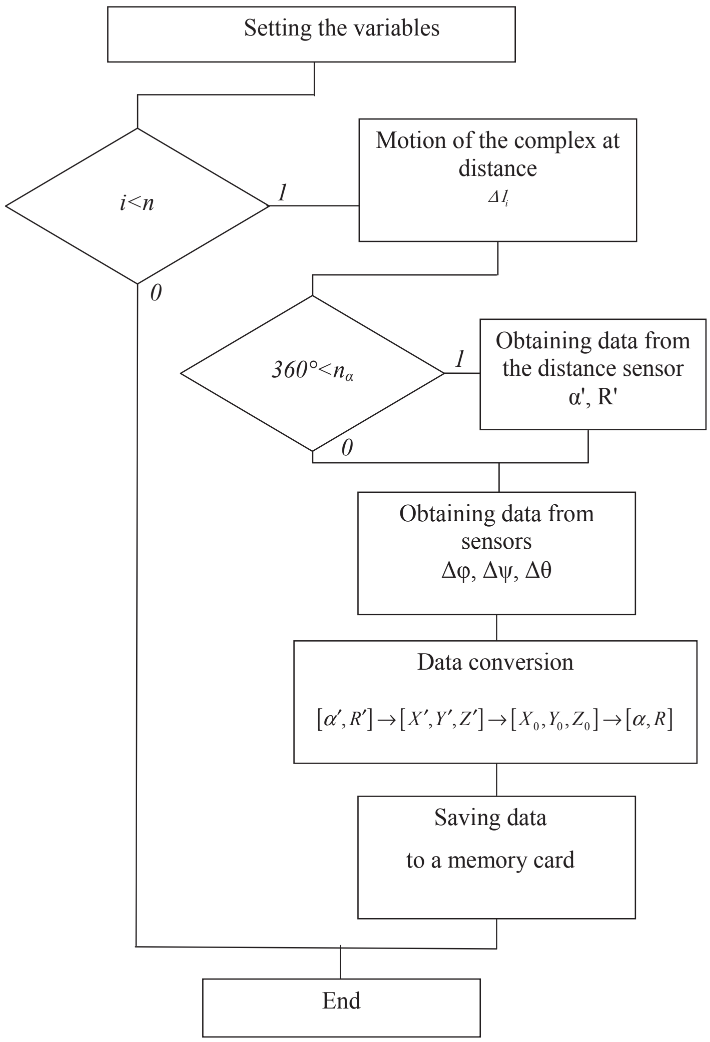

Fig. 4. Algorithm of work of geomechatronic complex software

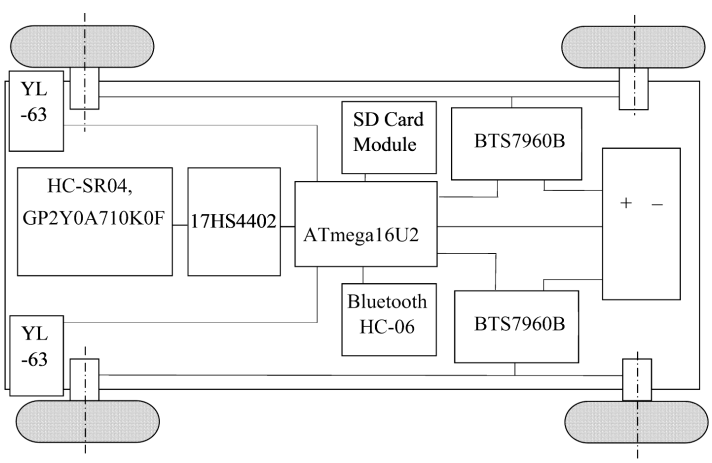

Fig. 5. Schematic layout of the complex for geotechnical monitoring of the contour of a mine working

The main elements of power electronics are the drivers BTS7960B and TB6560 which enable adjusting the direction of rotation and the speed of controlling elements (stepper motor 17HS4402 (China) and coupled motor-wheels. Using the stepper motor 17HS4402 with the driver TB6560 (with a peak value of current 3.5 A) also enables setting the angular position ’ of a distance sensor.

The main electromechanical converters control over which is executed using the drivers (BTS7960B and TB6560) is a motor-wheel and a stepper motor whose characteristics are given in Table 1. A motor-wheel consists of a DC motor, worm gear and a pneumatic wheel. Application of the worm gear allowed creating considerable torques at minimal complication of kinematic scheme of the drive, which allows the complex to overcome small obstacles. Along with this, the use of the worm gear leads to increased energy losses during constant displacement and heating of the drive's transmission. However, given the fact that the complex moves in steps Δl with stops for the time needed to perform a full rotation of the stepper motor 17HS4402, the overheating of the drive does not occur.

To supply the mechatronic complex with power, we used two DC power sources of various power, which is caused by a feature of connecting the driver of the stepper motor TB6560 and a dependence of the stable operation of the microcontroller on the changes in voltage. Voltage drop in the power system of the complex occurs as a result of high inrush currents of motor-wheels at step motion of the geomechatronic complex. We used as power sources the lead-acid batteries of the same level of voltage 12 V and different capacities of 1.2 and 60A·h.

Table 1

Characteristics of main electromechanical converters

Indicator	Motor-wheel	Stepper motor
Power voltage, V	12	12
Maximal capacity, W	70 W	20.4 W
Maximal rotation frequency, rev/min	60	120
Wheel diameter, m	0.25	–
Torque, N	11	0.4

Control over motion of the mechatronic complex is conducted by using the sensors of position of the pneumo-wheel of a motor reducer. As sensors of position of the motor-wheel, we used the infrared interference sensor YL-63 (SG035-SZ), which receives a signal reflection from the stiffeners of the wheel hub. For the given project we employed a wheel hub with six stiffeners that makes it possible to control the position of a mechatronic complex with an accuracy equal to 0.131 m. This value of step of the motion is sufficient to construct with high accuracy the three-dimensional geometric models of underground workings whose length is hundreds of meters.

When measuring the distance from the contour of the working to the turning axis of sensor R', we uses two types of sensors: the ultrasonic HC-SR04 and the infrared GP2Y0A710K0F. The applied ultrasonic sensor has a measuring accuracy of 0.003 m, effective angle of 15° and a distance measurement range of 0.02–0.4 m, which enables conducting research in the underground facilities with diameter of up to 0.4 m. The infrared sensor GP2Y0A710K0F has a larger radius of action to 5.5 m that makes it possible to build a profile of most known types of underground facilities. In addition, a comparison of the accuracy of data obtained from two types of sensors indicates better accuracy of the infrared sensor GP2Y0A710K0F.

Saving the received initial data from sensors to a SD memory flash card is performed using the module of an SD-card, which is powered by the microcontroller. Data are recorded in the form of an array to a text file where they are converted and can be subsequently used for constructing the three-dimensional geometric models.

We used a rigid pneumo-wheeled chassis with non-turning wheels (Fig. 6) as a base for the complex of geotechnical monitoring, which carried all the mounted above-mentioned components. Weight of the complex is about 17.4 kg.

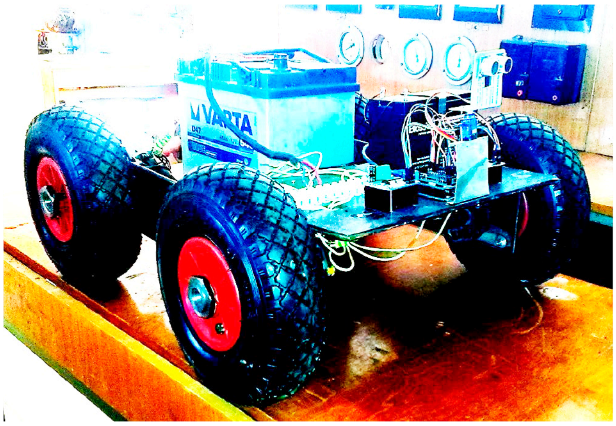

Fig. 6. General view of the chassis for a complex of geotechnical monitoring of the profile of a mine working

The designed platform of a pneumo-wheeled chassis enables the motion of the complex at angle 24° and makes it possible to overcome obstacles of height up to 0.1 m, which is sufficient for the most of mine workings.

6. Discussion of results of experimental research

A strong point of the study is that the proposed technique of determining the coordinates of position of the complex relative to the initial coordinate system by using the data from accelerometer and the length of trajectory makes it possible to eliminate hardware redundancy. This greatly reduces the cost of research.

Applying this method to determine positioning has an advantage over the method of pairwise registration for those workings that have a profile periodicity.

Fig. 7 shows a cross-section of the working with a diameter of 1.8 m, built by the results of obtained data from a distance sensor and converted in accordance with the position of the sensor relative to the initial coordinate system. A dotted line shows the data obtained while turning the axis of the sensor $\Delta\theta$ at 30 °, a solid line shows the converted values. It is possible to note a fairly high (95 %) accuracy (0.5 cm) of the obtained results despite the high values of the pitch angle.

Obtained data allow us to construct geometric models of underground space in the engineering programming packages ANSYS and SolidWorks. If we know initial conditions for loads from mine pressure and technological equipment, as well as a difference in the change of a project contour, it is possible to determine the stressed-strained state of the adjacent layers of underground working in order to prevent dangerous geotechnical manifestations.

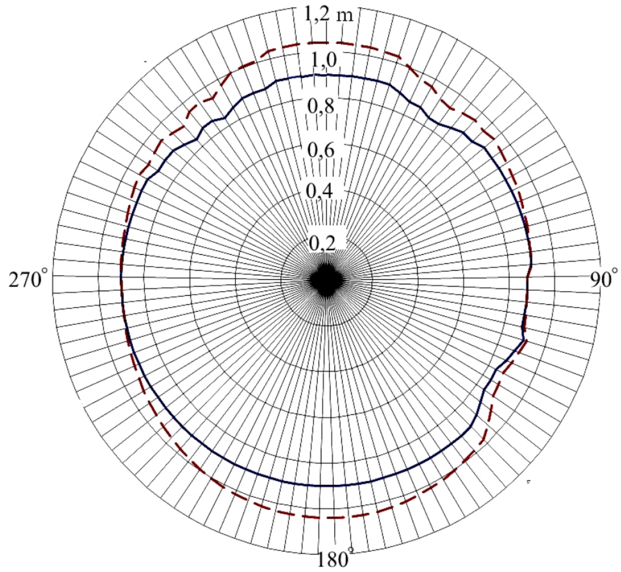

Fig. 7. Initial [α', R'] and converted [α, R] data on the contour of a working

Designed profilometer for underground workings based on the geomechatronic complex will significantly reduce labor complexity, materials consumption with a simultaneous improvement in the completeness and quality of data collection process on the behavior of surface of mine workings. The given complex allows installing additional equipment for data collection on the dust and gas concentration. Localization of sites of a mine with critical values of stresses, dust and gas concentrations makes it possible to decrease the number of accidents at the geotechnical enterprises.

Further development of the resulting algorithm of action of the geomechatronic complex will include new functional possibilities in the field of data collection on the status of pipelines and areas that have suffered the consequences of military conflicts.

7. Conclusions

1. It was established that among the existing methods of determining the geometry and displacement of the contour of mine workings, it is possible to isolate two independent groups – contact and contactless. The latter have a significant advantage in terms of speed and completeness of the information. The contactless methods are based on the use of ultrasonic, infrared and laser distance sensors.

2. An analysis of techniques for the positioning of mechatronic systems revealed that in order to determine position of the complex using the microelectronic systems, it is necessary to employ six components: three displacements Δx, Δy, Δz and three Euler angles $\Delta\varphi$, $\Delta\psi$, $\Delta\theta$. These parameters allowed us to establish a change in the position of the complex from the original coordinate system.

3. We developed basic approaches for the creation of geomechatronic complexes, which define the main tasks, the scope of application, and quality criteria. To build a profile of a working, the algorithm devised is a cyclical structure, which successively performs data registration from different sensors, data conversion taking into account position of the complex, and data recording to a memory card.

4. In order to implementation the proposed basic approaches to creation geomechatronic complexes, we designed an experimental sample of the profilometer, which, in contrast to the analogues for positioning, uses a microelectronic gyroscope that registers the distance it traveled. Using the developed algorithm allows us to establish with a high accuracy (0.5 cm) the geometry of a working taking into account a deviation of the distance sensor relative to the initial position.

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