Geo-navigation system for rotary percussion drilling in rocks of high and low electrical conductivity

AI Konurin, AP Khmelinin* and EV Denisova
Chinakal Institute of Mining, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia
E-mail: *khmelinin@misd.ru

Abstract. The currently available drill navigation systems, with their benefits and shortcomings are reviewed. A mathematical model is built to describe the inertial navigation system movement in horizontal and inclined drilling. A prototype model of the inertial navigation system for rotary percussion drills has been designed.

1. Introduction
Drilling is one of the most important processes in mineral mining and in construction. The issue of deviation of drilling from the preset direction remains topical though the market offers plenty of modern geo-navigation systems [1–3].

This problem of navigation is also topical in rotary–percussion drilling in hard rocks using, for example, air hammer drills [4]. Borehole devices to measure deflection of hole during drilling use acceleration transducers, or magnetic intrusion detectors and gyroscopic pickups which are insufficiently strong and reliable in operation under impact load [5].

Geotechnology of mineral mining with blasting needs information on spatial position of holes and their deviation from drilling-and-blasting design since standard drilling and blasting designs and explosive analyses leave out a probability of drilling deviation. In the meanwhile, deflection of a blast hole from the drilling path results either in oversizes or in overgrinding.

The horizontal direction drilling currently widely uses such locating and tracking systems as Digi Track F2, Digi Track F5, SNS-100, 200, etc., which allow sufficiently high precision (to 0.1°) of determining hole deflection in vertical plane but are low-accurate in estimating deviation angle in plan [1–3]. Moreover, their effective distance is limited, and the horizontal directional drilling is impossible in hard rocks.

The systems of measurement and logging (Measurement While Drilling, MWD; Logging While Drilling, LWD) estimate vertical deviation of holes using magnetic intrusion devices and acceleration meters as a rule [6].

More accurate measurement of hole deflection is possible with the systems using downhole gyroscopic inclinometers (Gyro Tracer Directional, UGI-42, IES-54, etc. system GWD90 manufactured by Gyro Data Inc., Gyro Pulse by Shlumberger, gyro MWD by Scientific Drilling and others) [6]. Such systems are insusceptible to magnetic anomalies and have smaller error as compared with the magnetic sensors.

The gyro inclinometers ensure measurement of hole incline angle and azimuth as well as the turn angle of drill bit at an accuracy from 0.1 to 1 deg (at the incline not less than 3 deg). The systems MWD/LWD perform the same measurement at an accuracy from 0.25 to 3 deg.
The devices based on the gyroscopic inclinometers are as a rule built in the data transmission and control of MWD, which makes them universal but inapplicable in drilling assemblies unequipped with MWD/LWD.

2. Problems of geo-navigation system application
Under conditions of development of the Far North and Arctic areas, new problems arise in the sphere of geo-navigation.

The difficulties for the operation of geo-navigation systems in the high-arctic zones are presented by the extremely severe climate and the depression of useful signal strength: horizontal component of the magnetic field of the Earth and horizontal component of the angular velocity of the Earth, which are the basis for operation of magnetic intrusion detectors and gyroscopic inclinometers of compass type [5].

Drilling in high-conductance rocks cannot use magnetic intrusion detectors which are widely employed as one of additional channels of useful signals for the correction of readings of gyro detectors. This limits the use of the current geo-navigation systems in locating of blat holes and in control over drilling.

In all available geo-navigation systems as well in the devices described in [7, 8], the sensor is either arranged at the drilling tool or built in it, which subjects the detector to the increased mechanical loading and, consequently, shortens its life.

High price and operation complexity of the current systems limits their wide application in industry. Furthermore, they usually contain no feedback devices for the operational adjustment of the hole path while drilling.

3. Development of inertial navigation systems
Inertial navigation systems (INS) enjoy now wider application owing to their small size, high positioning accuracy self-sufficiency and relatively simple manufacture.

It is of the current concern to develop mathematical models of INS to improve their accuracy and interference immunity. The model of dynamics of an augmented state vector of an integrated system within a strapdown inertial navigation system and an on-line long-range navigation system has been proposed in [9, 10]. The estimation algorithm for nonobservable errors of acceleration meters and gyros for the correction of their readings in the further independent operation of the inertial navigation system is presented. The approaches to improving accuracy of acceleration meters and gyros within a strapdown inertial navigation system by hardware and software rare described in [11, 12]. The authors suggest periodical adjustment and calibration of the inertial measurement unit before a measurement cycle. It is also proposed to use the procedure of optimal estimation and correction of basic errors of the system by means of special modes of motion of a source in the framework of complexing measurements obtained from the inertial and other measurement systems. It has been validated that the combined application of such procedures ensures sufficient precision of a navigation system.

4. Development of inertial navigation system for rotary–percussion drilling
Majority of the development mathematical models of INS are meant for the measurement devices used in the aerospace navigation and, accordingly, suitable for operation at high velocities and for arrangement inside an encasement of an objects. Such systems are inapplicable to modeling navigation devices for rotary–percussion or horizontal directional drilling for cardinally different movement velocities and arrangement at a navigation object.

For this reason, a new mathematical model is required to describe INS movement in rotary–percussion drilling of inclined–horizontal holes in rocks of high and low conductance.

At the present time, there is no a scientific framework for the underground collection of navigation information and for the analysis of geo-navigation system movement parameters with regard to their operating differences from the aerospace navigation systems. In this case, the most significant are the electromagnetic parameters of a hosting medium, external impact in the form of
blows and vibration, velocity and travel length of the system, hole incline angle and the ambient temperature.

In this connection, the geo-navigation system for the inclined–horizontal rotary–percussion drilling based on positioning principle and the mathematical model of the system movement in real conditions will ensure more reliable results refined using the readings of sensors based on different physical principle of operation. Integration of a number of measurement channels (based on gyro, Acceleration meters, tilt sensors, encoders, etc.) within a single system and the simultaneous processing of information from all measurement channels will enable using statistical processing of the results, which will improve the geo-navigation system accuracy and positioning reliability.

The inertial navigation systems based on accelerometer and gyro feature high accuracy within shorter time spans, which reduces with longer periods of operation. It is required to introduce additional measurement channels for the refinements of the positioning data, e.g. measurement channels operating on the ground surface, based on the use of GPS, magnetic intrusion and barometric detectors.

Such measurement channels are inapplicable in underground conditions. A geo-navigation system needs additional measurement channels serviceable in mines. Such as channels, rotation sensors, encoders, etc.

The authors of this paper have developed a structural layout of an inertial navigation system for rotary–percussion drilling (Figure 1). The layout includes a measurement probe composed of a unit of measurement sensors, a processing unit, a reception–transmission module as well as an operator’s block comprising a stationary navigation unit, processing unit, displaying facility and a data reception–transmission module.

In the proposed system of geo-navigation, the measurement probe is advanced in an uncased hole or inside drill rods while drilling. Due to this, the error accumulated by the gyro is decreased owing to the reduction in the measurement time and in the period of stay of the measurement probe in the hole, and due to the elimination of impact loads exerted by rotary–percussion drilling on INS.

The operator’s block is stationary mounted on a drill rig, or is arranged at the hole mouth; it informs on drilling parameters (rotation frequency, current hole length, blow frequency, etc.) and sends then, via the reception–transmission module, to the data processing unit. Due to this, INS becomes serviceable in underground conditions.

The geo-navigation data include angles of hole axis deviation from the accepted zero values of zenith (vertical) and azimuth (horizontal). These data are necessary for the hole positioning. After the processing, the data are displayed as a 3D trajectory of the hole by the displaying facility.

For the circuit optimization of a new INS, it is required to model its near-real operation mathematically. The mathematical model of INS operation should account for: ambient temperature, velocity and travel length, hole incline angle, shocks and vibrations on the hole and electromagnetic parameters of the hosting medium.

![Figure 1. Structural layout of inertial geo-navigation system.](image-url)
The mathematical model describes a measurement probe as a dynamic object, using differential
equations to reflect continuous temporal variation of its state. The equations of motion are written in
terms of components of the axes of the selected coordinate systems (CS).

1. The normal earthbound coordinate system. The origin is at any convenient point of the ground
surface. The axis X (northward) and axis Z (eastward) are arranged in the horizontal plane, and the
axis Y is directed upward (along the local vertical line).

2. The normal coordinate system. The origin is in the center of masses of the probe. The axes X
(northward) and Z (eastward) are arranged in the horizontal plane, and the axis Y is upward. Further
on, it is supposed that the axes of the normal earthbound CS and the normal CS are parallel. Their
relative position of these systems is governed by the vector \( r \) between their origins.

3. The coupled coordinate system. The origin is in the center of masses of the probe. The axis X is
oriented along the hole trajectory and is named the longitudinal axis. The axis Z is directed rightward
relative to the probe advance is named the transversal axis. The axis Y lies in the plane of symmetry, is
oriented upward (in horizontal drilling) and is named the normal axis.

The relative position of the coupled and normal CS is generally defined by 9 directional cosines
and is determined mathematically based on the angles of Euler–Krylov. In this case, for the transition
from the normal to the coupled CS, the sequence of turns is: turn by an angle of yaw (round the axis
Y), turn by an angle pith (round the axis Z) and turn by and angle of swing (round the axis X).

Below the authors present the calculation of the current positioning of a measurement probe in a hole
while drilling.

Let \( a_x, a_y, a_z \)—accelerations in along the corresponding axes in the system related with the
measurement probe; \( \Omega_x, \Omega_y, \Omega_z \)—angular velocities of rotation around the corresponded axes in the
system connected with the probe.

The turn angle \( \alpha_i \) around an \( i \)-th axis is given by:

\[
a_i = \int_{t_1}^{t_2} \Omega_i \, dt.
\]

where \( t_1 \) and \( t_2 \)—start and end of measurement, respectively.

The accelerometers compensate drift of gyros and determine the initial angles. The readings of
accelerometers include free fall acceleration, noise acceleration of the probe. In case that \( R \)—vector of
apparent acceleration measured by an accelerometer, let \( R_x, R_y, R_z \)—components of this vectors in X,
Y, Z. Then, the turn angle \( \alpha_i \) around an \( i \)-th axis axis measured by the accelerometer is:

\[
a_i = \arccos \frac{R_i}{R}, \quad \text{where} \quad R = \sqrt{R_x^2 + R_y^2 + R_z^2}.
\]

The noise of gyro is due to the eigen noise of the detector (distributed uniformly) and due to
the influence of the Earth rotation. Additional sensors are used to balance the drift of angles measured by
gyros since this value cannot be balanced by accelerometers in strictly vertical and horizontal motion.
The data on the current angles from accelerometer, gyro and other sensors, after fusion and filtration,
inform on the inclination angles of the measurement probe (Euler–Krylov angles) during advance
inside a hole and, accordingly, on the path trajectory of the hole.

The optimal way to calculate coordinates seems to be algorithm based on the mathematical
models with the Rodrigues–Hamilton parameters for the kinematic equation constructed using the
Rodrigues–Hamilton parameters and linear and integrable at any angles by Euler–Krylov.

![Figure 2. Pictures of the prototype INS (a) without the housing and (b) inside it.](image)
The researchers of the Mine Geophysics Laboratory, Institute of Mining, have designed and manufactured a simplified prototype of INS (Figure 2) with the measurement channels using gyroscopic detectors. Currently, the manufacture of the test bench for the INS prototype is in process.

5. Conclusion
The issues connected with the development methods and equipment towards resource saving and improved safety and efficiency in hard mineral mining, including drilling quality enhancement, become of increasingly higher concern.

This study aimed development of new approaches to locating and tracking in rotary–percussion drilling in rocks of low and high conductance is based on the integrated numerical and experimental research with regard to many parameters of INS operation.

The presented mathematical model of INS operation allows selecting optimal layouts of the equipment with a view to eliminating intersection and deviation of various-purpose horizontal drill holes, which, in its turn, will enable enhancing efficiency of hard mineral mining.

Acknowledgements
The study has partly been supported by the Novosibirsk City Executive Board, Grant for Young Scientists and Specialists for Research and Innovation Activities under Contract No. 16 dated July 4, 2017.

References
[1] Rybakov AP 2005 Foundations of Trenchless Technologies (Theory and Practice) Moscow: PressByuro (in Russian)
[2] SNS-200 Location System of Horizontal Directed Drilling (in Russian): http://sense-inc.ru/assets/templates/sense/doc/ SNS200-PRO.pdf
[3] Eclipsecomplex: http://russian.digital-control.com/products/discontinued/eclipse.html.
[4] Kondratenko AS, Timonin VV and Patutin AV 2016 Prospects for directional drilling in hard rocks J. Min. Sci. Vol 52 No 1 pp 129–134
[5] Scoblo VZ, Ropyanoy AYu and Lukht AI 2010 Gyroscopic orientation device KURS—tool for gyroscopic orientation of whipstock while drilling Vestn. Assots. Bur. Podryad. Vol 3 pp 31–34
[6] GyroPulsereal-Timegyro Orientation and Measurement while Drilling: http://www.slb.com/~media/Files/drilling/brochures/mwd/gyropulse.pdf
[7] Paderina TV and Sokolov DA 2012 Boreholes survey by inclinometer under high-latitude conditions Proc. XIV Conf. Young Scientists: Navigation and Movement Control pp 95–101 (in Russian)
[8] Sokolov DA 2013 Borehole device of universal gyroinclinometer Abstract of Candidate of Engineering Sciences Dissertation Saint-Petersburg (in Russian)
[9] Paderina TV and Sokolov DA 2013 Variants of constructive realizing diametric scheme of gyroinclinometer for high-latitude systems of underground navigation Izv. Vuzov. Priborostoenie Vol 56 No 7 pp 21–26
[10] Shalimov LN, Fokin LA and Shipitsin AG 2005 Strapdown INS accuracy analysis and synthesis software Aviakosm. Priborostr. Vol 12 pp 15–21
[11] Vasilev PV, Meleshko AV and Pyatkov VV 2014 Accuracy improvement of correctable inertial navigation system J. Izv. Vuzov. Priborostoenie Vol 57 No 12 pp 15–21
[12] Afonin AA, Tyuvin AV and Sulakov AS 2014 Hardware and algorithmic methods of reducing errors of graviinertial complex systems inertial sensors Mekhatron., Avtomatiz., Upravl. Vol 12 pp 42–52