ACCURACY IMPROVEMENT OF UNDERGROUND NAVIGATION ON THE BASIS OF INTEGRATION OF SINS, ODOMETERS AND GPS/GLONASS RECEIVERS

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Abstract

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Two ways of improvement of accuracy and reliability of production of navigation parameters using readouts of pipeline inspection pig (PIP) are considered. The first way uses methods of autonomous inertial navigation to determine the spatial coordinates of PIP during failures of the odometric system. The second way provides estimation and compensation of parameters of azimuthal drift of an attitude control system on the basis of construction of square spline-functions of errors of positioning of two adjacent intermark sections of the main pipeline (MP).

Introduction

Realization of orientation and navigation methods of PIP has the following peculiarities:

a) possibility of use of a method of postprocessing of signals of the onboard measuring equipment composed of the inertial measuring unit and odometric system;
b) limited possibilities of use of external information. Thus, coordinates of MP benchmark points can be determined by signals of satellite navigation systems (SNS) in points of their output to Earth surface which is located through 1 to 2 km (or through 4 to 35 minutes when PIP is moving at a speed of 1 to 4 m/s); noninertial means of PIP azimuth measurement are inaccessible.

Accuracy requirements of spatial positioning of an axial line, service elements and defective places of MP are defined by branch standard documents of OJSC "GAZPROM" at the level of 2 m per km. Provision such accuracy using methods of autonomous inertial navigation requires high cost precision sensors, which is not always affordable. CJSC «Gazpriboravtomatikaservis» and SSTU have a long-lasting experience of development and maintenance of navigating-topographical complexes (NTC) on the basis of midaccuracy inertial units, placed in a hermetic container of PIP and integrated with an odometric system and SNS. The mean square error of positioning of MP service elements and defects with the aid of NTC is, as a rule, no more than 0.5 m. It considerably surpasses all domestic analogues and corresponds to the best foreign samples of similar equipment. By now spatial positioning of more than 4000 km of MP of diameters from 420 to 1420 mm in Russia and abroad is executed using NTC by CJSC «Gazpriboravtomatikaservis». The present experience confirms the known proposition that use of an odometric reckoning in solution of problems of spatial positioning of mobile objects essentially reduces inertial unit accuracy requirements.

However the odometric system does not always work reliably enough. Material changes of an odometer transition factor are seen under changes of PIP speed, a relief of pipeline internal surface, degree of its impurity and other factors. Even temporary failures of the odometric system lead to accuracy degradation and necessity of PIP repassing through MP. In relation with premises the problem of accuracy improvement of MP positioning on the basis of use of the onboard SINS integrated with the odometric system using the MP benchmark point coordinates obtained with the aid of GPS/GLONASS receivers is solved in this work.

Application of autonomous inertial navigation methods

In normal conditions the navigating solution is worked out under postprocessing of signals of integrated system (a strapdown inertial system of orientation (SISO) and odometric system) with correction at benchmark points (fig. 1). In the case of short-term odometric system failures the navigating parameters are determined using autonomous system (SINS) readouts.

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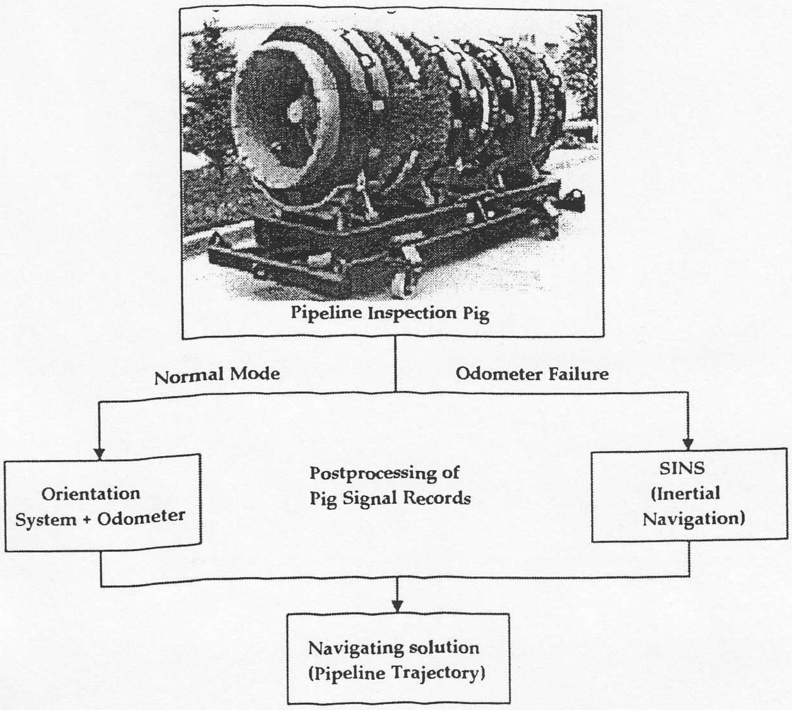

Fig. 1 Diagram of navigating solution workout

Following algorithms in quaternion parameters (quaternions of angular rates of mobile object and correction are determined in horizon basis ζ modelled in the onboard computer [1,2]) describing angular movement of orientation system are used for SISO functioning:

$$\begin{aligned}
2\dot{\hat{\nu}}_0 &= -\hat{\nu}_1(\hat{\omega}_{\zeta 1}+\omega^k_{\zeta 1})-\hat{\nu}_2(\hat{\omega}_{\zeta 2}+\omega^k_{\zeta 2})-\hat{\nu}_3(\hat{\omega}_{\zeta 3}+\omega^k_{\zeta 3})+\rho\left(1-\hat{\nu}^2\right)\hat{\nu}_0;\\
2\dot{\hat{\nu}}_1 &= \hat{\nu}_0(\hat{\omega}_{\zeta 1}+\omega^k_{\zeta 1})+\hat{\nu}_3(\hat{\omega}_{\zeta 2}+\omega^k_{\zeta 2})-\hat{\nu}_2(\hat{\omega}_{\zeta 3}+\omega^k_{\zeta 3})+\rho\left(1-\hat{\nu}^2\right)\hat{\nu}_1;\\
2\dot{\hat{\nu}}_2 &= -\hat{\nu}_3(\hat{\omega}_{\zeta 1}+\omega^k_{\zeta 1})+\hat{\nu}_0(\hat{\omega}_{\zeta 2}+\omega^k_{\zeta 2})+\hat{\nu}_1(\hat{\omega}_{\zeta 3}+\omega^k_{\zeta 3})+\rho\left(1-\hat{\nu}^2\right)\hat{\nu}_2;\\
2\dot{\hat{\nu}}_3 &= \hat{\nu}_2(\hat{\omega}_{\zeta 1}+\omega^k_{\zeta 1})-\hat{\nu}_1(\hat{\omega}_{\zeta 2}+\omega^k_{\zeta 2})+\hat{\nu}_0(\hat{\omega}_{\zeta 3}+\omega^k_{\zeta 3})+\rho\left(1-\hat{\nu}^2\right)\hat{\nu}_3;
\end{aligned} \tag{1}$$

$$\hat{\nu}^2 = \hat{\nu}_0^2+\hat{\nu}_1^2+\hat{\nu}_2^2+\hat{\nu}_3^2; \tag{2}$$

$$\omega^k_{\zeta_1} = -k_1^p\hat{W}_{\zeta_3} - k_1^I\int_{t_0}^{t}\hat{W}_{\zeta_3}\,d\tau;\quad \omega^k_{\zeta 2} = \omega^k_{\zeta 1}\frac{2(\hat{\varepsilon}_1\hat{\varepsilon}_2-\hat{\varepsilon}_0\hat{\varepsilon}_3)}{\sqrt{1-4(\hat{\varepsilon}_1\hat{\varepsilon}_2-\hat{\varepsilon}_0\hat{\varepsilon}_3)^2}};\quad \omega^k_{\zeta_3} = k_3^p\hat{W}_{\zeta_1} + k_3^I\int_{t_0}^{t}\hat{W}_{\zeta_1}\,d\tau, \tag{3}$$

where $\hat{\omega}_{\zeta i}$ are estimations of angular rate components in reference frame ζ; $\hat{W}_{\zeta i}$ are estimations of specific force components in reference frame ζ; $\rho = 1$ is a quaternion $\hat{\nu}$ normalization factor; $\omega^k_{\zeta i}$ are angular rates of correction in reference frame ζ; $\hat{\nu}_0$ to $\hat{\nu}_3$ are components of an orientation quaternion estimation; $\hat{\varepsilon}_0$ to $\hat{\varepsilon}_3$ are components of a navigation quaternion estimation; t is a current moment of time (pig movement time); t_0 is an initial moment of time; k_1^p, k_3^p are transition factors of positional correction terms; k_1^I k_3^I are transition factors of integral correction terms; $i=\overline{1,3}$.

In practice the norm of quaternion $\hat{\nu}$ can be departed from unity due to methodical and round-off errors what leads to appearance of additional deviations. Therefore the term of $\rho(1-\hat{\nu}^2)\hat{\nu}_i$ is included in (1) in order to normalize quaternion $\hat{\nu}$ [3,4].

Coordinate transformations that determine transition from reference frame ζ to object reference frame X are set by the following matrix expressed in quaternion components:

$$\hat{A} = \begin{bmatrix} \hat{\nu}_0^2+\hat{\nu}_1^2-\hat{\nu}_2^2-\hat{\nu}_3^2 & 2\left(\hat{\nu}_0\hat{\nu}_3+\hat{\nu}_1\hat{\nu}_2\right) & 2\left(\hat{\nu}_1\hat{\nu}_3-\hat{\nu}_0\hat{\nu}_2\right) \\ 2\left(\hat{\nu}_1\hat{\nu}_2-\hat{\nu}_0\hat{\nu}_3\right) & \hat{\nu}_0^2+\hat{\nu}_2^2-\hat{\nu}_1^2-\hat{\nu}_3^2 & 2\left(\hat{\nu}_0\hat{\nu}_1+\hat{\nu}_2\hat{\nu}_3\right) \\ 2\left(\hat{\nu}_0\hat{\nu}_2+\hat{\nu}_1\hat{\nu}_3\right) & 2\left(\hat{\nu}_2\hat{\nu}_3-\hat{\nu}_0\hat{\nu}_1\right) & \hat{\nu}_0^2+\hat{\nu}_3^2-\hat{\nu}_1^2-\hat{\nu}_2^2 \end{bmatrix}. \tag{4}$$

Reduction of angular rates and specific forces to horizon reference frame is carried out using transposed matrix $\hat{A}^T$ according to the next expressions:

$$\begin{aligned} \left[\hat{W}_{\zeta_1}\ \hat{W}_{\zeta_2}\ \hat{W}_{\zeta_3}\right]^T &= \hat{A}^T\left[\hat{W}_{X1}\ \hat{W}_{X2}\ \hat{W}_{X3}\right]^T; \\ \left[\hat{\omega}_{\zeta_1}\ \hat{\omega}_{\zeta_2}\ \hat{\omega}_{\zeta_3}\right]^T &= \hat{A}^T\left[\hat{\omega}_{X1}\ \hat{\omega}_{X2}\ \hat{\omega}_{X3}\right]^T, \end{aligned} \tag{5}$$

where $\hat{\omega}_{Xi}$, $\hat{W}_{Xi}$ are estimations of components of angular rates and specific forces in reference frame X, obtained from gyroscopes and accelerometers.

Euler-Krylov's angles are calculated using derived estimations of components of an orientation quaternion $\hat{\nu}_0..\hat{\nu}_3$ under the following formulas [3,4]:

$$\hat{\psi} = arctg\left(\frac{2\left(\hat{\nu}_0\hat{\nu}_2 - \hat{\nu}_1\hat{\nu}_3\right)}{\hat{\nu}_0^2 + \hat{\nu}_1^2 - \hat{\nu}_2^2 - \hat{\nu}_3^2}\right);\ \hat{\theta} = \arcsin\left(2\left(\hat{\nu}_0\hat{\nu}_3 + \hat{\nu}_1\hat{\nu}_2\right)\right);\ \hat{\gamma} = arctg\left(\frac{2\left(\hat{\nu}_0\hat{\nu}_1 - \hat{\nu}_2\hat{\nu}_3\right)}{\hat{\nu}_0^2 + \hat{\nu}_2^2 - \hat{\nu}_1^2 - \hat{\nu}_3^2}\right). \tag{6}$$

In the normal condition current coordinates of PIP in reference frame ζ are determined using signals of odometric system and solutions of an orientation problem with aid of SISO signals:

$$\left[\Delta\hat{\zeta}_k\right] = \hat{A}_k^T\left[\Delta\hat{x}_k\right];\quad \hat{\zeta}_i = \sum_{k=1}^{n}\Delta\hat{\zeta}_{ik},\quad (i = \overline{1,3}), \tag{7}$$

where $\Delta\hat{\zeta}_k = (\Delta\hat{\zeta}_{1k}, \Delta\hat{\zeta}_{2k}, \Delta\hat{\zeta}_{3k})$ is a vector of estimations of increments of the Cartesian coordinates at k-th time step; $\hat{A}_k$ is an estimation of the matrix of PIP orientation (reference frame X with respect to reference frame ζ) at k-th time step; $\Delta\hat{x}_k = (\Delta\hat{x}_{1k}, \Delta\hat{x}_{2k}, \Delta\hat{x}_{3k})$ is a vector of estimations of increments of the passed path by readouts of a discrete odometer at k-th time step (in case of PIP $\Delta\hat{x}_k = (\Delta\hat{x}_{1k}, 0, 0)$).

Navigating parameters are determined as follows:

$$\hat{\dot{\varphi}} = \frac{\hat{\dot{\zeta}}_1}{R};\ \hat{\dot{\lambda}} = \frac{\hat{\dot{\zeta}}_3}{R\cos\hat{\varphi}}. \tag{8}$$

Failures of odometric system functioning are revealed under postprocessing of whole set of information on the base of the following operations:

1) analysis of a difference of readouts of different odometric system channels;
2) comparison of estimations of a distance between the reference points according to PIP positioning system data (SISO + odometric system) and SNS receivers;
3) chekup with the aid of the observing device of level of an error closure between PIP direct-axis projections of absolute linear acceleration vector determined by SISO signals and relative linear acceleration vector determined using odometric system signals.

When the temporary odometric system failure is detected the workout of the navigating solution is carried out by SINS readouts. Following equations are corresponding to the solution of navigating problem [1,2]:

$$\begin{aligned} 2\dot{\hat{\varepsilon}}_0 &= \hat{\varepsilon}_1\omega_{\zeta 1}^{e} + \hat{\varepsilon}_2\omega_{\zeta 2}^{e} + \hat{\varepsilon}_3\omega_{\zeta 3}^{e};\quad 2\dot{\hat{\varepsilon}}_1 = -\hat{\varepsilon}_0\omega_{\zeta 1}^{e} - \hat{\varepsilon}_2\omega_{\zeta 3}^{e} + \hat{\varepsilon}_3\omega_{\zeta 2}^{e}; \\ 2\dot{\hat{\varepsilon}}_2 &= -\hat{\varepsilon}_0\omega_{\zeta 2}^{e} + \hat{\varepsilon}_1\omega_{\zeta 3}^{e} - \hat{\varepsilon}_3\omega_{\zeta 1}^{e};\quad 2\dot{\hat{\varepsilon}}_3 = -\hat{\varepsilon}_0\omega_{\zeta 3}^{e} - \hat{\varepsilon}_1\omega_{\zeta 2}^{e} + \hat{\varepsilon}_2\omega_{\zeta 1}^{e}. \end{aligned} \tag{9}$$

Here the estimations of navigating parameters expressed through quaternion parameters are also applicable under the following formulas:

$$\hat{\varphi} = arctg\left(\frac{2(\hat{\varepsilon}_1\hat{\varepsilon}_2 - \hat{\varepsilon}_0\hat{\varepsilon}_3)}{\sqrt{1 - 4(\hat{\varepsilon}_1\hat{\varepsilon}_2 - \hat{\varepsilon}_0\hat{\varepsilon}_3)^2}}\right);\ \hat{\lambda} = arctg\left(\frac{2(\hat{\varepsilon}_0\hat{\varepsilon}_1 + \hat{\varepsilon}_2\hat{\varepsilon}_3)}{\hat{\varepsilon}_0^2 + \hat{\varepsilon}_2^2 - \hat{\varepsilon}_1^2 - \hat{\varepsilon}_3^2}\right) - Ut. \tag{10}$$

In the presence of constant errors the growth of errors of navigating parameters determination can be seen.

Application of benchmark points

Under existing technique [5] of parameter estimations of azimuthal drift of orientation system based on use of coordinates of the beginning and the end of MP intermark section there is a ambiguity in the solution. In order to solve it the badly formalizable procedures are used. These procedures require additional information and availability of wide experience of an operator. Thus, under exact initial conditions (by coordinates) the error of determination of coordinates of the end of intermark section according to the PIP onboard equipment data is depended on both azimuthal drift of orientation system and accumulated error of an azimuth angle at the beginning of intermark section. The errors of odometric system can be compensated under repeated calculations of a trajectory of PIP movement on intermark section using transition factor correction as well as SISO signals.

Forming of PIP azimuth correction using an advanced way is carried out with use of not two but three coordinates of the benchmark points located sequentially on a movement trajectory.

The estimation of an azimuth angle is adopted as follows

$$\hat{\psi} = \psi + \psi_0 + \omega t\,, \tag{11}$$

where ψ is a true azimuth, ψ_0 is an azimuth angle error accumulated on the previous section, ω is an azimuthal angular rate of drift.

The equations describing coordinates of a movement trajectory of pig in an ideal aspect for a true azimuth and coordinates of estimating trajectory for an evaluation of an azimuth angle are derived:

$$\begin{cases} \zeta_1 = \int\limits_{t_0}^{t} V\cos\psi dt; \\ \zeta_3 = \int\limits_{t_0}^{t} V\sin\psi dt, \end{cases} \quad \text{and} \quad \begin{cases} \hat{\zeta}_1 = \int\limits_{t_0}^{t} \hat{V}\cos\hat{\psi} dt; \\ \hat{\zeta}_3 = \int\limits_{t_0}^{t} \hat{V}\sin\hat{\psi} dt, \end{cases} \tag{12}$$

where ζ_1, ζ_3 are northern and eastern coordinates accordingly, $V, \hat{V}$ are PIP speed and its estimation, $\hat{\zeta}_1, \hat{\zeta}_3$ are estimations of northern and eastern coordinates.

Errors of coordinate estimations

$$\Delta\zeta_1 = \hat{\zeta}_1 - \zeta_1,\ \Delta\zeta_3 = \hat{\zeta}_3 - \zeta_3 \tag{13}$$

basically are depended on parameters of SISO azimuthal drift. Neglecting an error of forming of estimations of speed of PIP onward movement and taking into account smallness of ψ_0 and ω we can write the following equations of errors for reference points of two adjacent intermark sections (i=1,2):

$$\begin{cases} \Delta\zeta_{1i} \approx -\int\limits_{t_0}^{t_i} V(\psi_0 + \omega t)sin\psi\, dt = -\psi_0\zeta_3 - \omega\int\limits_{t_0}^{t_i} Vt\, sin\psi\, dt, \\ \Delta\zeta_{3i} \approx \int\limits_{t_0}^{t_i} V(\psi_0 + \omega t)cos\psi\, dt = \psi_0\zeta_1 + \omega\int\limits_{t_0}^{t_i} Vt\, cos\psi\, dt. \end{cases} \tag{14}$$

Let us note that a trajectory of PIP movement through MP in plan, as a rule, has a piecewise linear appearance. And when $\psi = const$ the first and second equations of system (14) are proved to be linearly dependent. Thus, the system (14) is badly solvable relatively ψ_0 and ω for one intermark section.

In order to construct the three-point algorithm (for two adjacent sections) we will write expressions for position vectors of errors as follows:

$$\Delta R_i^2 = \Delta\zeta_{1i}^{\ 2} + \Delta\zeta_{3i}^{\ 2} = \psi_0^{\ 2}\left(\hat{\zeta}_{1i}^{\ 2} + \hat{\zeta}_{3i}^{\ 2}\right) +$$
$$+ 2\omega\psi_0\left(\hat{\zeta}_{3i}\int\limits_{t_0}^{t_i}\hat{V}t\sin\hat{\psi}\,dt + \hat{\zeta}_{1i}\int\limits_{t_0}^{t_i}\hat{V}t\cos\hat{\psi}\,dt\right) + \omega^2\left((\int\limits_{t_0}^{t_i}\hat{V}t\cos\hat{\psi}\,dt)^2 + (\int\limits_{t_0}^{t_i}\hat{V}t\sin\hat{\psi}\,dt)^2 \right). \tag{15}$$
$$(i=1,2).$$

The solution of system (15) of two nonlinear equations is four functions $\psi_0(f(\hat{\psi}, t_i, \hat{V}, \hat{\zeta}_{1i}, \hat{\zeta}_{3i}, \Delta R_i))$ and four corresponding functions $\omega(f(\hat{\psi}, t_i, \hat{V}, \hat{\zeta}_{1i}, \hat{\zeta}_{3i}, \Delta R_i))$. Their analytical form found with help of Mathematica software is very complicated and isn't given here. Therefore solutions are evaluated in a symbolic form using the computer. The pair of solutions wherein the movement trajectory is most approximated to the marker points is determined. Numerical values of solutions are determined after calculation of a trajectory of PIP movement with zero values of azimuthal drift parameters.

Approval of developed ways of accuracy improvement for a real object was performed on calculation of a trajectory of a gas pipeline section according to data of experimental-industrial trials of SIT-500 PIP by CJSC «Gazpriboravtomatikaservis». The problem was in a topographical connection of the pipeline to an electronic terrain map. Coordinates of gas pipeline have been determined on the line section which contained 42 benchmark points. Thus, the pig was in motion for 20746 s. For this time it has passed a total of 40,6 km in all. Diameter of a pipe was Ø0,5 m.

Benchmark points were arranged in advance with aid of GPS/GLONASS receivers which possessed an accuracy of positioning up to 5 cm.

Inertial measuring instrument of PIP includes a three-axial angular rate measurer (a fiber-optical gyroscope) SRS-500 by LPC "Optolink" Ltd and 3 accelerometers of AK-6 type.

Results of the navigating problem solution are shown on fig. 2.

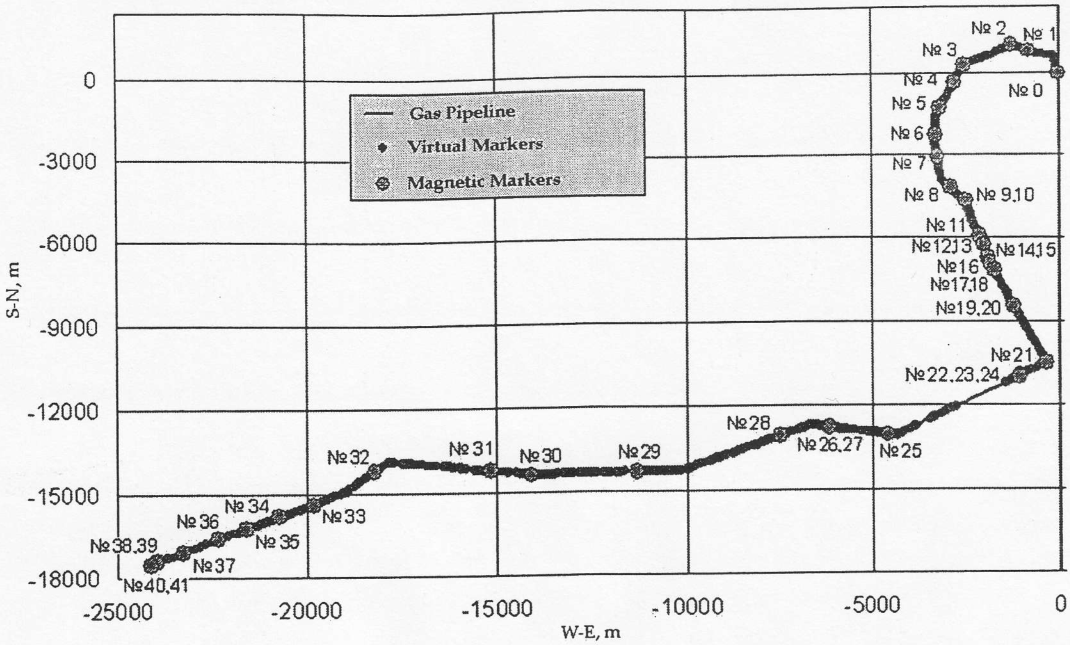

Fig. 2 Plan of a pipeline section

The reference points placed over MP markers were used for the purposes of correction using determination of parameters of azimuthal drift. In figure these makers are designated as «magnetic markers». Coordinates of 5 to 15 additional points (designated as «virtual markers») were determined on an axial MP between magnetic markers with the aid of SNS receivers of a geodetic grade of precision. Virtual markers were used for estimation of accuracy of the MP positioning problem solution. The maximum deviation of the calculated MP coordinates from coordinates of virtual markers was 0.8 m. Given accuracy differs from accuracy achieved by the "two-point" way only slightly. However, the "three-point" way allows us to determine parameters of azimuth correction practically without iterations.

It is obtained that the three-point algorithm is applicable under conditions of underground navigation with typical movement conditions of PIP. However, applicability of this algorithm is limited by precision of used measurers of an absolute angular rate (gyroscopes). Peculiarity of the developed method is the assumption that two adjacent sections have constant azimuthal drift of gyroscopes. This condition on intermark sections (which length is usually about 2 km) is feasible only for sensors of mid and high accuracy.

Processing of sections with different forms of a trajectory has shown that efficiency of the three-point method is various for cases of direct in horizon sections, sections with considerable bends of a trajectory by an azimuth (more than 30 degrees) and trajectories where the pig made stops. On direct sections efficiency is the highest; i.e., from the first calculation of a trajectory the corrections by azimuth are evaluated as closest to true values. For the final calculation only minor corrections are made. On sections with stops and considerable bends by azimuth the corrections are evaluated after several calculations of a trajectory. It connected with correction of factor of the coordinate increment sensor (odometer) because of which the movement trajectory can vary considerably at different stages of calculations. However, the number of calculations on such problem sections affects processing time and doesn't affect positioning accuracy. As a whole the three-point method has shown the efficiency and has allowed us to enhance automation of MP coordinates calculation.

Conclusion

It is shown that formation of estimations of azimuthal drift parameters for two adjacent MP intermark sections on the basis of the construction of square spline-functions of positioning errors allows us to determine unambiguously both the accumulated azimuthal drift and the average value of an uncompensated variation of the rate of azimuthal drift of orientation system on the considered MP section. Developed program realization of this approach allows us to essentially enhance automation of MP positioning problem solution.

During the researches it is also shown that with the use of FOG of TRS-500 type and accelerometers of AK-6 type as a part of the inertial module the determination of PIP spatial coordinates is possible with an error of no more than 1 m on a distance of about 100 m using methods of autonomous navigation. That makes it possible to determine and compensate for short-term parametric failures of the odometric system. As a whole, application of the specified ways allows us to improve MP positioning accuracy by 20-25% and at the same time to enhance processability of MP inspection data postprocessing.

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