Extended investigation into continuous laser scanning of underground mine workings by means of Landis inertial navigation system

E N Belyaev

Irkutsk National Research Technical University, 83, Lermontova St., Irkutsk, 664017, Russia

E-mail: Belyaev@baigeo.ru

Abstract. The paper investigates the method of applying mobile scanning systems (MSSs) with inertial navigators in the underground conditions for carrying out the surveying tasks. The available mobile laser scanning systems cannot be used in the underground environment since Global Positioning System (GPS) signals cannot be received in mines. This signal not only is necessary for space positioning, but also operates as the main corrective signal for the primary navigation system – the inertial navigation system. The idea of the method described in this paper consists in using MSSs with a different correction of the inertial system than GPS is.

1. Introduction

Nowadays, laser scanning is becoming more and more widespread in geodesy and surveying. Surface laser scanning is used for the following operations: topographic mapping of relatively small pieces of land, mapping of building facades and monuments, as-build mapping of various industrial structural units, and scanning of impenetrable underground enclosures. Aerial laser location can be used for providing topographic maps and plans of sizeable territories or long-distance linear objects such as petroleum pipelines, power transmission lines and different purpose highways.

The application of mobile scanning systems (MSSs) is further development of the surface laser scanning technology aimed at the effective increase and conveniences of conducting field and laboratory works. MSSs allow executing 3D mapping using laser scanners on the move. Wheel transport, railway locomotives and river boats can be used as a moving platform. In order to combine separate point clouds that were obtained on the move into a single point cloud using the specified coordinate system, surface laser scanners should be supplemented with an integrated navigational complex Global Positioning System (GPS)/IMU, incorporating GPS and inertial navigation system. Such facility complex enables one to locate the orientation of a moving platform with the installed surface laser scanner [5].

2. Tests

At present, surveyors at mining enterprises widely use electronic tachymeters and GPS facilities in their work. There is no doubt that GPS simplifies a lot of the surveyors' work on the surface on which a satellite signal can be found. On the other hand, what can be done for those who work underground? The use of tachymeters and laser reels definitely facilitates the operations in mines. However, these devices do not completely save from traditional mapping techniques; the specialists only use different equipment.

The surveyor has to control the mine roadway which is under his responsibility at his site. The list of duties that have to be performed by a surveyor is large: specification of the direction for mine working considering a height clearance and horizons, surveying for the calculation of the removed rock masses, control of the designed slopes for the rail tracks and conduits, as-build surveying of mine barring, development of surveying feasibility. The given list of mine surveyor's duties is just an extract. In addition to the above-mentioned tasks, a surveyor has to assure that all measurements are correct, hence measurements and surveys need to be checked.

It can often be necessary to carry out the survey of the whole mine working or of several horizons, the total length of which can reach several kilometers, in order to control or to re-establish lost documentation. Such amount of work even using electronic tachymeters may take longer than a week. Besides, the surveyor must timely provide the necessary measurements for his site. Because of fulfilling such massive amount of work, new errors based on the human factor can be expected. It takes a lot of extra time to eliminate them. It is rational to use MSSs for carrying out such works. Ordinary MSSs cannot be used in underground conditions, because there is no GPS signal, which is required for space positioning. It also acts as a synchronizing and modifying signal for all devices connected to the system.

Our conceptual idea consists in using MSSs with a different parameter adjustment of inertial system than GPS has.

The major disadvantage of inertial navigation system is that its data inaccuracy cumulates with the time. This is caused by an incorrect initial adjustment of measuring axes in gyroscope and an integrating influence of the system itself. The principal information content results from recalculation of accelerative forces into regional coordinate system by taking into account the local changes of gravitational acceleration. This procedure is specified by the equation:

$$A_L = B^L{}_B A_B + \boldsymbol{g}, \qquad (1)$$

where A_L is the entire acceleration vector in a regional coordinate system; $B^L{}_B$ — the transition matrix from instrument to a regional coordinate system; and $\boldsymbol{g}$ — the gravitational vector at a particular spot. The input elements of matrix B are specified at the initial stage of the system adjustment. Errors of accelerometer adjustment belong to errors in the initial parameters of matrix B. Inaccuracies in gyroscope adjustment cause some turning of an object which is factored at an onboard computer as a seeming turning of the system in space due to the inaccuracies in reciprocal non-orthogonality of gyroscope measuring axis. For example, the axis Z, turning around at an angular velocity θ_Z, will cause an error in an angular velocity relative to the gyroscope axis oriented towards Y which equals

$$\omega YZ = \phi YZ \theta Z \qquad (2)$$

where ϕ_{YZ} is the orientation error in the gyroscope measuring axis in plane YZ.

Hereafter, an on-board computer will sense vector $\theta_Z Z + \theta_Z \phi_{YZ} Y$ instead of an angular velocity vector $\theta_Z Z$. Error detection of matrix B will cause an orientation error and consequently will cause transformation errors that influence acceleration object. This results in velocity and location errors. In addition to the errors in input parameters, inaccuracies in gyroscope adjustment cause errors in transformation of perceived acceleration into a regional coordinate system [1,2,5].

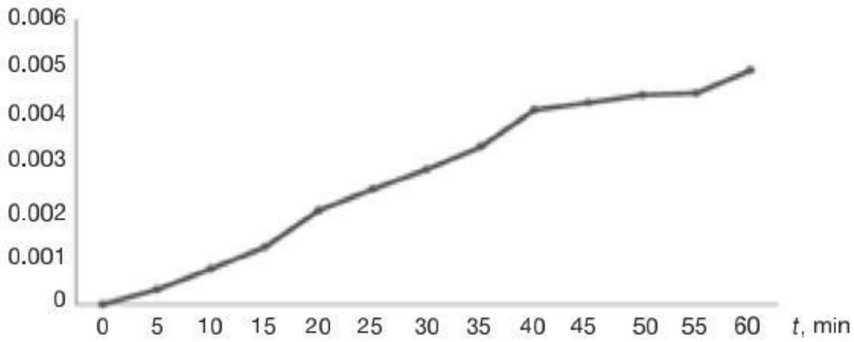

Figure 1: Cumulation of errors in INS trajectory

Figure 1 shows the error pattern of the inertial system that occurs with the circular route of motion.

In order to increase the accuracy of location coordinates, laboratory trajectory analysis is usually done in reverse direction of motion trajectory assuming that the reference point is the terminal point of the initial trajectory. The coordinates of such points are usually known. Thus, the error diagram of location coordinates has a mirror image. If the forward and the reverse diagrams are overlaid (Fig. 2), their cross point (point *K*) defines the maximum error in coordinate location within the site of using INS.

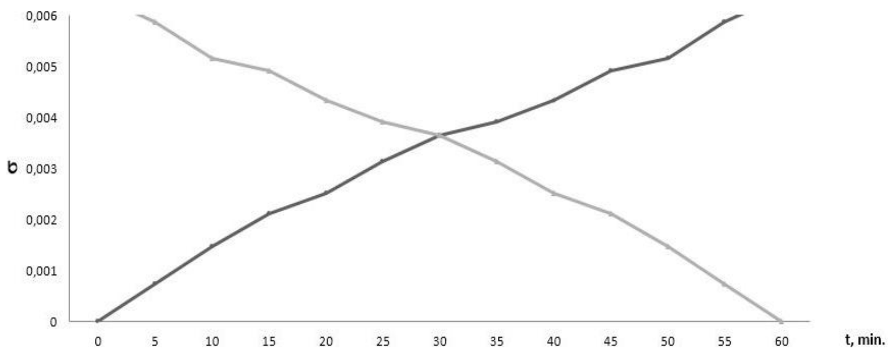

Figure 2: Overlaid forward and reverse cycles of trajectory analysis.

Adjustment of the inertial navigation system is necessary for minimizing cumulative errors and for the increased accuracy of the observed motion trajectory. For such adjustment, it is necessary to know at some particular moment of time all parameters of motion or at least some of them. Compensating data in the underground mining can have the following information:

1. Data about the mine roadway received from the odometer
2. The moments of time when velocity and acceleration are zero
3. Data about the current position of the system received from connection to the points of underground surveying network

Geodetic connection of MSS should be made to the points of underground surveying network with the established coordinates that are located along the whole mine working. The adjustment of INS requires a short break. During work suspension we know the exact velocity and acceleration according to gyroscopes measuring axis and accelerometers; they equal zero. As a result, while laboratory measuring data are being processed, the trajectory can be adjusted to the precision that meets precision requirements of the normative documents.

For the verification of the hypothesis, the experiment has been conducted using the Landis inertial system (produced by the French company IXSEA). The testing took place at the territory of the original equipment manufacturer – IXSEA Company in Marly-le-Roi, France.

The purpose of the experiment was to check the working capability of the inertial system without GPS compensating data and simultaneous production of the accurate data sufficient for the application of the system in underground conditions in compliance with precision requirements of the normative documents.

The Landis system was installed on an IXSEA demonstration car, where a holding plate, an odometer, GPS and an independent supply source were mounted. Furthermore, the necessary odometer calibration procedures were performed. A straight line motion trajectory with a maximal rotation angle of 5 degrees was chosen to ensure that the inertial system can "hang on" while performing a continuous straight line motion. The stretch of the road amounted to 2,500 m.

To adjust INS when velocity and acceleration according to measuring axis are zero, the "Stop and Go" method of car movement was chosen. The stops were done every minute of the movement at an average speed of 15 km/h. All the above-mentioned conditions most closely simulate the working environment in underground mines.

During the experiment, GPS operated separately from INS; therefore, two independent car movement trajectories were obtained.

3. Results.

Laboratory processing of INS results was made using DelphINS software. This is a special programme package for integrated post-processing of satellite and inertial data, including wheel sensor measurements.

The INS trajectory was processed in forward and reverse directions. In the processing, only INS data were used. As a result, the cumulative location error did not exceed 1 m per 2.5 km of the road. Figure 3 shows that the maximum location error appears in the middle section of the way. If the compensating data are adjoined during the vehicle stopping periods, the location error will decrease.

Figure 3: Root-mean-square error of trajectory after processing in forward and reverse directions.

For the INS trajectory adjustment at the stopping places, the GPS coordinates of the stopping points were typed in by hand and conventionally approved as points of underground surveying network. Figure 4 shows such fragment of the final INS trajectory processing in forward and reverse directions with manually input coordinates at the vehicle stopping periods of time. The GPS coordinates are taken as reference coordinates at the moments when the speed is zero.

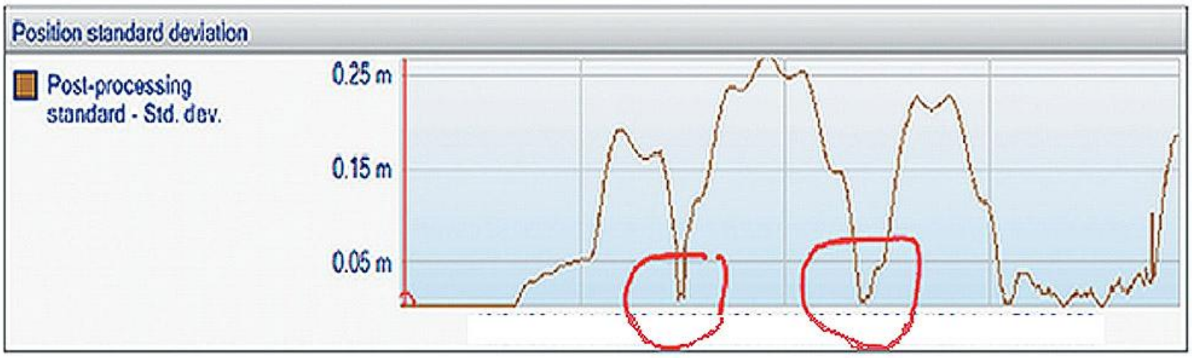

Figure 4: Root-mean-square error of the INS trajectory after adjustment.

Underground surveying networks constitute the basis for mine working survey and consist of survey traverses. The traverses are based on the main underground survey network points. Therefore, in MSS motion trajectory a number of traverses are connected to the main points. In accordance with the current instruction [4], a detailed survey of underground mine workings is conducted from survey network points that are set up through traverses. The relative error should not exceed 1/1,000.

The result of the described adjustment is that the maximal root-mean-square error does not exceed 0.26 m per 515 m. The relative error of the measurements accounts for 1/1,980 at this section. In accordance with the current instruction [4], a detailed survey of underground mine workings is conducted from survey network points that are set up through the closed traverses with the permissible relative linear error of 1/1,500. This allows one to conclude that the application of such INS is reasonable in order to create the MSS for confined space.

Thus, the technology of mobile laser scanning in underground conditions will include a platform with the installed equipment. This platform is mounted on various vehicles, depending on the surroundings and vehicles availability. The platform carries a laser scanner, an INS unit, a GPS antenna and an electronic tachymeter for connection to the main underground survey network points.

Before the survey work starts, it is necessary to label the main survey points which will be used when functioning. The survey points will be equipped with light-reflecting spheres in order to easily recognize them while working in laboratories.

Previous to surveying works, a start-up of the system is performed at the surface to initialize GPS and INS. After the system is delivered to the working site, it is connected to the underground surveying network using the traditional tachymeter measurements. At present, GPS just acts as a scanner and INS synchronizer in time by means of its inside clock.

During field measurements spatial information received from MSS is recorded via two independent dataflow lines. The first line data come from a laser scanner. The second line contains the data about the location and orientation of the mobile platform. Laser scanning data comprise a substantive input of linear scans, each containing the information about the geometrical profile in a form of multiple single measurements. The data on location and orientation of the mobile platform comprise multiple single measurements from the inertial system (lurching, tangage, “hunting”) that have their own time mark in UTC format or GPS time. These data are stored in a file. Simultaneous to the motion, the inertial system adjustment is done via vehicle stoppings and odometer usage. On work completion it is essential to transfer the system to the surface for GPS and INS initialization, that is obligatory for two-sided post-processing of the inertial system trajectory. Further methods of data processing received from laser scanners are well known and agree with data processing methods received by mobile laser scanning.

The technology presented above enables one to significantly shorten the surveying time of lengthy underground mine workings. In addition, it multiplies efficiency. The information content and its accuracy received via scanning methods are incomparable to the traditional measuring methods.

References

[1] Bromberg P V 1979 *The Theory of Inertial Navigation*. (Moscow: Nauka).
[2] Dmitriev S P 1997 *Inertial Methods in Engineering Surveying* (St. Petersburg: Elektropribor)
[3] Lukyanov D P, Mochalov A V and Odintsov A A 1989 *Inertial Navigational Systems for Marine Objects* (Leningrad: Sudostroenie)
[4] Surveying Manuals 2003, RD07-603-03
[5] ru.wikipedia.org
[6] Liu J, Pan Z, Xiangcheng L. *An accelerometer-based gesture recognition algorithm and its application for 3d interaction* //*Computer Science and Information Systems*. – 2010. – Т. 7. – №. 1.
[7] Pettersson G, Tysk J., Vallgren H. *Conversion of Hidden Markov Model computation to C#*, Uppsala University. – 2013
[8] Borza P V 2010 *Recognizing Physical Exercises* (BabesBolyai University, Faculty of Mathematics and Computer Science)
[9] Senin P 2008 *Dynamic Time Warping Algorithm Review*, Information and Computer Science Department, University of Hawaii at Manoa Honolulu, USA, December 2008