A NAVIGATION SYSTEM OF A PIPELINE INSPECTION SYSTEM FOR OIL AND GAS PIPELINES: THE RESULTS OF THE DEVELOPMENT AND TESTING

N.B. Vavilova[1], A.A. Golovan [2], A.V. Kozlov [3], I.V. Nikitin [4], A.A. Panyov [5], N.A. Parusnikov [6]

Lomonosov Moscow State University Laboratory of Navigation and Control, Moscow, Russia
E-mail: aagolovan@yandex.ru.

I.A. Solovyh[7], S.V. Nikiforov[8], A.M. Lavyrev[9], S.V. Morozov[10], A.V. Afanasyev[9]

«Orgenergogaz «Saratovorgdiagnostika», JSC, Saratov, Russia.

I.V. Vesnovskiy[9], A.V. Konon[11], A.A. Laptiev[10], D.V. Turusikov[10]

«Baker Hughes Technologies and Pipeline Service», JSC, Moscow, Russia
E-mail: Albert.Konon@bakerhughes.com

Abstract

The technique and algorithms for solving the navigation problem of the pipeline inspection system are presented. A strapdown inertial navigation system (SINS) makes a basis of the navigation system of the device. Readings of the odometers and geodetic data of the reference points are used for aiding. The questions of preparing and carrying out the experiment, the methods of the data quality control that can significantly improve speed and quality of the experiments are considered. The results of the experimental data processing are given.

Key words: pipeline inspection system, Kalman filter

Introduction

The problem of spatial referencing of the oil and gas pipeline defects arises during the execution of scheduled operations. Pipeline inspection systems (PIG) are used for the pipeline diagnostics.

An inertial measurement unit (IMU) and odometers are a mandatory part of all modern PIGs. Coordinates of the marker points are used as additional information for aiding. Markers passing time is fixed by the PIG sensors. In the postprocessing mode IMU – odometers – markers integrated navigation solution based on IMU data (accelerometers, angular rate sensors (ARS)), odometer readings and coordinates of the markers is built. The result is three spatial PIG coordinates are latitude, longitude, altitude and PIG body orientation angles - yaw, pitch and roll.

Tendency to minimize size and weight of constituent parts, to reduce power consumption of the IMU, to decrease cost but to keep solution accuracy, forced engineers to pay their attention to tactical grade inertial sensors which is available on the market.

In 2010, at the XVII Saint-Petersburg International Conference ICINS-2010 a report [1] was made. One described the prototype of the PIG navigation system developed by joint Moscow State University (MSU) – «Weatherford Pipeline Service» team in this paper. Navigation accuracy that was achieved in the experiments satisfies the customer. In subsequent years joint development to finalize the navigation software continued [2]. Now the team of PIG software developers relates to the company JSC «Baker Hughes technologies and pipeline service».

In 2012-2014 similar collaborations between MSU and «Orgenergogaz «Saratovorgdiagnostika» were conducted. The first test of PIG navigation in the gas pipeline was carried out in June 2014. The navigation accuracy that was achieved during the experiment mainly meets the requirements.

MSU works on the development of PIG mathematical software and staff training were conducted one by one with these companies independently. General information approach to the problem of PIG navigation unites these works. According to this approach, the data from inertial sensors is used for inertial reckoning but the data from odometer readings and information about coordinates of the markers is used for aiding.

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[1] Candidate of Physical and Mathematical Sciences, Leading researcher.
[2] Doctor of Physical and Mathematical Sciences, Head of the Laboratory.
[3] Candidate of Physical and Mathematical Sciences, Senior researcher.
[4] Postgraduate.
[5] Candidate of Physical and Mathematical Sciences, Senior researcher.
[6] Doctor of Physical and Mathematical Sciences, Professor.
[7] Head of branch.
[8] Deputy head of unit.
[9] Lead engineer.
[10] Engineer.
[11] Engineering Supervisor.

Further in this article, the main emphasis will be made on the informational component of the PIG navigation problem in oil and gas pipelines.

Typical navigation system architecture

The typical navigation system of a PIG consists of the following equipment:

- IMU, which has three angular rate sensors (typically, they are fiber-optic ones) and three accelerometers. The «Orgenergogaz «Saratovorgdiagnostika» company uses IMU BChE-500 provided by «Optolink» [8] and AT1104 accelerometers developed by «Temp-Avia» [9]. The «Baker Hughes Technologies and Pipeline Service» uses sensors with the similar accuracy class.
- Odometers, which usually have a minimum resolution of 3 mm (or 5 mm rarely).

The coordinates of reference points are the supplementary information required for the IMU surveys.

Method of preparation and carrying out navigational experiments, experimental data quality control

Within the framework of joint works the method of preparation and carrying out navigational experiments, experimental data quality control was developed. It includes:

- The method of calibration of the inertial measurement unit on a low-grade single axis turntable with horizontal rotation axis [3]. This gives the ability to compare IMU sensors accuracy with the data sheet. Calibration plan consists of three rotation cycles of the IMU in the assembly. During each cycle the IMU is attached to the stand platform so that the corresponding instrumental axis is almost parallel to the turntable rotation axis. Moreover between each cycle the instrumental rotation axes are changed in turn (Fig. 1).

$$\forall \Omega(t) \neq 0$$

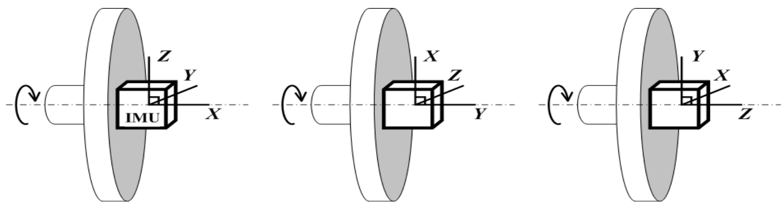

Fig. 1. Scheme of the IMU consistent rotation cycles

During the calibration experiment no additional information about the rotation parameters from the turntable is required. The only information one needs is the approximate value of the rotation axis azimuth angle. Data from IMU accelerometers and ARS are the only measures which are used in performing calibration task. The results of the calibration are inertial sensors zero offset, misalignment of their sensitivity axes, scale factors. Further evaluations of these parameters are taken into account in the main IMU navigation mode. In some cases conducted recalibration allows to improve significantly the navigation results.

- The method of verification of binding markers coordinates to the PIG trajectory. To determine the coordinates of the markers DGPS technology is used, but the presence of human factor in it may cause an error. For the verification purposes the distance between the markers (in areas with a small curvature) calculated by the odometer data is compared with the distance calculated using GPS coordinates of the marker points.
- The procedure of accuracy verification of the IMU characteristics, using the results obtained during the initial alignment stage.

Initial alignment

The task of the IMU initial alignment has its own features in the considered application. These features are:

- No strict limitation on the initial alignment time interval.
- The ability to specify the initial yaw. In order to do this one can set up two markers - at the beginning and at the end of starting camera. After that with help of the DGPS technology the azimuth angle of the base vector connecting those points is defined. This azimuth angle may further be used as an external yaw.
- There are three time slots during the process of placing the PIG in the starting camera:
  - The first interval – inserting the PIG in the camera, switching on the hardware system power supply. During this stage the behavior of the inertial sensors is unstable due to IMU self-heating.
  - Launching the gas (oil) in the camera. This stage is characterized by a strong vibration impact. Under the circumstances solving the alignment task is inappropriate.
  - In the third stage the IMU initial alignment is performed – there are no vibration effects moreover self-heating of the sensors is over. It takes 10 min. or more to complete this step.

Therefore to start the initial alignment one must algorithmically determine the beginning of the third stage. For example this may be done performing the smoothing procedure to the invariant characteristics of the inertial sensors data. Further the accelerometer measurements provide us pitch and roll angles. ARS data (in case of appropriate IMU accuracy class) determines the value of true yaw and latitude.

Comparison between the evaluations of yaw angle and latitude computed during initial alignment stage and the «satellite» based yaw angle and latitude gives the possibility to evaluate the ARS accuracy class and their compliance with the specifications.

One may show that the difference between the known latitude of the site φ and its estimate obtained in the initial alignment is proportional to the ratio combination of northern ν_N, vertical ν_{UP} gyro drifts to the angular rate *u* of Earth rotation:

$$\Delta\varphi = \varphi - \tilde{\varphi} = \frac{\nu_N \sin\varphi + \nu_{UP} \cos\varphi}{u},$$

Similarly using ARS signal ν_u drift along the axis paralleled to the axis of Earth rotation can be computed:

$$\nu_u = \nu_N \cos\varphi + \nu_{UP} \sin\varphi.$$

In the presence of «GPS yaw» ψ^{GPS} calculated using the coordinates of the markers near the starting camera the difference:

$$\psi^{IMU} - \psi^{GPS} = \frac{\nu_E}{u \cos\varphi},$$

will characterize the level of the eastern drift.

Main models and algorithm schemas

To solve the PIG navigation problem information approach [4] is performed. According to this approach the inertial sensors data uses as main information for the obtaining navigation reckoning – SINS solution. Odometers measurements, information about the coordinates of the markers are used for the dead reckoning – aiding algorithms. Due to the fact that the PIG navigation problem is solved in the postprocessing mode one can implement aiding algorithms on the basis of smoothing procedure.

Inertial navigation algorithms

Autonomous three dimensional navigation algorithms are used. The state vector consists of 9 components:

- Geographic coordinates (latitude, longitude, altitude) of the model point:

$$M^t: \varphi^t, \lambda^t, h^t.$$

- The components of the relative velocity vector:

$$V^t = (V_1^t, V_2^t, V_3^t).$$

- True yaw, roll and pitch angles: $\psi^t, \gamma^t, \vartheta^t$;

The 3D navigation mechanization equations are written in the geographical reference frame with the determined azimuth orientation. It can be for example wander azimuth orientation [4].

The equations of the vertical channel are not damped by any external height because the integrated solutions (which will be discussed below) uses odometer data feedback eliminating the well-known exponential instability of the vertical channel.

Models of the odometer

In the idealized model the odometer measurements are considered as the discrete traversed path *s(t)* - scalar measurement of the point *M* along the longitudinal axis of the PIG. The motion takes place without slipping and odometer permanently touches the walls of the pipeline. This allows interpreting the measurement as the integral of velocity of the object at all times directed along the longitudinal axis (to be specific, the 2-nd axis):

$$V^{odo} = (0, V_2, 0)^T.$$

The realistic model has to take into account the following factors:

- Instrumental errors: scale factor error *k*; the presence of the measurement dead zone due to the quantization of the discrete measurements.
- Geometric errors: odometer «measuring» axis and the longitudinal axis of the IMU instrumental frame may be misaligned (this property is characterized by two small angles (χ_1, χ_3)); reduced center of the IMU - the point M and the contact point of the odometer wheel with the pipeline surface do not match.

Taking into account scale factor error, misalignment angles leads to the following «vector» model of the odometer velocity measurement:

$$V^{odo} = (-\chi_3 V_2, (1+k)V_2 + \Delta V^{odo}, \chi_1 V_2)^T,$$

where ΔV^{odo} - a random measurement error of the odometer.

Informational redundancy of the IMU and odometer data

Informational redundancy means that use of odometer velocity measurements which can be interpreted either as a velocity information or as an information about the increment of the traversed path, the model values of the true yaw, roll, pitch angles delivered by SINS algorithms one can independently determine the second position solution - the coordinates $\varphi'', \lambda'', h''$ of the odometric model point M'':

$$\begin{pmatrix} \Delta s_E'' \\ \Delta s_N'' \\ \Delta s_{UP}'' \end{pmatrix} = D' \begin{pmatrix} 0 \\ \Delta s_{i+1}'' \\ 0 \end{pmatrix}, \qquad \lambda_{i+1}'' = \lambda_i'' + \frac{\Delta s_E''}{R_E cos\varphi_i}, \qquad \varphi_{i+1}'' = \varphi_i'' + \frac{\Delta s_N''}{R_N}, \qquad h_{i+1}'' = h_i'' + \Delta s_{UP}''.$$

Here $\Delta s_{i+1}''$ – is the increment of the odometer data on the interval $[t_i, t_{i+1}]$, D' – is the orientation matrix of the geographical and the instrument coordinate systems defined by the SINS algorithm, R_E, R_N - are the curvature radiuses of the prime vertical and meridian.

Two ways of building integration solutions

The first method is based on the interpretation of odometer measurements as the velocity. «Odometer» velocity is used for performing SINS aiding [2]. The second method [5] is based on the interpretation of odometer measurements as the position measurements. Separate kinematic odometer based navigation solution which is the coordinates of the «odometer» point M'' is constructed. Further these coordinates are used for positional SINS aiding. In both cases the markers coordinates are also used as the positional information for aiding.

Models of aiding and smoothing algorithms

Methodologically the PIG aided navigation task based on using the inertial sensor measurements, the odometer data and the markers coordinates is reduced to solving the standard linear stochastic estimation problem in the following form:

$$\frac{dx}{dt} = A(t)x + q, \qquad z = H(t)x + r.$$

Components of the state vector x are position, velocity, angular errors of the SINS, the parameters of the instrumental errors models of the inertial sensors, odometer scale factor error, misalignment angles of his «measuring» axis and longitudinal axis of the IMU, odometer positional errors. The vector x can be represented in the coagulated form:

$$x = \begin{pmatrix} x_I \\ x_{II} \end{pmatrix}, x_I = \begin{pmatrix} x_I^{(1)} \\ x_I^{(2)} \end{pmatrix}, x_{II} = \begin{pmatrix} x_{II}^{(1)} \\ x_{II}^{(2)} \end{pmatrix}.$$

Where x_I is the subvector of the state vector x which characterizes position, velocity and angular SINS errors (subvector $x_I^{(1)}$), the subvector $x_I^{(2)}$ describes the parameters included in the models of the gyro drift and accelerometer errors. The subvector x_{II} characterizes the odometer error (the subvector $x_{II}^{(1)}$), instrumental errors of the odometer including mounting angular error (the subvector $x_{II}^{(2)}$).

Then the structural model of the dynamic system takes the form

$$\begin{pmatrix} \frac{dx_I}{dt} \\ \frac{dx_{II}}{dt} \end{pmatrix} = \begin{pmatrix} A_{11} & 0 \\ A_{21} & A_{22} \end{pmatrix} \begin{pmatrix} x_I \\ x_{II} \end{pmatrix} + \begin{pmatrix} q_I \\ q_{II} \end{pmatrix}.$$

Here the zero matrix angle reflects the independence between the errors of the inertial reckoning and the odometric reckoning.

Measurement vectors $z_I, z_{II}, z_{III}, z_{IV}$ are based on positional solutions of the SINS and the odometer reckoning or "fast" odometer measurement or else marker coordinates:

$$z_I = H_I x_I^{(1)} + r_I, \qquad z_{II} = H_{II} x_{II}^{(1)} + r_{II}, \qquad z_{III} = H_{III} \begin{pmatrix} x_I^{(1)} \\ x_{II}^{(2)} \end{pmatrix} + r_{III}, \qquad z_{IV} = H_{IV} \begin{pmatrix} x_I^{(1)} \\ x_{II}^{(2)} \end{pmatrix} + r_{IV}.$$

Vectors z_I, z_{II} correspond to the aiding measurements while using the information about coordinates of the marker point, when measurement z_{III} corresponds to the SINS aiding using the results of continuous positional odometer reckoning, finally measurement z_{IV} matches to the SINS aiding when odometer data is interpreted as a velocity information. Vectors r_I, r_{II}, r_{III}, r_{IV} characterize the corresponding random measurement error.

The task of SINS aiding in the postprocessing mode is posed as a problem of smoothing. Its solution is based on known technique when the smoothed estimate is determined by «gluing» the two estimates obtained by Kalman's type correction algorithms in forward $\tilde{x}^f$ and backward $\tilde{x}^b$ time t.

Numerical implementation of Kalman's filter involves the use of U-D factorization of the covariance matrix. To implement the filter in backward time one may apply the technique when the value of the covariance matrix $\tilde{p}^b$ in the final time T (limiting value) is given by the «big» matrix: $\tilde{P}^b(T) = m \cdot I, m \gg 1, I -$ *the identity matrix.*

SINS aiding algorithms in forward and backward time due to the low accuracy class of the inertial sensors, a long PIG operating time and, accordingly, a long time of the navigation mode are implemented in the form of feedbacks in the inertial navigation reckoning algorithms [6]. The feedbacks are built on the basis of the extended Kalman's filter [7].

One may mark the feature that arises when implementing these smoothing algorithms. Feedbacks are applied to the algorithms of the inertial reckoning in both forward and backward time. The «gluing» is not exposed to dead reckoning error estimates, but to the estimates of coordinates, velocity, orientation angles obtained by solving the navigation task in forward and backward time. In the formal mathematical operations «gluing» involved navigation parameters of different dimensions: angular coordinates [rad], height [m], velocity [m/s], orientation angles [rad].

Note that when PIG passes U-shaped pipelines, the problem of pitch angle degradation appears and should be carefully regularized under «gluing» estimates.

Practical application

As a result of joint work of Moscow State University first with «Weatherford Pipeline Service» and then with «Baker Hughes Technologies and Pipeline Service» the latest has mastered the outlined navigation technology and now offers the market PIG navigation software with the following specification (www.bakerhughes.com):

The accuracy of the navigation as a function of distance between the correction markers

Marker distance (m)	Horizontal accuracy (m) at 80% certainty	Vertical accuracy (m) at 80% certainty
500	0.5	0.5
1000	1.0	1.0
1500	2.0	2.0

It was also shown that the use of periodic re-calibration of the inertial sensors will increase the precision and stability of the navigational determinations.

Test results of the «Orgenergogaz «Saratovorgdiagnostika» PIG sample model

Navigation experiment was carried out in June 2014 on the main pipeline «Union». The length of the inspected area was about 114 km. The diameter of the gas pipeline was 1420 mm. Average PIG velocity was about 3 m/s.

Along the gas pipeline using GPS receivers was marked 60 control points + 1 for the determination of the initial azimuth. The distance between the markers ranged from 2 km (the most common distance) to 7 km.

Before the beginning of motion process PIG was hold in the starting camera for about 40 minutes. This time interval was used to solve the problem the initial alignment of SINS.

The starting camera was under vibration impact caused by filling gas into the chamber. Last 10 minutes (approximately) were chosen to conduct initial alignment.

Evaluation of integrated navigation solutions accuracy was determined in the following ways:

- By comparing with the coordinates of the special test markers.
- By excluding a marker from the solution and following checking accuracy of determining the coordinates with the same navigation algorithm.
- By comparing with «Google Earth» map where one can see the relief profile of the pipeline route and computed PIG route profile.

Preliminary results of the processing have shown that:

- In areas where the distance between markers is up to 2 km the accuracy of the topographic binding of the PIG trajectory is approximately 1-2 m.
- In areas where the distance between markers is from 2 to 6 km the accuracy degrades to 15 m.

Conclusions

The elaborated method and software-implemented mathematical model were used for the analysis of the PIG data and it gave good results. It has been proved that mid-grade (tactical) inertial sensors can provide meter level accuracy to a user when they are used with high resolution odometers and markers which are placed in one km distance between each other.

This method, mathematical models and software are also applicable for similar navigation solutions when the moving vehicles contain the above sensors or their equivalents. The potential scope of the application includes inertial navigation tasks that can be carried out with the help of a vehicle and topographic surveys during rail and road infrastructure projects.

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