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Positioning Accuracy of a Pipeline Surveying System Based on MEMS IMU and Odometer: Case Study

QIJIN CHEN[1], QUAN ZHANG[1], XIAOJI NIU[1], AND YI WANG[2]
[1]GNSS Research Center, Wuhan University, Wuhan 430072, China
[2]Shenzhen Datie Detecting and Surveying Inc., Guangzhou 510670, China

Corresponding author: Quan Zhang (zhangquan@whu.edu.cn)

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ABSTRACT An inertial navigation system (INS) aided by odometers and a series of reference points has been extensively used to determine the location of pipeline inspection gauges (PIGs) in long-range gas and oil pipeline inspection. However, little attention has been paid to short-range urban underground pipeline surveying and the use of a low-cost inertial measurement unit (IMU) for location determination. The positioning performance of PIGs using low-cost microelectromechanical systems (MEMS) INS for short-range urban underground pipeline surveying applications has seldom been comprehensively evaluated. In this paper, we analyzed the positioning accuracy of a PIG based on a MEMS IMU and odometer through a real pipeline surveying case study. Numerous pipeline surveying cases, covering different pipeline lengths, pipe conditions, and surveying times, are included to achieve a practical conclusion with respect to the surveying accuracy. The results demonstrated that the maximum measurement repeatability errors of PIGs based on MEMS IMU and odometer do not exceed 0.25% and 0.1% of the pipeline length in the horizontal and vertical directions, respectively. These results not only provide powerful support for the PIG developers but also provide the expected PIG accuracy in urban underground pipeline surveying by using low-cost IMUs.

INDEX TERMS Pipeline surveying, urban pipeline, aided INS, pipeline inspection gauge, accuracy analysis.

I. INTRODUCTION

Urban underground pipeline networks have become increasingly complicated with city development, where the risk of accidental damage to existing pipelines increases. The knowledge of the accurate location of existing pipelines is of critical importance for protecting them from being damaged during new construction or digging and for reducing repair costs. Accurate position information can also be used to create a geographic information system of the pipeline network and to locate the pipeline features, defects, unusual distortions and some other faults for maintenance purposes [1]–[4].

Mobile pipeline inspection gauges (PIGs) integrated with positioning sensors are generally used to survey the pipeline position by passing through the pipes. Aided inertial navigation systems (INSs) have been extensively exploited for PIG position determination over a long time period [2], [4]–[6]. The positioning solution of a stand-alone INS is known to drift due to inherent sensor errors; thus, it is necessary to provide periodic external corrections to maintain the position error at an acceptable level for the desired survey accuracy. Available external updates for the INS include zero velocity updates (ZUPTs), points with known coordinates, wheel odometer measurements, and non-holonomic constraints (NHCs). Points on the pipeline with known positions provide coordinate updates (CUPTs) to limit the growth of the INS position errors. Wheel odometer sensors are generally used to provide either additional velocity or distance information to aid the INS [1], [2], [4]. NHCs refer to the fact that the motion of a PIG is constrained by the pipeline, where the PIG can only move in the longitudinal direction inside the pipeline, i.e., the velocity in the plane perpendicular to the longitudinal direction is almost zero [7]. Odometers and NHCs have been proven to significantly improve

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the positioning accuracy and enhance the performance of INSs [4], [8], [9].

Since determining the location of the underground pipeline from the trajectory of an aided INS-based PIG is not a new topic, numerous other previous studies can be found. However, their applications have mainly been concentrated on long-range oil or gas pipelines, where the PIGs work continuously for a long time and travel dozens of kilometers [4], [10]. In this case, tactical- or navigation grade inertial measurement units (IMUs) are required to maintain acceptable positioning accuracy [3]. However, the situation is much different for urban underground pipeline inspection or surveying applications, where the pipelines are relatively short, for example, several hundred meters to one or two kilometers, and the site surveying operation usually lasts only several minutes to one or two hours. Therefore, a low-cost IMU, such as a microelectromechanical system (MEMS) IMU, instead of a high-grade IMU is usually integrated into the PIG apparatus.

There are some reports on the PIGs and their applications in urban underground pipeline surveying based on low-cost IMUs. Chowdhury and Abdel-Hafez [1] proposed to determine the position of the PIG by using low-cost IMU, odometer and a set of reference points, and evaluated the performance with Monte Carlo simulations. Guan *et al.* [11] proposed using a MEMS IMU for PIG localization and enhanced by pipeline junction detection in small diameter pipeline. Simulation results were presented and a primary conclusion was given in his research. Sahli and El-Sheimy [3] also proposed enhancing the pipeline trajectory determined by a MEMS IMU using pipeline junctions detection in the long-range pipeline inspection applications. Reduct NV is a well-known Belgian company located in Schelle, Belgium, which manufactures a variety of pipeline mapping systems tailored to different utility pipe requirements. This company provides PIGs based on MEMS IMU, which can be used for urban underground pipeline surveying, but the measurement accuracy has not been reported in detail in the open literature.

To date, the positioning accuracy of PIGs, especially their performance in real surveying applications based on the MEMS IMU and odometers designed for urban underground pipeline surveying, has seldom been studied. Analytic analysis of the aided INS performance is known to be too complicated and even impossible when considering realistic trajectories and maneuvers [12], [13]. Therefore what surveying accuracy can be expected is an issue concerned by both the developer of positioning system and the PIG users. In this research, we address this crucial issue by analyzing the positioning accuracy of a PIG based on MEMS IMUs and odometers in the urban underground pipeline surveying through real cases.

The remainder of this paper is organized as follows. In section II, the PIG hardware, data post-processing concept and site operation procedures are introduced. The experimental description and detailed performance analysis are presented in section III.

TABLE 1. IMU Specifications.

gyro	
Input range (°/s)	±400
Angular random walk (°/√h)	0.15
Bias instability (°/h)	0.3
Scale factor accuracy (ppm)	±500
Accelerometer	
Input range (g)	±30
Velocity random walk (m/s/√h)	0.07
Bias instability (mg)	0.05
Scale factor accuracy (ppm)	±300

II. PIPELINE SURVEYING SYSTEM BASED ON A MEMS IMU

A. PIG HARDWARE

The PIG hardware is designed and manufactured by Shenzhen Datie Detecting & Surveying Instrument Technology Co., LTD., located in Guangzhou, China. As shown in Fig.1, the PIG contains two exchangeable and self-adjusting wheelsets that enable it to adapt to pipes and ducts with different inner diameters. The self-adjusting wheelsets will push the wheels, maintain contact with the pipe and ensure that the PIG's motion is governed by the pipe, in which case the PIG exhibits only a nonzero speed along in the longitudinal direction. The PIG can be pulled forward and backward manually or with an electrical winch system. The IMU and data recording system are housed in a rigid shell as shown in subplot (b) in Fig.1. A STIM300, high-precision (quasi-tactical grade) MEMS IMU (Sensor Co., Norway), consisting of 3 high-accuracy MEMS-based gyros and 3 high-stability accelerometers, is embedded in the PIG, Table 1 presents the IMU specifications. Odometers measure the traveled distance by counting the number of rotations of the wheels, and three transducers are integrated into one wheelset to enhance the performance. The IMU outputs and odometer measurements are all recorded and synchronized by an onboard data recording system. The IMU and odometer sensors output raw measurements at 125 Hz and 20 Hz, respectively.

B. SITE SURVEYING OPERATION

In urban underground pipeline surveying applications, points with known position coordinates are only available at the starting (entry) and ending (exit) terminals, as shown in Fig. 2. The site surveying operation procedure is as follows.

1) Install the pulling rope.

2) Insert the PIG into the pipe and align with the entry terminal.

3) Power on the PIG to start data logging, and keep the PIG stationary for several seconds, e.g., 60 s.

4) Pull the PIG forward either manually or with an electrical winch toward the exit terminal.

5) Align the PIG with the exit terminal, and keep the PIG stationary for several seconds.

FIGURE 1. The pipeline surveying apparatus based on the MEMS IMU and odometers. (a) PIG suites, (b) PIG, and (c) self-adjusting wheelset.

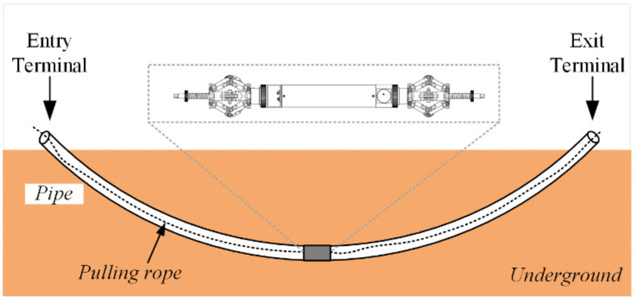

FIGURE 2. PIG's site operation procedure.

6) Pull the PIG backward without changing its orientation, and align it with the entry terminal. Then, keep the PIG stationary for several seconds, e.g., 60 s.

7) Collect the logged data, and power off the PIG to finish the surveying operation.

In such a procedure, the pipe is surveyed twice, and the measurement accuracy is improved by processing the raw data as a whole. The synchronized data from the IMU and odometers together with the reference point coordinates at the entry and exit terminal are fused with post-processing software to produce the final solutions. The data processing can be completed within several minutes immediately at the surveying site. The data post-processing software, named PipeSurvey, is developed by the author at the Navigation Group of GNSS Research Center at Wuhan University.

C. DATA POST-PROCESSING CONCEPT

The post-processing software adopts a cascading design, as depicted in Fig.3. The sensor outputs are preprocessed prior to being fed into the data fusion Kalman filter; the preprocessing includes fault detection and an integrity check. A loosely coupled architecture is adopted for aided INS integration for its flexibility. Then, the integrated solutions are synchronized with respect to the distance. Finally, the software output the solutions, including the three-dimensional (3D) position coordinates, i.e., the horizontal trajectory and height/depth profile, 3D attitude of the pipe, curvatures and slope plot along the pipeline.

The fusion of the IMU raw measurement and external auxiliary information, including odometer data, CUPT, NHC and

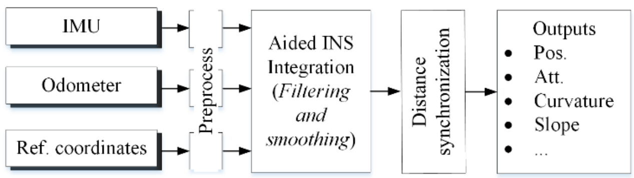

FIGURE 3. Concept of PIG data post-processing.

ZUPT, is implemented in a loosely coupled architecture. The equations discussed in the following assume that a navigation frame (i.e., n-frame, north-east-down) INS mechanization is used.

1) SYSTEM MODEL OF THE AIDED INS

The error state vector for the extended Kalman filter, including the 3 position errors, 3 velocity errors, 3 attitude errors, residual biases and scale factor errors of the gyroscopes and accelerometers, is written as

$$\boldsymbol{x}(t) = \left[(\delta \boldsymbol{r}^n)^{\mathrm{T}} \; (\delta \boldsymbol{v}^n)^{\mathrm{T}} \; \boldsymbol{\phi}^T \; \boldsymbol{b}_g^{\mathrm{T}} \; \boldsymbol{b}_a^{\mathrm{T}} \; \boldsymbol{s}_g^{\mathrm{T}} \; \boldsymbol{s}_a^{\mathrm{T}} \right]^{\mathrm{T}} \tag{1}$$

where operator δ denotes the error of a variable; $\delta \boldsymbol{r}^n$ and $\delta \boldsymbol{v}^n$ are the INS-indicated position and velocity errors resolved in the n-frame, respectively; $\boldsymbol{\phi}$ refers to the INS-indicated attitude errors; $\boldsymbol{b}_g$ and $\boldsymbol{b}_a$ are the residual bias of the gyros and accelerometers, respectively; and $\boldsymbol{s}_g$ and $\boldsymbol{s}_a$ are residual scale factor errors of the gyros and accelerometers, respectively.

The system model in continuous time form is expressed as

$$\dot{\boldsymbol{x}}(t) = \mathbf{F}(t)\,\boldsymbol{x}(t) + \mathbf{G}(t)\,\boldsymbol{w}(t) \tag{2}$$

where $\mathbf{F}(t)$ is the system matrix describing the system dynamics; $\mathbf{G}(t)$ is the system noise distribution matrix and $\boldsymbol{w}(t)$ is the system noise vector. To obtain the aided INS system model, the time derivative of each state variable must be calculated. The position, velocity and attitude error differential equations are [14]:

$$\begin{aligned} \delta \dot{\boldsymbol{r}}^n &= -\boldsymbol{\omega}_{en}^n \times \delta \boldsymbol{r}^n + \delta \boldsymbol{\theta} \times \boldsymbol{v}^n + \delta \boldsymbol{v}^n \\ \delta \dot{\boldsymbol{v}}^n &= \mathbf{C}_b^n \delta \boldsymbol{f}^b + \boldsymbol{f}^n \times \phi - \left(2\boldsymbol{\omega}_{ie}^n + \boldsymbol{\omega}_{en}^n\right) \times \delta \boldsymbol{v}^n \\ &\quad + \boldsymbol{v}^n \times \left(2\delta \boldsymbol{\omega}_{ie}^n + \delta \boldsymbol{\omega}_{en}^n\right) + \delta \boldsymbol{g}_l^n \\ \dot{\boldsymbol{\phi}} &= -\boldsymbol{\omega}_{in}^n \times \boldsymbol{\phi} + \delta \boldsymbol{\omega}_{in}^n - \mathbf{C}_b^n \delta \boldsymbol{\omega}_{ib}^b \end{aligned} \tag{3}$$

where $\boldsymbol{\omega}_{en}^{n}$ is the angular rate of the n-frame with respect to the Earth frame (e-frame) resolved in the n-frame; $\delta\boldsymbol{\theta}$ is a rotation vector describing the misalignment of the computer frame with respect to the true n-frame [15]; $\boldsymbol{v}^{n}$ is the velocity in the n-frame; $\mathbf{C}_{b}^{n}$ represents the body frame (b-frame) to the n-frame transformation matrix; $\delta\boldsymbol{f}^{b}$ refers to the accelerometer measurement errors; $\boldsymbol{f}^{n}$ is the specific force resolved in the n-frame; $\boldsymbol{\omega}_{ie}^{n}$ is the angular rate of the e-frame relative to the inertial frame (i-frame) in the n-frame; $\delta\boldsymbol{\omega}_{ie}^{n}$ and $\delta\boldsymbol{\omega}_{en}^{n}$ denote errors in $\boldsymbol{\omega}_{ie}^{n}$ and $\boldsymbol{\omega}_{en}^{n}$, respectively; $\delta\boldsymbol{g}_{l}^{n}$ is the local gravity error in the n-frame; $\boldsymbol{\omega}_{in}^{n}$ is the angular velocity vector $\boldsymbol{\omega}_{in}^{n} = \boldsymbol{\omega}_{ie}^{n} + \boldsymbol{\omega}_{en}^{n}$ with the corresponding error denoted by $\delta\boldsymbol{\omega}_{in}^{n}$; and $\delta\boldsymbol{\omega}_{ib}^{b}$ is the gyroscope's measurement error.

The parameters $\boldsymbol{b}_{g}$, $\boldsymbol{b}_{a}$, $\boldsymbol{s}_{g}$ and $\boldsymbol{s}_{a}$ are modeled by the first-order Gauss-Markov process described by

$$\dot{x}_{GM}(t) = -\frac{1}{T_c}x(t) + w_{GM}(t) \tag{4}$$

where T_c is the correlation time of the process, and $w_{GM}(t)$ is the driving white noise process. Refer to the literature [16] for more details regarding this stochastic process.

2) MEASUREMENT MODEL

For urban underground pipeline surveying applications, the available external updates include the position coordinates of the reference points and odometer measurements. When the PIG arrives at either the entry (starting) or exit (ending) terminals, the coordinates update from the reference points is available to update the aided INS Kalman filter. The measurement equation can be derived as [14]

$$z = \delta\boldsymbol{r}^{n} + \left(\mathbf{C}_{b}^{n}\boldsymbol{l}_{c}^{b}\times\right)\boldsymbol{\phi} + \boldsymbol{e}_{c} \tag{5}$$

where $\boldsymbol{l}_{c}^{b}$ is the level arm vector from the IMU center to the reference point and resolved in body frame and $\boldsymbol{e}_{c}$ represents the error of the reference point coordinates.

The relationship between the PIG's wheel velocity and the IMU velocity can be expressed as:

$$\boldsymbol{v}_{odo}^{v} = \mathbf{C}_{b}^{v}\mathbf{C}_{n}^{b}\boldsymbol{v}^{n} + \mathbf{C}_{b}^{v}\left(\boldsymbol{\omega}_{nb}^{b}\times\right)\boldsymbol{l}_{odo}^{b} \tag{6}$$

where $\boldsymbol{l}_{odo}^{b}$ is the lever-arm vector from the IMU measurement center to the wheel sensor, resolved in the b-frame. Notably, the lever-arm will change with a small magnitude (for example 2 cm) with respect to the nominal value when the wheelsets adjust to pipes with different diameters, but the corresponding effect for the integrated solution is ignorable. $\mathbf{C}_{b}^{v}$ is the b-frame to v-frame transformation matrix; it is not an identity matrix if misalignment angles exist between b-frame and v-frame. The INS-indicated velocity at the wheel point is denoted by $\hat{\boldsymbol{v}}_{odo}^{v}$.

As mentioned in section II, subsection A, the PIG's motion is governed by the duct when passing through the pipe, in which situation the PIG's velocity components in the plane perpendicular to the longitudinal direction are almost zero. This constraint is named NHC. The longitudinal speed derived by differentiating the odometer outputs in combination with the NHC constitutes the 3D external velocity measurement as follows:

$$\tilde{\boldsymbol{v}}_{odo}^{v} = \begin{bmatrix} v_{odo} & 0 & 0 \end{bmatrix}^{\mathrm{T}} \tag{7}$$

where $\tilde{\boldsymbol{v}}_{odo}^{v}$ is the velocity measurement in the v-frame and v_{odo} is the odometer-derived speed. The real velocity measurement can be expressed as

$$\tilde{\boldsymbol{v}}_{odo}^{v} = \boldsymbol{v}_{odo}^{v} - \boldsymbol{e}_{\mathrm{v}} \tag{8}$$

where $\boldsymbol{e}_{\mathrm{v}}$ is the velocity measurement noise, modeled as Gaussian white noise. The first element of $\boldsymbol{e}_{\mathrm{v}}$ is the error in the odometer-derived speed, and the other two elements represent the uncertainty of the NHC. Therefore, the v-frame velocity error measurement equation can be expressed as [14]:

$$\begin{aligned} z &= \hat{\boldsymbol{v}}_{odo}^{v} - \tilde{\boldsymbol{v}}_{odo}^{v} \\ &= \mathbf{C}_{b}^{v}\mathbf{C}_{n}^{b}\delta\boldsymbol{v}^{n} - \mathbf{C}_{b}^{v}\mathbf{C}_{n}^{b}\left(\boldsymbol{v}^{n}\times\right)\boldsymbol{\phi} - \mathbf{C}_{b}^{v}\left(\boldsymbol{l}_{odo}^{b}\times\right)\delta\boldsymbol{\omega}_{ib}^{b} + \boldsymbol{e}_{\mathrm{v}} \end{aligned} \tag{9}$$

When the PIG is stationary, the odometer-derived speed v_{odo} is zero, and in this case, a zero velocity update can be used to update the INS solution.

3) TRAJECTORY SMOOTHING

Rauch-Tung-Striebel (RTS) smoothing is applied to improve the estimation accuracy utilizing all past, current and future measurements. Details regarding the implementation of the RTS smoothing algorithm can be found in [17], [18]. Finally, once the PIG attitudes are determined, dead reckoning (DR) using the PIG's attitude and traveled distance is used to adjust the PIG position coordinates and reconstruct the smooth trajectory and depth profile; the algorithm and implementation details can be found in [2].

III. EXPERIMENTS AND RESULTS

Five pipelines at different locations with different materials and lengths spanning from 110 m to 1700 m were surveyed to evaluate the measurement accuracy. In the field test, each pipeline was surveyed multiple times to evaluate the measurement repeatability. Table 2 summarizes the surveying information.

TABLE 2. Information regarding the surveyed pipelines.

Case No.	Pipeline material	Time span of one surveying (s)	Length (m)	Number of runs
1	HDPE	500	110	4
2	Steel	700	300	4
3	HDPE	1200	420	6
4	Steel	3800	1700	4
5	HDPE	960	195	4

In case 1, an high-density polyethylene (HDPE) duct, owned by a power energy company located in Foshan, Guangdong Province, China, was surveyed. The pipeline was measured back and forth two times. In the first time,

FIGURE 4. Photos of site surveying operation.

the PIG was pulled from the entry terminal to the exit terminal and then moved back to the entry terminal without turning around, i.e., without changing the PIG's orientation. Then, the second time, the PIG was powered off and on again to survey the pipeline for the second time in the reverse orientation. Therefore, four trajectories were obtained in this test. The pipeline length is approximately 110 m. In case 2, the surveyed pipeline is a 300-m-length steel duct owned by a gas fuel company. The duct is over-ground, as shown in the fourth photo in Fig.4, so we had the opportunity to survey the duct with a geodetic surveying apparatus (total station) to obtain the reference trajectory with centimeter accuracy. In case 3, a 420-m-length pipeline was surveyed back and forth three times in an analogous manner, and 6 trajectories were obtained. In case 4, a 1700-m-length steel fuel gas pipeline was surveyed, as shown in the third photo in Fig.4. This pipeline (across a river) is the longest urban underground pipeline that we have ever surveyed in recent years. This case is considered a challenge for the PIG positioning using MEMS IMU because the pipeline is long and it took a long time, more than an hour, to finish the site surveying operation. In case 5, a 195-m-length HDPE pipeline was surveyed in a similar manner, and 4 trajectories were obtained.

Since it is not convenient to survey the urban underground pipeline with an accurate geodetic apparatus to obtain ground reference every time, we choose to assess the measurement repeatability, i.e. the degree of agreement between multiple individual measurements carried out on the same pipeline, by graphically comparing the multiple surveyed profiles of the same duct. Then, we evaluate the degree of agreement between the repeatability measures and the actual errors in the case where a reference is available to prove the feasibility of indicating the system accuracy with repeatability measure.

A. REPEATABILITY ANALYSIS

The maximum excursion sequences between the multiple trajectories in both the horizontal and vertical directions are used as measures of the repeatability. Notably, this is a stricter measure than the root mean square of the repeat error sequences. The repeatability measures in the horizontal direction are calculated as follows:

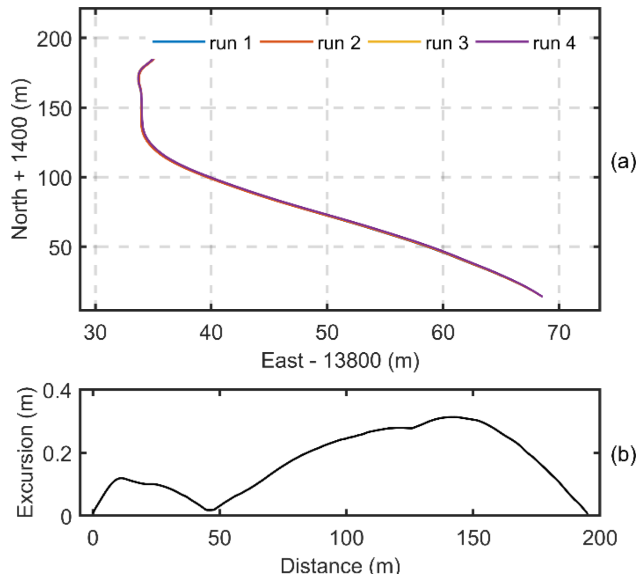

FIGURE 5. Repeatability of the surveyed horizontal profiles. (a) Four surveyed trajectories and (b) the maximum excursion plot between the four samples.

1) use the multiple surveyed profiles to generate an average trajectory.
2) calculate the perpendicular lines of the average trajectory at each distance constant along the trajectory.
3) calculate the intersection points of each surveyed trajectory with the perpendicular lines at the given mileage.
4) calculate the distance between every two intersection points and choose the maximum distance as the horizontal excursion at this mileage.

Therefore, the horizontal excursion is the absolute spread between multiple individual measurements. The vertical excursion is calculated as the height difference between multiple runs at each mileage in a similar manner.

Case 5 is taken as an example for the repeatability analysis. The subplot (a) in Fig.5 and Fig.6 depict the four surveyed horizontal and vertical profiles, respectively. The trajectory is almost in the south-north orientation, and the duct bends

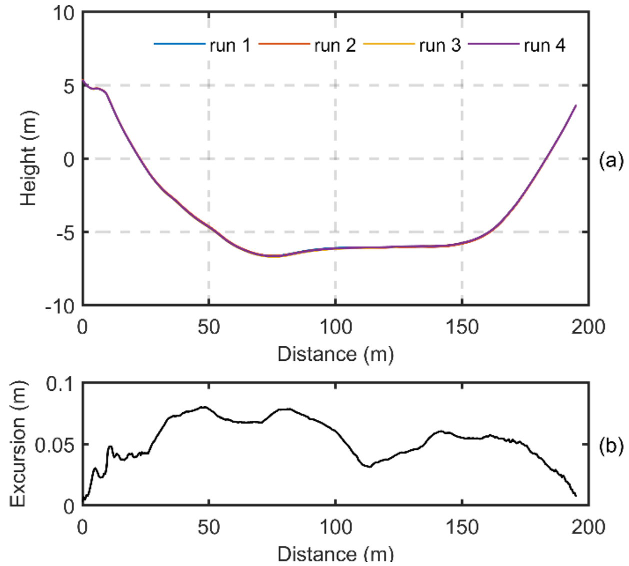

FIGURE 6. Repeatability of the surveyed vertical/depth profiles. (a) Four surveyed depth profiles and (b) the maximum excursion plot between the four samples.

at several sections with a small curvature radius. The corresponding repeatability measures are plotted in subplot (b). Fig.5 indicates that the maximum difference between the four surveyed trajectories along the whole pipeline section is 0.35 m. The repeatability in the height measurement is within 0.1 m for the four runs, as illustrated in subplot (b) in Fig.6.

Fig.7 summarizes the repeatability measures in both the horizontal and vertical directions for the other four field tests. The first observation of this figure is that the vertical excursions are smaller than those in the horizontal direction because the INS with aiding has better accuracies in roll and pitch angles than in the heading measurement. But these plots seem to have no simple functional relation with regard to the pipeline length.

B. ACCURACY ANALYSIS

In case 2, we surveyed the over-ground pipeline using the total station and obtained reference point sequences that are accurate to within 1 cm. The sampling distance interval of the reference points is approximately 20 m. The subplot (a) in Fig.8 and Fig.9 shows the surveyed trajectory and depth profiles in four runs, respectively. The trajectory is quite straight, and the duct is smooth, i.e., the PIG's vibrational motion is quite small due to the pipe junction. The reference points measured by the total station have no mileage tags and do not align with the PIG trajectories in the longitudinal direction. Therefore, the PIG trajectories are graphically compared with the reference point sequences, as illustrated above. Subplot (b) in Fig.8 shows the maximum excursions of the reference points to the PIG trajectories. The difference between the reference points and surveyed trajectories is within 0.1 m. The difference in height is within 5 cm, as depicted in subplot b in Fig.9.

TABLE 3. Correlations between surveying the time and pipe lengths with measurement accuracy.

Case No.	Time span of one surveying (s)	Length (m)	Max. horiz. Error (m)	Max height error (m)
1	500	110	0.14	0.05
2	700	300	0.08	0.04
3	1200	420	0.87	0.35
4	3800	1700	4.5	0.26
5	960	195	0.32	0.07

Comparing Fig.8, Fig.9 with subplot (b) in Fig.7, we find that the actual measurement errors are consistent with the above calculated repeatability errors, implying that the surveying repeatability is a feasible measure for evaluating the PIG's performance in the case where reference trajectories are not available.

C. DISCUSSION

With further observation, we find that the PIG's measurement accuracy correlates to both the surveying time span and the pipeline length, as summarized in Table 3. The measurement accuracy seems to degrade as the surveying time and pipe length increase, i.e., the longer it takes for the site surveying operation or the longer the pipe is, the larger the repeatability error is. However, the relation is more complicated than a simple linear correlation because the PIG's surveying performance is influenced by a variety of error sources in addition to the operating time and pipe length; these sources include the use of NHC updates, trajectories, maneuvers and dynamics experienced by the PIG, and the stability of the PIG structure.

The NHC has been proven to significantly improve the positioning accuracy and enhance the performance of the INS, especially for urban underground pipeline surveying applications where CUPTs are only available at the starting and ending terminals. However, using NHC updates requires that the axes of the IMU align with the host vehicle body frame as accurately as possible to exploit their fullest potential. An attitude misalignment of the IMU with respect to the host PIG, also called mounting angles, will degrade the benefit of the NHC update. In practice, residual mounting angles exist even after calibration. Additionally, the PIG mounting on two wheelsets is not a rigid body, which means that the mounting angles may vary while passing through the pipeline and that the condition of using the NHC update correlates with the stability of the wheelsets. Long pipelines are generally constructed by connecting short pipe sections together end to end, with small gaps or bulges, i.e., pipeline junctions exist between every two sections. The PIG will necessarily vibrate when passing through the pipeline junctions or joints, in which case the condition of using NHC update deteriorates. As shown in Fig.10, spikes appear in the accelerometer measurement when traveling through the joint points.

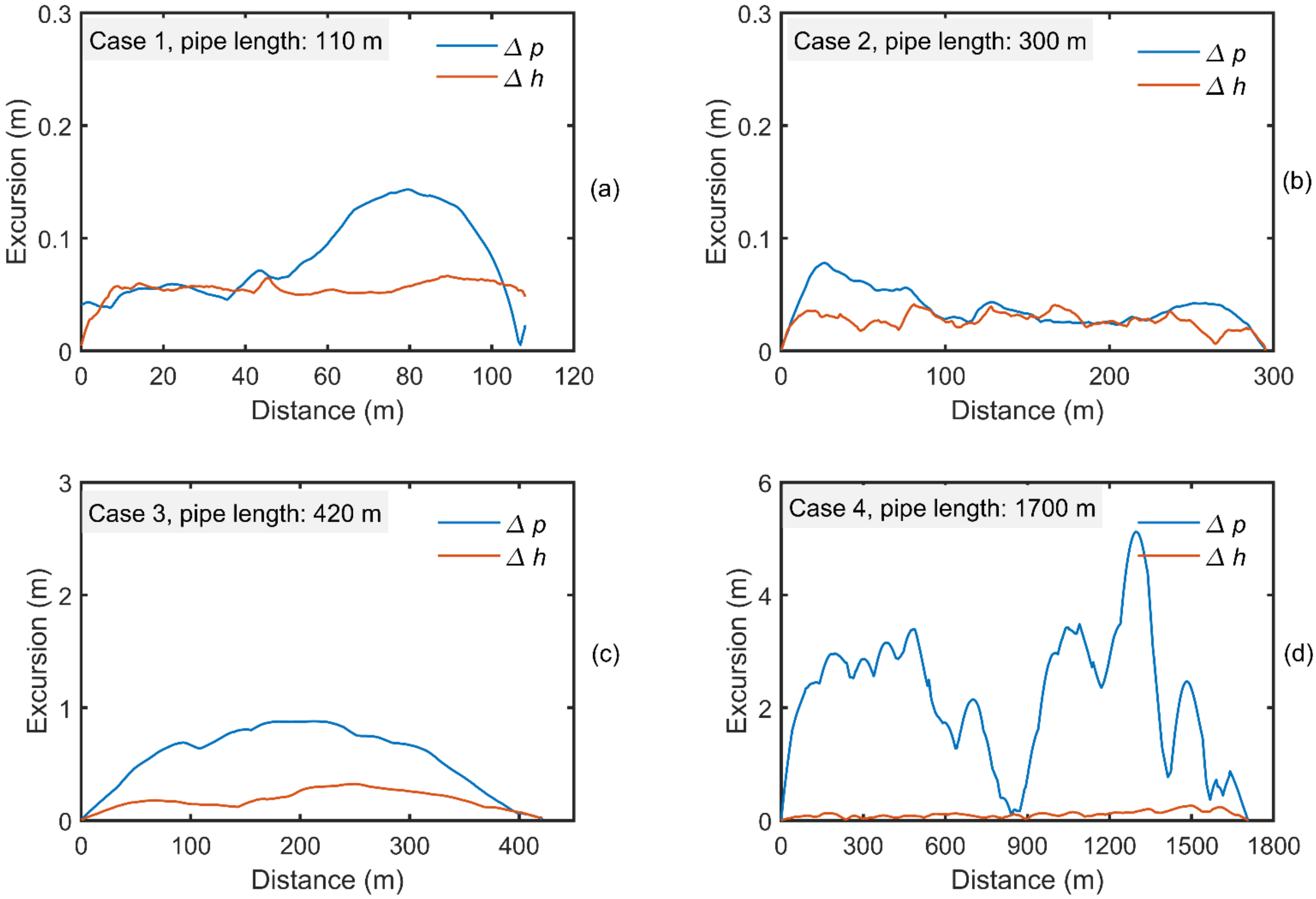

FIGURE 7. **Repeatability of the surveyed profiles in four cases (Δ p is the horizontal excursion, Δ h is the vertical excursion).**

For example, cases 2 and 5 are compared to illustrate this issue. In case 2, the steel duct is quite straight and has a smaller gap at the joint points, so the PIG's motion is quite smooth, which can be interpreted from the corresponding accelerometer outputs, as shown in Fig.10. In contrast, in case 5, the duct has a larger gap at the joints and distorts at several sections, which can be interpreted from the corresponding accelerometer outputs, as shown in Fig.10. In addition, the distorted duct makes it more difficult for the PIG to pass through the duct and causes the PIG to rotate, in which case it is not possible to estimate the mounting angle of the IMU with respect to the PIG. Besides, more time is required to pass through the shorter duct in case 5 than in case 2. Considering these factors, the negative effects of the duct condition on the NHC update in case 5 are more significant. As a consequence, case 2 has a better positioning accuracy even though the pipeline is longer than that in case 5.

The main error sources affecting the positioning accuracy are analyzed qualitatively above. However, obtaining the exact error propagation of the INS/odometer/NHC integrated solution and the corresponding theoretical accuracy is too complicated. In a more practical approach, we choose to draw the positioning error trend with respect to the pipeline length and surveying time length. To achieve this goal, another

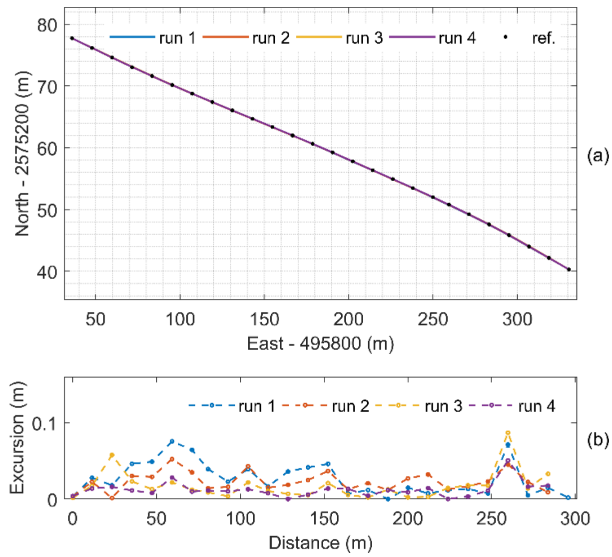

FIGURE 8. **Measurement accuracy analysis in the horizontal direction. (a) Horizontal profiles and (b) measurement errors of the surveyed trajectories.**

8 cases together with the 5 cases discussed above were evaluated. These cases are selected by taking into account the pipeline length spanning from 110 m to 1700 m. In each

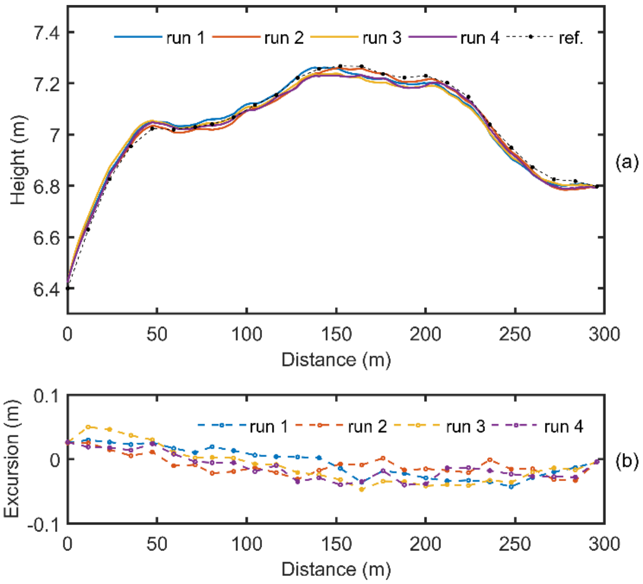

FIGURE 9. **Measurement accuracy analysis in the vertical direction. (a) Depth profiles and (b) measurement errors of the surveyed vertical profile.**

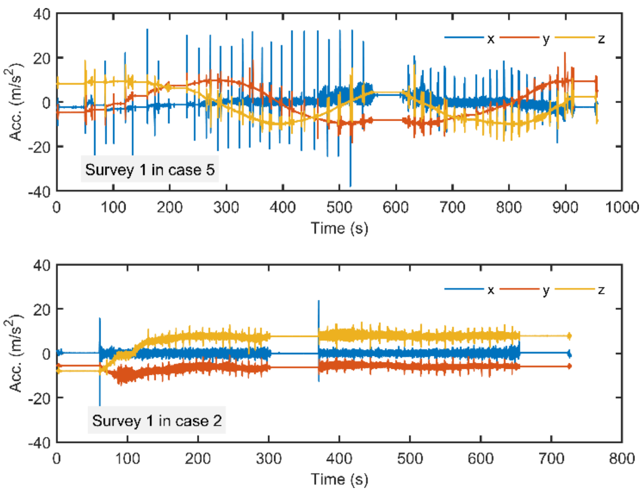

FIGURE 10. **Accelerometer outputs of the IMU embedded the PIG in case 2 and case 5.**

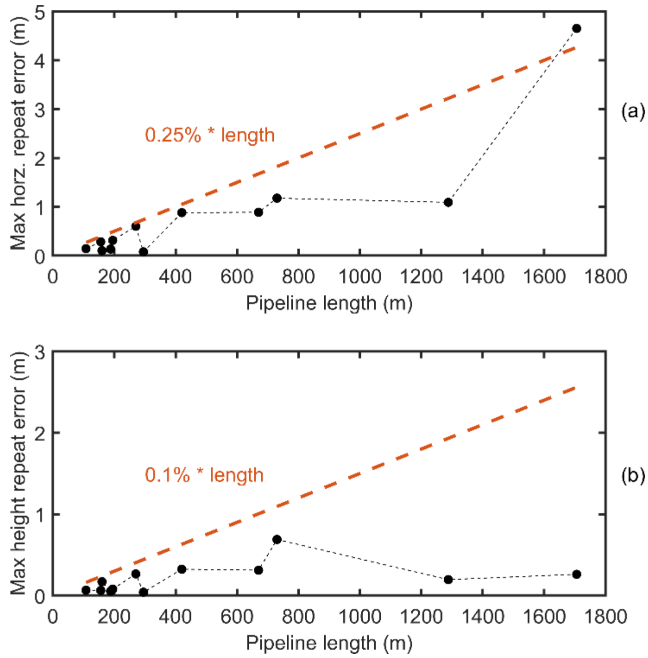

FIGURE 11. **Maximum repeat errors versus the pipeline length.**

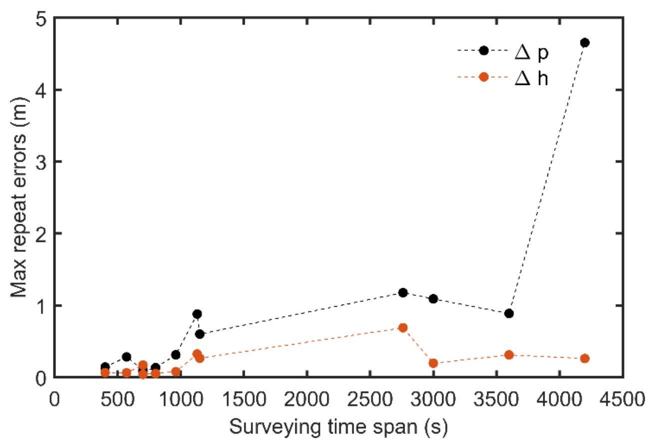

FIGURE 12. **Maximum repeat errors versus site operation time span.**

case, the maximum horizontal and vertical excursion values between the surveyed profiles are selected as a measure of the positioning error in the horizontal and vertical directions, respectively, and then these measures are plotted versus the pipeline length and the site operation time length, as depicted in Fig.11 and Fig.12, respectively.

Both figures show increasing trend in the horizontal position errors with the pipeline length and surveying time length, while the height errors are much smaller and show an indistinctive correlation with the pipeline and surveying time lengths. Because the measurement error was commonly described by the percentage of the pipeline length in previous studies, we can obtain the practical conclusion in a similar manner: the PIG's maximum positioning errors do not exceed 0.25% and 0.1% of the pipeline length in the horizontal and vertical directions, respectively. Notably, this is a stricter measure to evaluate our repeatability errors compared to the commonly used root mean square (RMS) of the error sequences.

Since the measurement accuracy correlates with the pipeline length, surveying time span, and conditions of using the NHC. This above conclusion implies that in order to improve the surveying accuracy, PIG users are suggested to clean the duct before the surveying operation, check the wheelsets' stability, periodically calibrate the PIG's mounting angle, and shorten the site surveying time length.

IV. CONCLUSION

The problem of location determination of a PIG using aided INS has been comprehensively studied in previous studies.

The focus of these studies was concentrated on long-range gas and oil pipeline inspection using high-grade IMUs, such as tactical or navigation grade. Surveying the short-range urban underground pipeline by a PIG based on a low-cost INS with aiding has seldom been studied, but is now becoming a crucial issue as the urban pipeline network becomes increasingly complicated with city development. In this research, we have studied the fundamental question on what positioning accuracy and surveying performance of a PIG using a MEMS based IMU and odometer can be expected in the real field test.

We evaluated the positioning accuracy of the PIG via a real case study. A practical conclusion can be achieved that the maximum repeatability errors of the PIG using a high-grade MEMS IMU, i.e., STIM300, do not exceed 0.25% and 0.1% of the pipeline length in the horizontal and vertical directions, respectively. Our results in this study provide powerful support for PIG developers and users regarding the surveying accuracy of the PIG based on a MEMS IMU for urban underground pipeline applications.

However, some limitations of this study are worth noting. Although the practical positioning accuracy was supported statistically, the samples we used cannot cover every exact error source in the real surveying cases. Future work will include a follow-up work on accuracy improvement by using an adaptive Kalman filter and combining the multiple profiles in one survey.

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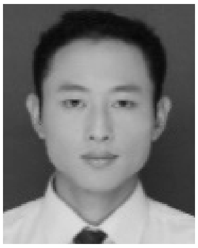

QIJIN CHEN received the B.Eng. and Ph.D. degrees in geodesy and survey engineering from Wuhan University, Wuhan, China, in 2011 and 2016, respectively, where he is currently a Postdoctoral Fellow with the GNSS Research Center. His research interests include INS with aiding and its applications in geodesy and precise surveying engineering including railway track geometry measuring and underground pipeline surveying.

QUAN ZHANG received the B.S. degree in geomatics engineering from the Shandong University of Science and Technology, in 2009, and the Ph.D. degree from Wuhan University, in 2015. From 2017 to 2018, he was a Postdoctoral Researcher with the Digital Photogrammetry Research Group (DPRG), Lyles School of Civil Engineering, Purdue University. He is currently a Research Assistant and a Postdoctoral with the GNSS Research Center and Collaborative Innovation Center of Geospatial Technology, Wuhan University. His research interests include the inertial navigation and GPS/INS integration technology.

XIAOJI NIU received the bachelor's and Ph.D. degrees from the Department of Precision Instruments, Tsinghua University, in 1997 and 2002, respectively. He did his Postdoctoral Research with the University of Calgary. He was a Senior Scientist with SiRF Technology Inc. He is currently a Professor with the GNSS Research Center, Wuhan University, China. He has published more than 90 academic papers and own 28 patents. He leads the Multi-Sensor Navigation Group focuses on GNSS/INS integrations, low-cost navigation sensor fusion, and its new applications.

YI WANG received the B.Eng. degree in electronic information engineering from Xiangtan University, Xiangtan, Hunan, China, in 2001, and the M.S. degree in control theory and engineering from the Guangdong University of Technology, Guangzhou, China, in 2004. He has 15 years' experience in positioning and navigation system design and development. He is currently one of the founders of Shenzhen Datie Detecting and Surveying Inc., Shenzhen, China.