Development of Inspection Gauge System for Gas Pipeline

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An autonomous pipeline inspection gauge system has been developed for determining position, orientation, curvature, and deformations such as dents and wrinkles of operating pipelines by Korea Gas Company and Seoul National University. The most important part of several subsystems is the Strapdown Inertial Measurement Unit (SIMU), which is integrated with velocity and distance sensors, weld detection system, and digital recording device. The Geometry Pipeline Inspection Gauge (GeoPIG) is designed to operate continuously and autonomously for a week or longer in operating gas pipelines. In this paper, the design concepts, system integration, and data processing/analysis method for the PIG will be presented. Results from the recent experiment for a 58 kilometer gas pipeline will be discussed.

Key Words: Pipeline Inspection Gauge (PIG), Navigation, Extended Kalman Filter (EKF)

1. Introduction

The structural failure of a pipeline may result in environmental damage and financial losses. By regularly monitoring the pipelines, it is possible to predict some failure modes and plan maintenance (Kim et al., 2001). A pipeline might fail for several reasons which are related to deformation if we interpret deformation in a wide sense (Czyz and Falk, 2000). The most common ruptures are caused by a physical damage, change of curvature or length of a pipe, and pipe wall corrosion (Lee and Pyun, 2002). The damaging forces are usually external. The inspection of a pipe has to accomplish two tasks. Critical deformations have to be detected and also located. A pipe can be buried, underwater, hanging from bridges and passing tunnels where the classical surveying methods and instruments are not appropriate. These classical surveying methods or instruments cannot access the pipe directly, and even if some of them can, it is not from the inside. In addition, they measure only point by point (Porner et al., 1990; Wade and Adams, 1995; Cox et al., 1995). For many years, the only method of monitoring what was happening to the inside of the pipeline was by inspecting pipelines that were opened for any reason. Because of these reasons, the high performance inspection

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tool such as geometry Pipeline Inspection Gauge (GeoPIG) has been deployed for a number of years in many countries. The GeoPIG is defined as a PIG designed to record conditions, such as dents, wrinkles, ovality, bend radius and angle, and occasionally indications of significant internal corrosion by making measurements of the inside surface of the pipeline. It improves the safety and efficiency of pipeline operations. The PIG is now the most widely accepted term for any device driven by the product flow (Nguyen et al., 2001a ; 2001b), which is inserted into a pipeline and travels freely through it. From changes in the measured dynamic behavior of the PIG, information on the condition and alignment of the pipeline as well as the presence of internal damage and anomalies are determined. Today, there are more than three hundred and fifty PIGs of all types. A large number of specialized services and several thousand related products are available as well (Cordell and Vanzant, 1999).

For the increasing needs for the precise inspection of a pipeline, Korea Gas Company (KOGAS) and Seoul National University (SNU) have jointly developed a geometry PIG with SINS (Strapdown Inertial Navigation System) (Lee et al., 2002). The fundamental purpose of the PIG development was to create a system that identifies the internal surface condition of the lines and maps its route while indicating the presence of any damage which may have occurred. When this PIG system was developed, it was applied to a field experiment in a gas pipeline between the Jeongup and Wolchul in Korea. It was turned out to be very successful to collect the necessary data regarding the condition of pipeline with Strapdown Inertial Measurement Unit (SIMU), odometer, and tracking system for the position information. A post-processing of the pipeline condition was performed by a nonlinear two-filter smoothing algorithm (Loendes et al., 1970 ; Yu et al., 2002) to obtain the accurate positions of interest and the map of the pipeline trajectory. In this paper, the overall subsystems and algorithm for the developed PIG system will be explained, and the performances of the system in the real field experiment are also investigated. Especially, the design method and principles embodied in the odometer, which is a distance sensor, and the post-processing method for locating the PIG will be discussed in detail. The odometer is implemented to meet the needs for the PIG system and its reliability has been confirmed by the test using a simulator.

The following sections describe the hardware of the PIG system, the post-processing scheme of the measured data, and finally some experimental results.

2. PIG System Hardware

The PIG system is designed to meet a large variety of user requirements by using a modular system which integrates a various number of different sensors (Cordell and Vanzant, 1999). Our current version can inspect pipelines of 30 inch diameter. The choice of appropriate mixing of instrumentations was essential to ensure the ability of PIG to detect important features and events in pipelines. The current suite of onboard PIG has been chosen so that each instrument not only gives useful information in its own rights, but also complements the other instruments.

The location of a critical part of a pipe can be roughly determined by one-dimensional instruments like odometers and tracking systems. For the PIG position information, odometers operate internally while the tracking systems are monitored externally to the pipe. Primary role of the tracking systems is to provide helpful information for correcting possible errors in position of the PIG. They are also required by most of the pipeline operators to find the PIG when it gets stuck in the pipeline during operation. However, such one-dimensional instruments are not sufficient for determining the location and for the autonomous operation of the PIG. In three dimensional cases, a Strapdown Inertial Measurement Unit (SIMU) is an effective solution. It is the heart of the GeoPIG and delivers the position and attitude of the PIG along its trajectory within the pipe. Due to the nature of inertial measurements, regular "updates" of attitude, position, and velocity are required. The location of landmark points for position update of the PIG is spaced at regular intervals and its precise position information must be determined once by an actual and precise survey. Several receivers in tracking system are laid down at every landmark points. These receivers enable us to obtain the auxiliary position measurement and more accurate position result. A full picture of the shape of the pipeline is generated from information obtained by weld detector, such as mechanical fingers in our system. The information for dents and wrinkles can be extracted from the shape information. In other words, it is vitally important that every significant deviation from ideal shape for a pressure vessel, i.e. perfectly round, is investigated.

The PIG is functionally organized into three parts: PIG body, DAS (Data Acquisition System), and various sensors. The GeoPIG is suspended in the pipeline by rubber disks, and these restrict the GeoPIG to move close to the pipeline wall. The inspection device and sensors are fully self-contained and mounted in a pressure casing within the body of the PIG, and the body is designed to be large enough to contain overall systems, such as instrumentation, interface board, processing unit, power, and data storage. The function of the DAS is to store the outputs of the sensors in real-time and to communicate with the data processing computer. The clock of the DAS, which is important for the PIG navigation process, is synchronized with the tracking system clock before launching the PIG. A SIMU provides the information on the position and attitude of the PIG. These quantities are accurate over short intervals, but have to be "updated" for longer periods. In our GeoPIG, an LN-200 (Litton) SIMU is used. Odometers measure the distance traveled along pipeline track. The wheels of odometer give accurate measurements of traveled distance (chainage). The speed of the PIG can be derived from these time tagged distances. Mechanical fingers detect the welds and pipe joints in the wall of pipeline, which can be used for structural analysis and as feature identifiers. These features are key identifiers for the radius of pipeline. Pressure and temperature sensors determine operating conditions of the pipeline. The transmitter of tracking system is attached to the tail part of the PIG and transmits the signal indicating the passage of the GeoPIG. Storage device and power supply allow independent operations for long measurement periods. The power and memory requirements are dependent on the instrumentation (power consumption and number), data acquisition rate, length of line to be surveyed, and the PIG (flow) velocity. The last two factors are combined to determine the duration of the survey, necessary storage, and battery capacity. Thus, a long traveling time with a low gas flow rate, will consume more power and require greater data storage capacity than a short line with normal flow rate. In the power system, an extensive development has been required to minimize the power requirements of the devices. Other principal components of the GeoPIG are:

A main processing unit — embedded PC with LINUX operation system

A digital tape recording system above 12 gigabyte capacity

Several PIG tracking systems (Receiver Module) on landmark positions

Interface electronics,

- Batteries, (24 hours operation capacity)
- Micro-processor controllers for sensor data interface, (80C196KC 16 bit)
- Power management module, (low voltage warning, voltage regulation)

The arrangement of components is shown in Fig. 1 for the 30 inch version of the GeoPIG and

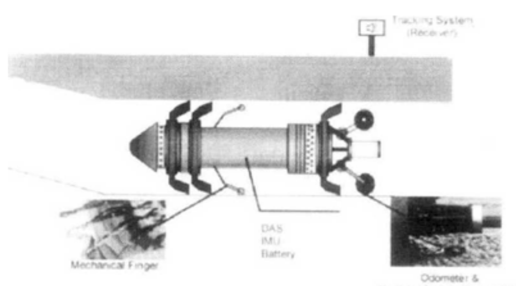

Fig. 1 Configuration of GeoPIG

Table 1 Error characteristics of sensors (1σ)

	Characteristics	Magnitude
Gyro	Bias	3 deg/hr
	White noise	0.35 deg/hr
Accelerometer	Bias	1 mg
	White noise	50 μg
Landmark (position)	White noise	0.2 m
Odometer (speed)	Scale factor error	0.1%
	White noise	20 mm/s

the characteristics of sensors are summarized in Table 1.

3. Data Processing

While the PIG travels through pipelines to be inspected for geometric conditions, the geometry PIG system stores various kinds of sensor outputs. In this section, the basic concepts for the PIG navigation by using the stored data in storage device are discussed.

In general on-line SINS (Strapdown Inertial Navigation System) as shown in Fig. 2, the coordinate transform matrix, position and attitude of the vehicle can be calculated by using the information from the sensors of gyro and accelerometer in SIMU. In the SINS, navigation solutions have a tendency for navigation errors to grow with time due to the inherited errors of the SIMU and its initial errors (Titterton and Weston, 1997). To solve this problem, non-inertial sensors which is represented by AUXILIARY SENSOR in the Fig. 2 are used to construct an aided SINS (Pong et al., 2002) and the aided information from the sensors is processed by Kalman filter. As non-inertial sensors, odometers and tracking system are used in our PIG system (KOGAS-SNU PIG). The odometers measure the traveled distance of the PIG, and the traveling speed can be obtained by using the incremental distance of the odometer output during a finite time interval. Using the calculated speed from odometer, SIMU navigation errors can be compensated. Since KOGAS-SNU PIG have three odometers in every 120 degree position of circular frame in the tail

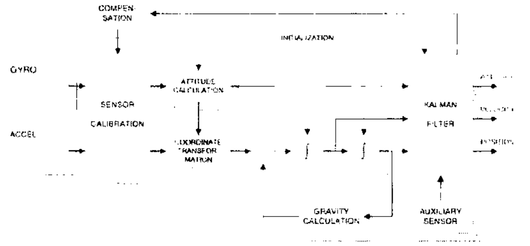

Fig. 2 General indirect feedback navigation

part of the PIG, its traveling distance and speed are calculated by using an appropriate combination of three odometer outputs such as average, maximum, middle or minimum of these measurements. The tracking system consists of transmitters and receivers to detect when the PIG passes landmarks whose positions are precisely measured by Carrier Differential GPS (CDGPS). When the passage of the PIG is detected by tracking receiver located on the landmark, the passing time is stored in the receiver. Because the clock of tracking system is synchronized with that of DAS board in the PIG, the stored times on passing landmarks can be used to make the corresponding position measurements of the PIG with having CDGPS accuracy.

Contrary to the on-line navigation algorithm in Fig. 2, an off-line and post-processed navigation procedure was adopted in our PIG system as in Fig. 3. The stored data in the PIG from the sensors are post-processed to identify suspicious leaks and to identify their locations within a reasonably accurate boundary. The identified locations are used as very effective information to facilitate digging and fixing the abnormal parts. In our navigation algorithm, a modified nonlinear smoothing algorithm (Yu et al., 2002) is adopted as shown in Fig. 3. In a conventional nonlinear two-filter type smoothing algorithm, an optimal estimate is obtained by combining two estimates from the forward and backward filters as in the linear case (Fraser and Potter, 1969; Wall et al., 1970). The forward filter predicts the future values (states) and backward filter does the past values (states) of state model. Conventionally, an extended Kalman filter (EKF) is used as a forward filter and a linearized Kalman

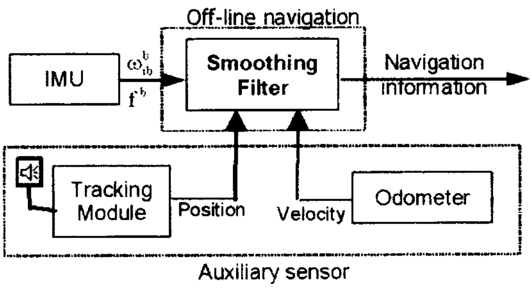

Fig. 3 Navigation algorithm with smoothing filter

filter as a backward filter (Gelb et al., 1974). Although the forward filter in our smoothing algorithm has the same form in the common nonlinear two-filter case, the backward filter is different. The main difference is that the backward filter is formulated using a state error vector instead of a conventional state variable vector. By using such backward filter, the error of the forward filter is compensated because the backward filter is linearized at the nominal state values which are established by the forward filter (Yu et al., 2002). The typical forward and backward filter can be expressed in the following several equations.

Consider the following nonlinear system :

$$\dot{\mathbf{x}}(t)=\mathbf{f}[\mathbf{x}(t),t]+\mathbf{G}(t)\mathbf{w}(t) \tag{1}$$

$$\mathbf{z}(t_i)=\mathbf{h}[\mathbf{x}(t_i),t_i]+\mathbf{v}(t_i) \tag{2}$$

where $\mathbf{x}(t)$ is the state vector of navigation and $\mathbf{z}(t_i)$ is the discrete measurement vector. The process noise $\mathbf{w}(t)$ and measurement noise $\mathbf{v}(t_i)$ are assumed to be white noise processes with zero mean and mutually uncorrelated. The noise covariance kernels are $E\{\mathbf{w}(t)\mathbf{w}^T(t+\tau)\}=\mathbf{Q}(t)\delta(\tau)$ and $E\{\mathbf{v}(t_i)\mathbf{v}^T(t_j)\}=\mathbf{R}(t_i)\delta_{ij}$, respectively, where $\delta(\tau)$ is the Dirac-delta and δ_{ij} the Kronecker-delta functions.

Forward filter

The filter algorithm with discrete measurement employing an EKF is given as follows :

(i) the time propagation for $t\in(t_{k-1},t_k)$

$$\begin{aligned}\dot{\hat{\mathbf{x}}}_f(t\mid t_{k-1})&=\mathbf{f}[\hat{\mathbf{x}}_f(t\mid t_{k-1}),t]\\ \hat{\mathbf{x}}_f(t_{k-1}\mid t_{k-1})&=\hat{\mathbf{x}}_f(t^+_{k-1})\end{aligned} \tag{3}$$

$$\begin{aligned}\dot{\mathbf{P}}_f(t\mid t_{k-1})&=\mathbf{F}(t)\mathbf{P}_f(t)+\mathbf{P}_f(t)\mathbf{F}^T(t)\\&\quad+\mathbf{G}(t)\mathbf{Q}(t)\mathbf{G}^T(t)\\ \mathbf{P}_f(t_{k-1}\mid t_{k-1})&=\mathbf{P}_f(t^+_{k-1})\end{aligned} \tag{4}$$

(ii) the measurement update at $t=t_k$

$$\hat{\mathbf{x}}_f(t_k^+)=\hat{\mathbf{x}}_f(t_k^-)+\mathbf{K}_k\{\mathbf{z}(t_k)-\mathbf{h}[\hat{\mathbf{x}}_f(t_k^-),t_k]\} \tag{5}$$

$$\mathbf{K}_k=\mathbf{P}_f(t_k^-)\mathbf{H}^T(t_k)\{\mathbf{H}(t_k)\mathbf{P}_f(t_k^-)\mathbf{H}^T(t_k)+\mathbf{R}(t_k)\}^{-1} \tag{6}$$

$$\begin{aligned}\mathbf{P}_f(t_k^+)&=[\mathrm{I}-\mathbf{K}_k\mathbf{H}(t_k)]\mathbf{P}_f(t_k^-)[\mathrm{I}-\mathbf{K}_k\mathbf{H}(t_k)]^T\\&\quad+\mathbf{K}_k\mathbf{R}(t_k)\mathbf{K}_k^T\end{aligned} \tag{7}$$

where

$$\mathbf{F}(t)=\left.\frac{\partial\mathbf{f}[\hat{\mathbf{x}}_f(t),t]}{\partial\mathbf{x}(t)}\right|_{x=\hat{x}_f(t\mid t_{k-1})}$$

$$\mathbf{H}(t)=\left.\frac{\partial\mathbf{h}[\hat{\mathbf{x}}_f(t_k),t_k]}{\partial\mathbf{x}(t)}\right|_{x=\hat{x}_f(t\mid t_k^-)}$$

and $\mathbf{K}_k$ is the filter gain matrix. The superscripts "$-$" and "$+$" represent a time before and after the measurement update, respectively. The backward filter is derived by linearization method at the forward filter estimates.

Backward filter

The backward filter is implemented by a linearized Kalman filter. Because the operation of the backward filter starts from final time and proceeds to initial time, a new time variable is defined as $\tau=t_f-t$ for convenience. In general, an initial covariance of backward filter is set to be infinite, that is, $\mathbf{P}_b(t_f^-)=\infty$. For this reason and the convenience of implementation, a form of information filter is widely used. The filter initial values are finite but unknown, which can be expressed in terms of new variable as follows.

$$\begin{cases}\hat{\mathbf{y}}_b(t_f^-)=\mathbf{P}_b^{-1}(t_f^-)\hat{\mathbf{x}}_b(t_f^-)=0\\ \hat{\mathbf{y}}_b(t_k^-)=\mathbf{P}_b^{-1}(t_k^-)\hat{\mathbf{x}}_b(t_k^-)\\ \hat{\mathbf{y}}_b(t_k^+)=\mathbf{P}_b^{-1}(t_k^+)\hat{\mathbf{x}}_b(t_k^+)\end{cases} \tag{8}$$

By Eq. (8) and the new time variable τ, the time propagation equation of the backward filter can be written as

$$\begin{aligned}\frac{d}{d\tau}\hat{\mathbf{y}}_b(\tau)&=\left[\frac{d}{d\tau}\mathbf{P}_b^{-1}(\tau)\right]\hat{\mathbf{x}}_b(\tau)+\mathbf{P}_b^{-1}(\tau)\left[\frac{d}{d\tau}\hat{\mathbf{x}}_b(\tau)\right]\\&=[\bar{\mathbf{F}}^T(\tau)-\mathbf{P}_b^{-1}(\tau)\bar{\mathbf{Q}}(\tau)]\hat{\mathbf{y}}_b(\tau)\\&\quad-\mathbf{P}_b^{-1}(\tau)\{\mathbf{f}[\hat{\mathbf{x}}_f(\mu),\mu]-\bar{\mathbf{F}}(\tau)\hat{\mathbf{x}}_f(\mu)\}\end{aligned} \tag{9}$$

$$\frac{d}{d\tau}\mathbf{P}_b^{-1}(\tau)=\mathbf{P}_b^{-1}(\tau)\bar{\mathbf{F}}(\tau)+\bar{\mathbf{F}}^T(\tau)\mathbf{P}_b^{-1}(\tau) \\ -\mathbf{P}_b^{-1}(\tau)\bar{\mathbf{Q}}(\tau)\mathbf{P}_b^{-1}(\tau) \quad (10)$$

where $\mu=t_f-\tau$, $\bar{\mathbf{F}}(\tau)=\mathbf{F}(\mu)$, $\bar{\mathbf{Q}}(\tau)=G(\mu)\mathbf{Q}(\mu)G^T(\mu)$, and $\hat{\mathbf{x}}_f(\mu)$ is the estimated state vector of the forward filter.

The measurement update equation at $\tau_k(=t_f-t_k)$ is given as

$$\hat{\mathbf{y}}_b(\tau_k^+)=\hat{\mathbf{y}}_b(\tau_k^-)+\mathbf{H}^T(\mu_k)\mathbf{R}^{-1}(\mu_k)\{\mathbf{z}(\mu_k)-\mathbf{h}[\hat{\mathbf{x}}_f(\mu_k^-),\mu_k] \\ +\mathbf{H}(\mu_k)\hat{\mathbf{x}}_f(\mu_k^-)\} \quad (11)$$

$$\mathbf{P}_b^{-1}(\tau_k^+)=\mathbf{P}_b^{-1}(\tau_k^-)+\mathbf{H}^T(\mu_k)\mathbf{R}^{-1}(\mu_k)\mathbf{H}(\mu_k) \quad (12)$$

where $\mathbf{P}_b^{-1}(\tau_k^+)\mathbf{K}_b(\tau_k)=\mathbf{H}^T(\mu_k)\mathbf{R}^{-1}(\mu_k)$.

Smoothing algorithm

From the results of the forward filter, $\hat{\mathbf{x}}_f(t_k^+)$ and $\mathbf{P}_f(t_k^+)$, and the results of the backward filter, $\hat{\mathbf{y}}_b(\tau_k^-)$ and $\mathbf{P}_b(\tau_k^-)$, the smoothed state vector at t_k can be obtained as

$$\hat{\mathbf{x}}_s(t_k)=\mathbf{P}_s(t_k)[\mathbf{P}_f^{-1}(t_k^+)\hat{\mathbf{x}}_f(t_k^+)+\hat{\mathbf{y}}_b(\tau_k^-)] \quad (13)$$

$$\mathbf{P}_s^{-1}(t_k)=\mathbf{P}_f^{-1}(t_k^+)+\mathbf{P}_b^{-1}(\tau_k^-) \quad (14)$$

where $\tau_k=t_f-t_k$.

Because the smoothed state vector can be obtained only at the time of measurement, the following nonlinear system equation should be solved to obtain the state vector during the time interval between the two adjacent measurements:

$$\dot{\hat{\mathbf{x}}}_s(t)=\mathbf{f}[\hat{\mathbf{x}}_s(t),t],\ t\in(t_k,t_{k+1}) \quad (15)$$

4. Experimental Results

4.1 Odometer performance test

The increase of navigation error in the case of using only SDINS measurement can be suppressed by the odometer measurements. The odometer implemented by using Hall sensors can measure the rotation angle of its wheel and give the speed information.

The odometer produces a pulse chain generated at every resolution angle of the wheel. Fig. 4 shows the odometer in our GeoPIG system. In the odometer, there is a Hall sensor, which can detect the passing of saw tooth of the wheel and generate as many pulses as the passed saw teeth.

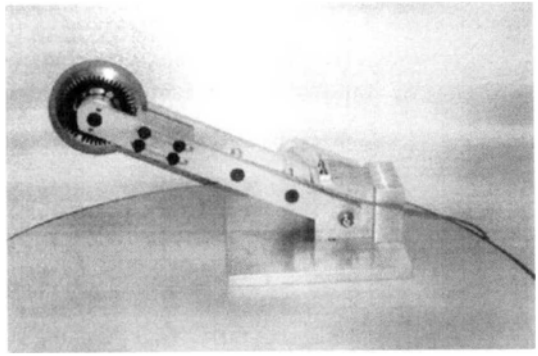

Fig. 4 Odometer

Since the distance and speed information from the odometer are very critical to PIG position error, its error source should be considered carefully. The following equations describe the odometer error model. Equations (16), (17) and (18) express the measurement, true value, and error of the PIG speed, respectively.

$$\hat{d}/\Delta t=\frac{1/50(l_0+\delta l_0)(n_0+\delta n_0)}{\Delta t} \quad (16)$$

$$d/\Delta t=\frac{1/50\,l_0 n_0+m_0}{\Delta t} \quad (17)$$

$$\delta d/\Delta t=\frac{1/50(l_0\delta n_0+\delta l_0 n_0+\delta l_0\delta n_0)-m_0}{\Delta t} \quad (18)$$

where

l_0 : circumference of odometer wheel
n : number of saw teeth (=50)
m_0 : round-off distance less than odometer resolution
Δt : measurement time interval
δl_0 : measurement error of circumference of wheel
δn_0 : measurement error of pulse number
d : true value of distance
$\hat{d}$: measurement value of distance
δd : error of distance
n_0 : measured number of pulses from odometer

In Eq. (18), it should be noted that the main factor of the speed error is the quantity of $\delta l_0 n_0$ because the value of n_0 is very large. Hence, the accurate measurement for the wheel diameter is necessary. The abrasion-resisting and heat-resisting property of wheel material is very important,

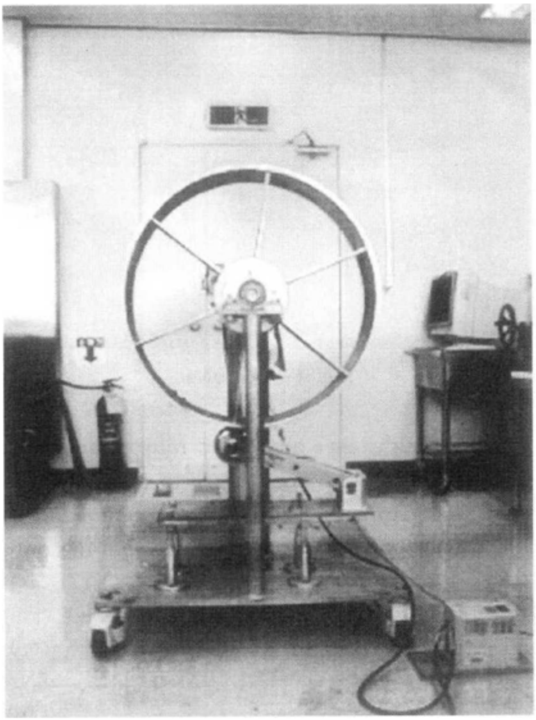

Fig. 5 Simulator for odometer test

since the wheel diameter needs to be constant for the whole inspection period (may be several days or weeks) against abrasion and heat. In order to prepare the odometer for serious vibrating environment, loose-resisting parts should be considered. In our case, the wheel is designed to be interchangeable, and is made of urethane to withstand abrasion and heat.

In order to investigate the odometer properties, a simulator for evaluation experiment was made as in Fig. 5. In the upper part of simulator, there is a cylinder obtained by cutting off a pipeline to simulate the real situation in pipeline. The precise motor controller in the simulator makes the cylinder to rotate in a constant rate. In the lower part, the designed odometer is fitted in. It keeps contact to the cylinder surface and rotates together with the cylinder.

Each odometer was considered in terms of its ability to respond to the PIG dynamics and pipeline characteristics, and the practicality of fitting to the PIG body. It is followed by extensive testing, if found to be suitable, deployment in field. The testing, under closely controlled laboratory simulations, is of fundamental importance. It is only by performing tests on each odometer under known conditions that its response to each factor can be evaluated. The experimental tests for odometer were performed in the aspects of repeatability, effects according to sampling interval and speed of the PIG, and the accumulated odometer error according to running time. In these experiments, the repeatability was confirmed through 24 tests in which the total distance is 2384 meters. The maximum deviation among 24 measurements was 61 centimeters. Also, it is found that the appropriate measurement interval is 0.2 seconds, which gives the speed error less than 20 millimeter per second, and the odometer bias error and its standard deviation are independent on the odometer running time.

4.2 PIG navigation performance

In order to have a realistic experiment, the PIG was launched at Jeongup and received at Wolchul for pipeline inspection in Korea. The gross traveling length of the 30-inch diameter pipeline was approximately 58 kilometers. The unit worked successfully according to the specification made in Table 2 and logged data over the entire length of the lines. No mechanical or electrical problems were encountered during the survey. A PIG-tracking system which is operated with a transmitter and a receiver, provides the detection of the passage of the PIG on a landmark whose position information is precisely measured by CDGPS. Because the system's clock in the processing computer within the PIG is synchronized with the receiver's in tracking system, the passing time at landmark can be obtained accurately and stored in. During entire PIG traveling through the pipeline, DAS (Data Acquisition System) logged all data from the sensors in the storage device.

The initial position and azimuth angle of the PIG can be obtained by using the CDGPS surveying result. Initial roll and pitch angles are determined from accelerometer outputs in the SIMU. The interval between two adjacent landmarks at which tracking receivers locate is ap-

Table 2 KOGAS-SNU PIG specifications

	KOGAS-SNU PIG
Max. Pressure	2200 psi
Temperature Rating	0-80℃
Range	24 hours
Line Size	30″
Instrumentation :	
Pressure	Available
Temperature	Available
Acceleration	Available
Attitude	Available
Information :	
Dent	Available
Ovality	Available
Curvature	Available
Survey	Available

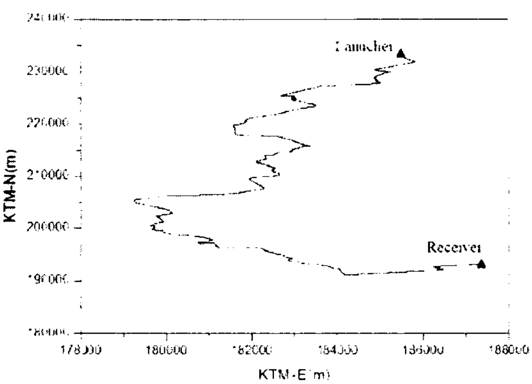

Fig. 6 Trajectory of PIG

proximately 800 meters in this experiment.

The calculated average speed of the PIG is approximately 2.9 meter per second. The odometer output is sampled at 10 Hertz. The geographic position, which is one of navigation results of the geometry PIG, is transformed into Korea Transverse Mercator (KTM) whose origin is at 127°E and 38°N. In the following Fig. 6, the entire PIG trajectory is shown. In Fig. 6, "launcher" and "receiver" denote the positions of launching at Jeongup and of arrival at Wolchul, respectively. In this experiment, there are 67 landmark points in the whole trajectory.

To verify the performance of the PIG, several check points on the pipeline are selected. The positions of the check points are precisely measured using the CDGPS to compare with the navigation results. The compared results are shown in Fig. 7. The difference between two results at each check point is less than 0.4 meters. One is obtained by using the smoothing filter and the other is precisely measured by using CDGPS. The average difference of 67 check points is 0.1443 meters. It is remarkable that every 800 meter traveling of the PIG has only 0.15 meters position error. This demonstrates that the whole PIG system is designed and manufactured in effective and reliable way, and the powerful error correction can be accomplished by off-line navigation algorithm with smoothing filter in the presence of a harsh physical environment.

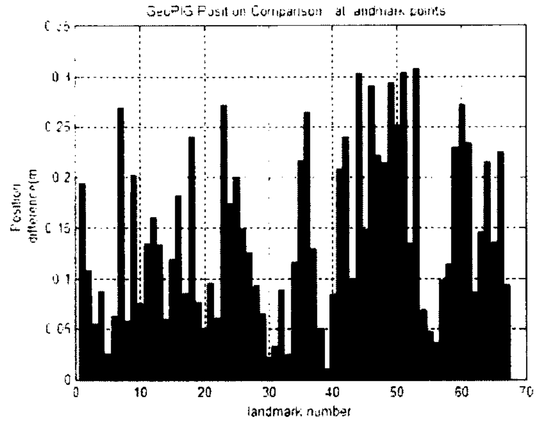

Fig. 7 Post-processed position error

5. Conclusions

This paper presented some of the capabilities of Korean PIG, which were illustrated using actual field data, and discussed how it is being used as a monitoring tool. The intent of this paper was to provide how to implement a geometry PIG system and to post-process the stored data for position of abnormal parts in the pipeline. The geometry PIG system can provide users with valuable information for the assessment of pipeline condition and prevention of pipeline failures. In this research, the several areas related on PIG system, such as design, manufacture, operating, and data-processing, were explained. Especially, within the framework of the navigation, the off-line data processing for PIG position was done by adopting the smoothing filter. Many experiments for the component part/whole system evaluation were carried out. In a 58 kilometer pipeline experiment, the reliability and performance of developed PIG system were investigated. The navigation error is less than 0.2 meter in the field experiment and it is expected that the system will be used in various pipeline inspections.

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