Research and evaluation of the measurement uncertainty with the pipeline robot

Chang’an Hu1,a, Shutong Luo2, Wanze Li3, Fei Lv4, Dongyan Cai5, Linghui Kong6

1National Institute of Measurement and Testing Technology, Chenghua District, Chengdu, Sichuan, China
2Chengdu University of Technology, Chenghua District, Chengdu, Sichuan, China
3National Institute of Measurement and Testing Technology, Chenghua District, Chengdu, Sichuan, China
4Chengdu Normal University Wenjiang District, Chengdu, Sichuan, China
5National Institute of Measurement and Testing Technology, Chenghua District, Chengdu, Sichuan, China
6National Institute of Measurement and Testing Technology, Chenghua District, Chengdu, Sichuan, China
aemail: 569964114@qq.com

Abstract—The pipeline robot used to detect and maintain the pipeline is a novel technical means, which changes the single traditional mode of excavation sampling inspection of pipeline. This detection technology not only improved the accuracy of pipeline detection but also is easy to analyze the causes of pipeline defects for pipeline engineering management maintenance staff. It is possible to carry out a review of defect and develop pipeline maintenance solutions. Using this method can eliminate the security hidden danger before repairing or replacing section. Thus, the use of a pipeline can save a lot of maintenance costs and reduce pipeline maintenance cost, which can also ensure the safety of people's life and property. In addition, this method can also reduce the toxic gas or liquid leakage to protect environmental pollution. Therefore, the research of a pipeline detection robot has an important scientific significance and social value. In this paper, our group has a base of the long-term research with the geometric measurement technology, so the measurement uncertainty of the common pipeline robot is studied. The measurement uncertainty of error about positioning is defined as $U=0.59mm+9\times 10^{-2}L$, $k=2$ (L unit is m), and the uncertainty evaluation of angle errors measured, including the forward and backward pitching angle, left-right tilt angle, is $U=0.10^{\circ}+4.6\times 10^{-3}\theta$ ($\theta$ unit is $^{\circ}$).

1. Introduction
Foreign pipeline robot started in the 1960s, 70s, petroleum, chemical, natural gas and nuclear industry for the application of pipeline robot provides a broad prospect and attractive, and robotics, the development of the theory and technology such as computer, sensors, also for tube and pipe outside the research and application of autonomous mobile robot provides technical assurance. Japan, the United States, France, Germany and other countries have done a lot of research work in this area, among which Japan engaged in pipeline robot research personnel and research results the most. Since the 1980s, Japan
has developed not only a robot that can be detected through l-shaped curved pipes, but also a robot that can inspect the inlet pipe of a thermal power station and work in the operation of the thermal power station. Olympus Optical Co., LTD., Japan, has invented a duct-type micro-robot suitable for overhaul of narrow and complex areas between closed vessels or bundles. Japan Mitsubishi Electric Corporation, Sumitomo Electric Industrial Corporation and Matsushita Technical Research Corporation have jointly developed a chain micro-robot system for the external surface inspection of heat transfer tubes for steam generators in nuclear power plants. The German company Siemens has developed a spider robot that crawls in tubes for various types of tube motion. Not only is it suitable for moving in horizontal pipes, but its legs can also support its weight and walk freely in vertical pipes. Later, Technische University in Technische also designed a pipe robot that walks on rubber balls and can adapt to pipes between 60cm and 70cm in diameter. After the development in recent years, domestic pipeline robots have made great progress, but they are mainly concentrated in institutions of higher learning, such as Harbin Institute of Technology, Shanghai Jiaotong University and other institutions of higher learning and scientific research institutions, such as Daqing Petroleum Administration Bureau, Shengli Oilfield, CNPC and other units. From the current domestic situation, domestic pipeline robots put into the market are mostly used in the cleaning industry, with too single functions and mostly caterpillar driving mode. They are not only poor in adaptability, difficult to adapt to the complex environment in the pipeline, but also have poor stability. Generally speaking, the development and application of pipeline detection robot in China have already had a certain foundation, but it is still in its infancy. Domestic pipeline robot in particular in the non-damage detection is a particularly attractive and huge market [1].

The importance of pipeline is self-evident, as an effective means of material transport, it is widely used in urban rain water, natural gas transport, industrial material transport, water supply and drainage, building ventilation system and other fields. In order to improve the life of the pipeline, prevent leakage and other accidents, and ensure the normal operation of the pipeline, it is necessary to carry out effective detection and maintenance of the pipeline, etc. As a fast and safe detection method, pipeline robot has been more and more applied in pipeline detection. In this paper, the measurement uncertainty of positioning accuracy, forward and backward pitch angle and left and right tilt angle error of common pipeline robot has been studied by referring to relevant documents [2-5], relying on the company engaged in the research of geometric measurement technology for a long time.

2. pipeline robot
Pipeline robot, which can automatically walk along the inside or outside of a small pipeline, carry one or more sensors and operating machinery, and carry out a series of pipeline operations under remote control or automatic computer control, integrating machine, electricity and instrument. It is mainly composed of the main controller, crawler, rotating camera and cable reel. It takes the place of personnel to enter the pipeline for video recording and photo taking to check the internal failure of the pipeline, and provides important analysis basis and guidance and Suggestions for making maintenance and repair plans. At present, there are many types of pipeline robots developed at home and abroad, which can be divided into two types according to the way of energy supply: cable-free and cable-free. According to the driving mode can be divided into self-driven pipeline robot, fluid - driven pipeline robot, elastic rod - driven pipeline robot. Pipeline robot can be divided into three types according to its size: large, ordinary and micro. According to the walking mechanism, the pipeline robot can be divided into piston mobile, roller mobile, crawler mobile, foot mobile, peristaltic mobile, screw mobile.

3. Calibration Method

3.1. Positioning Error (static)
By operating the human-machine interface of the main controller, the robot is controlled to walk along a straight line and drive the cable winding to put out the wire. Li, the length displayed by the meter meter, is read from the human-machine interface of the main controller. Meanwhile, L0i, the length of the cable, is measured with a steel tape measure.

\[ \Delta L_i = L_i - L_{0i} \] (1)
Type:
\[ \Delta L_i \] Positioning error of pipeline robot at position I, mm;
\[ L_i \] - The man-machine interface meter indicator value of pipeline robot main controller at position I, mm;
\[ L_{0i} \] - Measurement value of steel tape at L0i - position I, mm;
\[ i \] - Measuring position number.

Five lengths were selected in a roughly uniform distribution within the cable length range, and the above operation was repeated to calculate the positioning errors \( \Delta L_i \) of each position respectively. The maximum absolute value was taken as the positioning error of the pipeline robot.

3.2. Left-right tilt Angle error (static)
Stop the pipeline robot sideways on the calibration workbench, and put the digital display inclinometer on the workbench, and keep it perpendicular to the pipeline robot body. After adjusting the calibration table to produce a certain Angle, read the left and right tilt Angle I on the pipe robot main controller interface. The dip Angle displayed by the readout dipmeter is \( \theta_{0i} \), and the left-right dip Angle error is calculated according to formula (2).

\[
\Delta \theta_i = \theta_i - \theta_{0i}
\] (2)

Type:
\[ \Delta \theta_i \] -- Deviation of left-right tilt Angle of pipeline robot at position I, °;
\[ \theta_i \] -- The human-machine interface display value of the left and right tilt Angle of the pipeline robot master controller at position I, °;
\[ \theta_{0i} \] -- The tilt Angle indication value of the digital display dipmeter at position I, °;
\[ i \] - Measuring position number;

Within the range of the maximum inclination Angle to the left and right of the pipeline robot, 3 positions are selected to calculate the tilt Angle error of each position respectively, and the maximum absolute value is taken as the left-right tilt Angle error.

3.3. Pitch Angle error (static)
The remote control pipeline robot crawls to the calibration workbench while placing the digital display inclinometer on the workbench and keeping it parallel to the pipeline robot body. After adjusting the calibration table to a certain Angle, read the forward and backward pitch Angle error (j) on the pipe robot main controller. The Angle indication value of the readout dipmeter is \( \theta_{0j} \), and the forward and backward pitching Angle error is calculated according to formula (3).

\[
\Delta \theta_j = \theta_j - \theta_{0j}
\] (3)

Type:
\[ \Delta \theta_j \] - Pitch Angle error at the JTH position, °;
\[ \theta_j \] - The man-machine interface pitch Angle of the robot main controller at the JTH position, °;
\[ \theta_{0j} \] - The tilt Angle indication value of the digital display dipmeter at the JTH position, °;
\[ j \] - Measuring position number;

Within the maximum inclination range of forward and backward of pipeline robot, 3 positions are selected for each position to calculate the forward and backward pitching Angle errors respectively, and the maximum absolute value is taken as the forward and backward pitching Angle errors.

4. Evaluation and analysis of measurement uncertainty

4.1. Examples of uncertainty evaluation of positioning error measurement results of pipeline robot

4.1.1. Measurement model
During the measurement process, the positioning error is the difference between the meter indicator value of the human-machine interface meter of the pipeline robot master controller and the measurement...
value of the steel tape measure. The measurement model is established according to the following formula.

$$
\Delta L_i = L_i - L_{0i}
$$

(4)

Type: $\Delta L_i$ - Positioning error of position I, mm;

$L_i$ - the man-machine interface meter indicator value of pipeline robot master controller at position I, mm;

$L_{0i}$ - measurement value of steel tape at position I, mm;

i - The number of the measuring position;

4.1.2. Sensitivity coefficient

By $u^2(y) = \sum \left[ \frac{\partial f}{\partial x_j} \right]^2 u^2(x_j)$, it can be obtained that the uncertainty of synthetic standard satisfies the following equation.

$$
u_c(\Delta L)^2 = c_{i,1}^2 u_{B1}(I_{oi})^2 + c_{i,2}^2 u_A(L_i)^2
$$

(5)

Type: c(•) -- Sensitivity coefficient, $c_{i,1} = 1$, $c_{i,2} = 1$.

Therefore, the synthetic uncertainty of the measurement result of positioning error $u_c(\Delta L)$ is:

$$
u_c(\Delta L) = \sqrt{u_{B1}^2(I_{oi})^2 + u_A^2(L_i)}
$$

(6)

4.1.3. Source analysis of uncertainty

The source and description of the standard uncertainty component are shown in Table 1.

| number | symbol | Source of standard uncertainty components |
|--------|--------|-------------------------------------------|
| 1      | $u_{B1}(I_{oi})$ | The uncertainty component introduced by the uncertainty of steel tape measure |
| 2      | $u_A(L_i)$ | The standard uncertainty component introduced by measurement repeatability |
| 3      | $u_{B2}(L_i)$ | The environment deviates from the uncertainty component |

4.1.3.1 Uncertainty component introduced by pipeline robot for repeatability measurement

At the same conditions, 10 measurements were repeated at the point $L=5m$, and the experimental standard deviation was measured by Bessel formula.

$$
u_A(L_i) = \sqrt{\frac{\sum_{i=1}^{n} (O_i - D)^2}{n-1}} = 0.52mm
$$

4.1.3.2 Uncertainty component introduced by measurement uncertainty of steel tape

According to the steel tape calibration certificate, the error of the indicating value is $\pm (0.1 + 10^{-4}L)$ mm, and its half-width interval is 0.1mm. The quantity is uniformly distributed in this interval, and $k= 0.58$, so the uncertainty component introduced thereby is:

$$
u_{B1}(I_{oi}) = 0.1 / \sqrt{3} = 0.058mm
$$

4.1.3.3 Uncertainty component $u_{B2}(L_i)$ induced by environmental deviation

The uncertainty component $u_{B2}(L_i)$ will be introduced when the actual environmental temperature, humidity and atmospheric pressure are inconsistent with the specified conditions during calibration.
However, the uncertainty component \( u_{R2}(L_i) \) is much smaller than the meter meter error of the pipeline robot, so the uncertainty component introduced by environmental deviation can be ignored.

4.1.4. Synthetic uncertainty

\[
u_c = \sqrt{u_a(L_i)^2 + u_{R1}(L_{oi})^2 + u_{R2}(L_i)^2} = 0.52\text{mm}
\]

4.1.5. Extended uncertainty

\[
U = 1.04\text{mm} \quad (k = 2) \quad L = 5\text{m}
\]

Similarly, within the whole measuring range (0.2 ~ 100) m,

\[
U = 0.59\text{mm} + 9 \times 10^{-2} L, \quad k = 2 \quad (\text{L unit is m})
\]

(7)

4.2. Examples of uncertainty evaluation of measurement results of forward and backward pitching Angle error of pipeline robot

4.2.1 Measurement model

During the measurement process, the forward and backward pitch Angle error is the difference between the display Angle of the pipeline robot main controller and the Angle measured by the digital display dipmeter. The measurement model is established according to the following formula.

\[
\Delta \theta_i = \theta_i - \theta_{oi}
\]

(8)

Type: \( \Delta \) \( \theta \) \( i \)- The forward and backward pitching Angle error of pipeline robot at position I, \( ^\circ \);

\( \theta_i \)- Reading of the forward and backward pitch Angle of the human-machine interface of the robot main controller at position I, \( ^\circ \);

\( \theta_{oi} \)- Angle reading of digital display inclinometer at the ith position, \( ^\circ \);

\( i \)- The number of the measuring position;

4.2.2 Sensitivity coefficient

It can be obtained that the synthetic standard uncertainty \( u_c(\Delta L) \) satisfies the following equation.

\[
u_c(\Delta \theta)^2 = c_{\theta x}^2 u_{R1}(\theta_{oi})^2 + c_{\theta}^2 u_a(\theta_i)^2
\]

(9)

\[
u^2(y) = \sum \left( \frac{\partial f}{\partial x_i} \right)^2 u^2(x_i)
\]

Type:

\( c(\bullet) \)- Sensitive coefficient, \( c_{\theta x} = 1, c_{\theta} = 1 \).

Therefore, the resultant uncertainty \( u_c(\Delta \theta) \) of the pitch Angle error measurement results is:

\[
u(\Delta \theta) = \sqrt{u_{R1}^2(\theta_{oi}) + u_a^2(\theta_i)}
\]

(10)

4.2.3 Source analysis of uncertainty

The source and description of the standard uncertainty component are shown in Table 2.

| number | symbol | Source of standard uncertainty components |
|--------|--------|------------------------------------------|
| 1      | \( u_{R1}(\theta_{oi}) \) | The uncertainty component introduced by digital display inclinometer to measure uncertainty |
| 2      | \( u_a(\theta_i) \) | The standard uncertainty component introduced by measurement repeatability |
| 3      | \( u_{R2}(\theta_i) \) | The environment deviates from the uncertainty component |
4.2.3.1 Uncertainty component introduced by Angle measurement repeatability of pipeline robot

When the inclination Angle of the pipeline robot is \( \theta = 5^\circ \) under repetitive conditions, 10 measurements were made, and the experimental standard deviation was measured in a single time.

\[
u_A(L_i) = s(D) = \sqrt{\frac{\sum_{i=1}^{n} (D - \bar{D})^2}{n - 1}} = 0.043^\circ
\]

4.2.3.2 Uncertainty component introduced by digital display dipmeter measurement uncertainty

According to the digital display dipmeter calibration certificate, the uncertainty is: \( U = 0.05^\circ \), \( k = 2 \), so:

\[
u_{b1}(L_{oi}) = 0.025^\circ
\]

4.2.3.3 Uncertainty component of environmental deviation

When the temperature, humidity and atmospheric pressure of the actual environment are inconsistent with the specified conditions during calibration, the uncertainty component \( u_{b3}(L_i) \) will be introduced. However, the uncertainty component \( u_{b3}(L_i) \) is far smaller than the forward and backward pitching Angle error of the pipeline robot, so the uncertainty component introduced by environmental deviation can be ignored.

Synthetic uncertainty

\[
u = \sqrt{u_A(L_i)^2 + u_{b1}(L_{oi})^2 + u_{b2}(L_i)^2} = 0.05^\circ
\]

Extended uncertainty

\[
U = 0.10^\circ(\theta = 5^\circ),
\]  

Similarly, within the entire measurement range (0 ~ 90) \( ^\circ \):

\[
U = 0.10^\circ + 4.6 \times 10^{-3} \theta, \quad k = 2 \quad (\theta \text{ unit is } ^\circ)
\]  

(11)

4.3. An example for evaluating the uncertainty of measurement results of left and right tilt Angle error of pipeline robot

4.3.1. Measurement model

In the measurement process, the left and right tilt Angle error is the difference between the display Angle of the pipeline robot master controller and the Angle measured by the digital display dipmeter. The measurement model is established according to the following formula.

\[
\Delta \theta_i = \theta_i - \theta_{oi}
\]  

(12)

Type:

\( \Delta \theta_i \) — The left and right tilt Angle error of the pipe robot at position I, \( ^\circ \);

\( \theta_i \) — Left and right tilt Angle readings for the human-machine interface of the pipe line robot master controller at position I, \( ^\circ \);

\( \theta_{oi} \) — Angle reading of the digital display inclinometer at position I, \( ^\circ \);

\( i \) — The number of the measuring position.

4.3.2. Sensitivity coefficient

It can be obtained that the synthetic standard uncertainty \( u_s(\Delta L) \) satisfies the following equation.

\[
u_s(\Delta \theta)^2 = c_{\theta}^2 u_{b1}(\theta_{oi})^2 + c_{\theta}^2 u_A(\theta_i)^2
\]  

(13)

Type:

\[
u^2(y) = \sum \left[ \frac{\partial f}{\partial x_i} \right]^2 u^2(x_i)
\]
\( c(\bullet) \)—Sensitivity coefficient, \( c_{\theta} = 1 \), \( c_{\psi} = 1 \).

Therefore, the synthetic uncertainty \( u_{i}(\Delta \theta) \) of pitch Angle error measurement results is:

\[
u_{i}(\Delta \theta) = \sqrt{u_{B}^{2}(\theta_{oi}) + u_{A}^{2}(\theta_{i})}
\]

(14)

4.3.3. Source analysis of uncertainty

The source and description of the standard uncertainty component are shown in Table 3.

| number | symbol | Source of standard uncertainty components |
|--------|--------|------------------------------------------|
| 1      | \( u_{B1}(\theta_{oi}) \) | The uncertainty component introduced by digital display inclinometer to measure uncertainty |
| 2      | \( u_{A}(\theta_{i}) \) | The standard uncertainty component introduced by measurement repeatability |
| 3      | \( u_{B2}(\theta_{i}) \) | The environment deviates from the uncertainty component |

4.3.3.1 Uncertainty component introduced by Angle measurement repeatability of pipeline robot

When the inclination Angle of the pipeline robot is \( \theta = 5^\circ \) under repetitive conditions, 10 measurements were made, and the experimental standard deviation was measured in a single time

\[
u_{i}(L_{i}) = s(D) = \sqrt{\frac{\sum_{i=1}^{n}(D_{i} - \bar{D})^{2}}{n-1}} = 0.043^\circ
\]

4.3.3.2 Uncertainty component introduced by digital display dipmeter measurement uncertainty

According to the digital display dipmeter calibration certificate, the uncertainty is: \( U = 0.05^\circ, k = 2 \), then:

\[
u_{B1}(L_{oi}) = 0.025^\circ
\]

4.3.3.3 Uncertainty component of environmental deviation

When the temperature, humidity and atmospheric pressure of the actual environment are inconsistent with the prescribed conditions, uncertainty component will be introduced. However, the uncertainty component \( u_{B2}(L_{i}) \) is far less than the left-right tilt angle error of the pipeline robot, so the uncertainty component introduced by the environmental deviation can be ignored.

4.3.4. Synthetic uncertainty

\[
u = \sqrt{u_{A}(L_{i})^{2} + u_{B1}(L_{oi})^{2} + u_{B2}(L_{i})^{2}} = 0.05^\circ
\]

4.3.5. Extended uncertainty

\[
u = 2 \times u = 0.10^\circ \quad (\theta = 5^\circ, k = 2)
\]

Similarly, within the entire measurement range (0 ~ 90)°:

\[
u = 0.10^\circ + 4.6 \times 10^{-3} \theta, k = 2 \quad (\theta \text{ unit is } ^\circ)
\]

(15)

5. Conclusion

With the development of society, more and more equipment can replace people to do some work. At present, the application of pipeline robot in the field of engineering measurement is increasing year by year. The evaluation of the measurement uncertainty of this equipment is helpful to analyze the measurement results.
References

[1] Jian Yu. Research on Design and Motion Control of Pipeline Robot[D]. ChangChun: ChangChun University of technology, 2019.
[2] JJF 1071-2010, The Rules for Drafting National Calibration Specification [S].
[3] JJF 1059.1-2012, Evaluation and Expression of Uncertainty in Measurement[S].
[4] JJF 1001-2011, General Terms in Metrology and Their Definitions[S].
[5] JJG966-2010, Verification Regulation of Hand-held Laser Distance Meters[S]