



# 3D localization of non-metallic pipelines using rotating magnetic base stations

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## ABSTRACT

Polyethylene (PE) pipelines are difficult to locate due to their non-magnetic and non-conductive properties. High-precision inertial navigation-based methods require pipeline shutdown, depressurization, and disconnection for internal detector deployment. Acoustic wave and electromagnetic field based methods require repeated lateral scanning using handheld instruments on the ground above the pipeline. This paper presents a blind positioning method for non-metallic pipelines based on extremely low-frequency dual rotating magnetic base stations and in-pipe Spherical Detector (SD). A position calculation method for magnetometers of the SD in arbitrary orientations relative to one single magnetic base station is proposed; and based on this, a pipeline positioning approach using dual magnetic base stations is developed. Scaled-down experiments are carried out and demonstrate that when the lateral distance is 1.29 m, the mean localization error in the horizontal and vertical directions are 6.23% and 6.15%. Due to the use of magnetic sources with frequency of several Hz, the obstruction by the wet soil does not reduce the accuracy of pipeline positioning. For 10 m deep PE pipeline in the field, the magnet should be increased by 10 times in three dimensions to achieve the same absolute positioning accuracy.

## 1. Introduction

In the development of urban gas distribution system, polyethylene (PE) pipeline has become the preferred choice for underground infrastructure due to their excellent corrosion resistance and flexibility. Unlike metal pipelines, PE pipes are non-magnetic and non-conductive, making them difficult to locate. To address this technical challenge, several methods are currently employed in engineering practice, including the inertial navigation system (INS), acoustic detection method, and electromagnetic field detection method. These approaches aim to improve the accuracy of locating non-metallic pipelines and reduce the risks associated with accidental damage. However, these methods fail to achieve efficient blind 3D localization of in-service PE pipelines.

The INS method primarily relies on an in-pipe pipeline inspection gauge (PIG) equipped with the inertial measurement unit (IMU). As the inspection device operates inside the pipeline, it is typically driven by

either the pressure differential of the fluid medium or an external pulling system, allowing it to move axially along the pipeline [1]. First, the acceleration data are time-integrated to obtain velocity and displacement increments. Simultaneously, the orientation of the device is calculated from gyroscope measurements using a quaternion-based algorithm. Second, based on rigid body kinematics, the displacement increments are transformed into global coordinates by applying the orientation matrix. Finally, the accurate 3D position of the pipeline centerline is reconstructed through coordinate transformations [2]. When using the INS to localize the gas PE pipeline, it is necessary to depressurize and cut the pipeline in order to insert the PIG and ensure that its support wheels are coaxially aligned with the inner wall of the target pipe. A steel wire rope is also required at the other end of the pipeline to pull the PIG. This inevitably leads to gas supply interruptions and additional on-site construction tasks such as pipeline cutting and welding, causing a certain degree of inconvenience and economic loss.

The acoustic detection method can be categorized into two types

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based on acoustic waves excitation method: the in-pipe excitation method and the seismic wave method [3]. The in-pipe excitation method directly couples acoustic waves into the target pipeline through a connection port, allowing the pipe structure and its internal gas column to collectively form a linear acoustic source. By detecting and analyzing the acoustic signals that propagate from the pipeline to the ground surface, horizontal positioning of the pipeline can be achieved. This method is only effective in acquiring horizontal coordinated information of the pipeline. However, acoustic signals received are susceptible to interference from the surrounding soil environment, which can affect the accuracy of the positioning results [4]. The seismic wave method generates acoustic waves through a surface vibration source, which propagate into the subsurface medium. When these waves encounter interfaces with acoustic impedance contrasts along their propagation path, reflections are produced. Due to the significant differences in acoustic properties such as density and elastic modulus between buried pipelines and the surrounding soil, acoustic waves are reflected at the soil-pipe interface and travel back to the surface. By deploying an array of surface sensors to capture the reflected wave signals and utilizing time-frequency analysis techniques to extract features such as arrival time, phase, and amplitude, the spatial position of the pipeline can be reconstructed, enabling accurate localization of the target pipeline [5,6]. This method does not require direct contact with the pipe and is not constrained by the availability of access ports. However, it is affected by subsurface anomalies and soil conditions [7]. It also suffers from soil-related interference and demands prior knowledge of the pipeline approximate horizontal position. Accurate localization of these two methods is achieved by manually scanning the area above the pipeline with a handheld instrument, which leads to relatively low detection efficiency.

The electromagnetic field detection methods include ground-penetrating radar (GPR) method, tracer wire method and low-frequency electromagnetic localization method. GPR is a non-destructive subsurface detection technology based on medium-frequency to high-frequency electromagnetic waves, typically operating in the frequency range of 10 MHz to several GHz [8]. Its working principle involves radiating electromagnetic pulses into the subsurface medium through a transmitting antenna. When electromagnetic waves encounter underground interfaces with variations in dielectric constants during propagation, a portion of the energy is reflected to the surface following the Fresnel reflection law and its time-domain waveform is recorded by a receiving antenna. By analyzing parameters such as the amplitude and propagation time of the reflected waves, it is possible to invert the geometric and physical properties of the subsurface structures, thereby achieving accurate localization of buried pipelines [9,10]. However, the signal-to-noise ratio (SNR) of GPR signal is susceptible to soil humidity and conductivity, which can obscure weak reflection signals from deep buried structures [11]. The tracer wire method determines the position of underground pipelines by detecting the electromagnetic field generated by the current through the tracer wire. However, the tracer wire must have an exposed endpoint, and it needs to be installed alongside the pipeline during the pipeline construction phase. During pipeline location detection, it is also necessary to perform lateral scans near the ground surface above the pipeline, resulting in relatively low detection efficiency.

In summary, the gap in the research of various positioning technologies for in-service gas pipelines does not lie in the research level of each technology itself, but in the convenience and adaptability of on-site implementation. The INS method requires cutting the pipeline, emptying the natural gas, and then placing the inertial measurement device into the pipeline and pulling it with a steel wire rope that has been passed through in advance. Therefore, the inertial navigation system cannot achieve the measurement of the coordinates of in-service gas pipelines. GPR, acoustic wave method and tracer line method all require prior knowledge of the approximate location of the pipeline. Their sensors are used to repeatedly scan the ground near the pipeline in

a lawn mower pattern, and the horizontal position of the pipeline is determined through extremum search. GPR can simultaneously obtain the horizontal position and depth information of the pipeline. When the soil is moist, GPR measurement fails due to electromagnetic shielding. The acoustic wave method requires a flat and soft ground surface to ensure good contact between the sensor and the ground. The tracer line method requires the pre-burial of tracer lines. Pipelines without pre-buried tracer lines or with damaged or broken tracer lines cannot be used.

Low-frequency magnetic field signals are less likely to be obstructed by objects such as soil, concrete walls, or rock formations. Furthermore, low-frequency magnetic field signals are less susceptible to multipath effects or signal delay, demonstrating strong resistance to interference. Additionally, they are relatively easy to generate and detect [12]. To address the challenges of localization in highly electromagnetically shielded environments such as buildings and underground mines, researchers proposed a low-frequency magnetic localization technique based on magnetic beacons. This method involves deploying magnetic beacons at known locations to emit low-frequency magnetic signals, and the receiver calculates its relative position with respect to the beacons by analyzing the characteristic parameters of the magnetic field. Valter Pasku et al. [13] proposed the use of a pair of resonant coils to enhance the sensitivity of electromagnetic transmission and reception. This method leverages the principle of electromagnetic coupling between resonant coils, enabling resonance at a frequency of 24.4 kHz. Within a 15 m × 12 m area, the system achieves a mean localization error of less than 0.3 m and a maximum error of less than 0.9 m. In this method, the transmitter and receiver coil is maintained in a coplanar configuration to achieve maximum signal strength and optimal accuracy, which makes this approach more suitable for 2D horizontal positioning. Kai, H. et al. [14] utilized a 22 Hz extremely low frequency signal to achieve positioning for metallic pipelines buried at depths of up to 5 m. However, this method could only achieve two-dimensional positioning and requires prior knowledge of the pipeline location, with sensors needing to be deployed near the area directly above the pipeline. R. Kusche, et al. [15] proposed an indoor horizontal positioning system. A magnet with a diameter of 0.01 m and a length of 0.1 m is used as the beacon, rotating at a frequency of 10 Hz. The system employs the triaxial anisotropic magneto resistive sensor as the receiver. Within a 3 m radius space, the system achieves an average localization error of 1.0 m with a standard deviation of 0.81 m for the horizontal position of the target points. However, the study utilizes only a single base station, leading to phase ambiguity issues that may result in the estimated position appearing at the opposite side of the actual location.

Due to the non-conductive and non-magnetic properties of PE pipelines, they do not interfere with external electromagnetic signals, but they also don't shield magnetic fields. This paper proposes a novel 3D localization approach for in-service PE gas pipelines using extremely low-frequency rotating magnetic base stations deployed on the ground and a compact in-pipe spherical detector (SD). The SD serves as a receiver that is inserted into the pipeline and propelled by the internal gas flow for rolling inspection. Multiple extremely low-frequency magnetic base stations are strategically deployed on the ground surface as transmitters. As the SD traverses the pipeline, it continuously receives magnetic signals from the rotating magnetic base stations. Upon retrieval of the SD, the collected magnetic field and acceleration data are processed to reconstruct the SD's 3D trajectory, which enabling accurate spatially positioning of the PE pipeline.

The remainder of this article is organized as follows. Section II establishes the pipeline positioning methodology. Section III introduces the main components of the pipeline 3D positioning system, including rotating magnetic base stations and the SD. Section IV presents the preparation procedures and feasibility analysis to demonstrate the effectiveness of the proposed positioning method. Section V conducts a scaled-down pipeline positioning experiment to verify the method's effectiveness. The positioning errors and future application prospects

are subsequently discussed. Finally, Section VI provides concluding remarks.

## 2. Pipeline position method

The pipeline positioning method proposed in this paper does not require prior knowledge of the pipeline's burial location, nor does it require cutting the pipeline or emptying the natural gas. The overall localization scheme is illustrated in Fig. 1. Two rotating magnetic base stations are strategically positioned near the target pipeline to transmit low-frequency magnetic signals at designated frequencies. Meanwhile, the SD is inserted into the pipeline and propelled by the internal gas flow to perform axial movement along the pipeline. As it traverses the pipeline, the SD continuously measures and records magnetic field data at various locations. Upon completion of the inspection and retrieval of the SD, the collected magnetic field and acceleration data are processed and analyzed. Using the known coordinates of the rotating magnetic base stations and the established spatial magnetic field model, a localization algorithm is employed to determine the pipeline's 3D position. A pair of base stations is placed starting from the drop point of the SD, and based on the positioning results, the base station positions is re-arranged along the downstream direction of the pipeline to achieve blind positioning of the entire in-service pipeline. Alternatively, many pairs of base stations can be deployed at once, enabling the measurement of the coordinates of the entire pipeline with a single SD launch.

### 2.1. Coordinates of the rotating magnetic base station in the magnetometer coordinate system

Within the spatial coordinate system, a measurement unit and a rotating magnet are considered, as shown in Fig. 2. The measurement unit comprises a triaxial magnetometer and a triaxial accelerometer, which are employed to capture the spatial magnetic field and monitor the device's motion state, respectively. To characterize the spatial orientation of the magnetometer, a magnetometer attitude coordinate system O-XYZ is established with the unit's position as the origin. The X, Y, and Z axes correspond to the three mutually orthogonal sensing axes of the magnetometer.

A rotation matrix, parameterized by the pitch and roll angles, is applied to transform the magnetometer attitude coordinate system O-XYZ into the magnetometer horizontal coordinate system O-xyz. In this transformed coordinate system, the x and y axes are aligned parallel to the horizontal plane, while the z axis remains perpendicular to the horizontal plane.

With the geometric center of the rotating magnet serving as the origin O', a rotating magnetic base station coordinate system O'-x'y'z' is

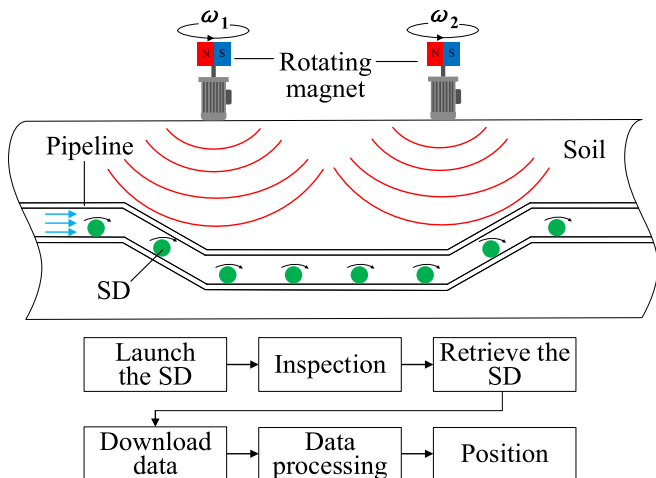


Fig. 1. PE pipeline positioning principle.

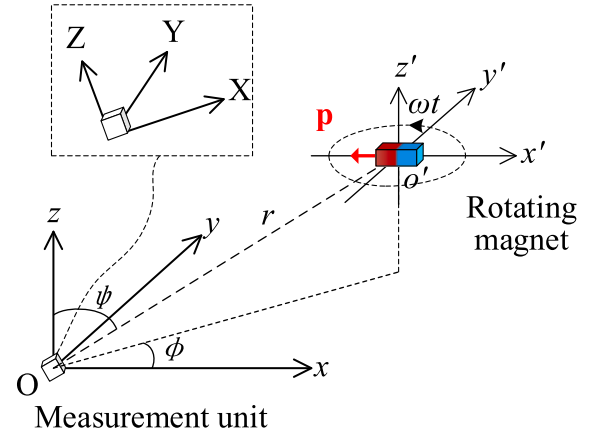


Fig. 2. Relative position schematic of the measurement unit and the rotating magnet.

established, where the coordinate axes  $x'$ ,  $y'$ , and  $z'$  are parallel to the  $x$ ,  $y$ , and  $z$  axes of the magnetometer horizontal coordinate system O-xyz, respectively. During the measurement process, the magnet rotates uniformly around the  $z'$  axis. This ensures that the magnetic dipole moment  $\mathbf{p}$  of the magnet rotates periodically within the horizontal plane.

To avoid the influence of factors such as magnet shape or non-uniform magnetic moment distribution on the magnetic dipole formula, the distance from the observation point to the magnet should be greater than 3 times the magnet's size [16]. In the magnetometer's horizontal coordinate system O-xyz, the magnetic field generated by the rotating magnet at the measurement unit is expressed as shown in Equation (1):

$$\mathbf{B}(\mathbf{r}, t) = \begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix} = \frac{\mu_0}{4\pi} \left( \frac{3(\mathbf{p}(t) \cdot \mathbf{r})\mathbf{r}}{|\mathbf{r}|^5} - \frac{\mathbf{p}(t)}{|\mathbf{r}|^3} \right) \quad (1)$$

The magnetic dipole moment of the magnet is denoted as  $\mathbf{p}(t)$ , as defined in Equation (2):

$$\mathbf{p}(t) = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} = \begin{bmatrix} p \cos(\omega t + \theta_0) \\ p \sin(\omega t + \theta_0) \\ 0 \end{bmatrix} \quad (2)$$

$p$  is the magnitude of the magnetic dipole moment of the magnet,  $\omega$  is the angular frequency of the rotation magnet,  $\theta_0$  is the initial phase angle of the rotation magnet and  $\mathbf{r}$  is the position vector of the rotating magnet in the magnetometer horizontal coordinate system O-xyz, as defined in Equation (3):

$$\mathbf{r} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} r \sin \psi \cos \phi \\ r \sin \psi \sin \phi \\ r \cos \psi \end{bmatrix} \quad (3)$$

Chiba A et al. [17] demonstrated that the unknown parameters  $\psi$ ,  $\phi$  and  $r = |\mathbf{r}|$  can be calculated. Firstly, based on Equation (1), the expression of  $B_x + iB_y$  is expressed as shown in Equation (4):

$$B_x + iB_y = \frac{\mu_0}{4\pi} \left( \left( \frac{3}{2} \frac{((p_x + ip_y)(x - iy) + (p_x - ip_y)(x + iy))}{r^5} - \frac{p_x + ip_y}{r^3} \right) (x + iy) \right) \quad (4)$$

Substituting formulas (1) and (2) into formula (4), and using the Fourier transform method to orthogonally demodulate  $B_x + iB_y$ , the result is shown in Equation (5) and (6):

$$\int_0^{NT} (B_x + iB_y)e^{-i\omega t} dt = \frac{p\mu_0}{4\pi r^3} \frac{3\sin^2\psi - 2}{2} NT e^{i\theta_0} \quad (5)$$

$$\int_0^{NT} (B_x + iB_y)e^{i\omega t} dt = \frac{p\mu_0}{4\pi r^3} \frac{3\sin^2\psi}{2} NT e^{-i\theta_0} e^{i2\phi} \quad (6)$$

$T$  represents the period of the permanent magnet's rotation.  $N$  is an any integer, generally equal to 1. By using the same method, the expression for  $B_z$  is shown in Equation (7):

$$B_z = \frac{p\mu_0}{4\pi r^3} \frac{3\sin\psi\cos\phi}{2} (e^{-i(\omega t + \theta_0 - \phi)} + e^{i(\omega t + \theta_0 - \phi)}) \quad (7)$$

From this, the Equation (8) can be obtained:

$$\int_0^{NT} B_z e^{i\omega t} dt = \frac{p\mu_0}{4\pi r^3} \frac{3\sin\psi\cos\phi}{2} NT e^{-i\theta_0} e^{i\phi} \quad (8)$$

According to equations (6) and (8),  $\psi$  and  $\phi$  can be obtained in equations

$$(9) \text{ and } (10): \psi = \arctan \left| \frac{\int_0^{NT} (B_x + iB_y)e^{i\omega t} dt}{\int_0^{NT} B_z e^{i\omega t} dt} \right| \# (9)$$

$$\phi = \arg \frac{\int_0^{NT} (B_x + iB_y)e^{i\omega t} dt}{\int_0^{NT} B_z e^{i\omega t} dt} \quad (10)$$

According to equations (5) and (6),  $r$  can be obtained in equations (11):

$$r = \left[ \frac{p\mu_0 NT}{8\pi} \sqrt{\frac{(3\sin^2\psi)^2 + (3\sin^2\psi - 2)^2}{\left| \int_0^{NT} (B_x + iB_y)e^{-i\omega t} dt \right|^2 + \left| \int_0^{NT} (B_x + iB_y)e^{i\omega t} dt \right|^2}} \right]^{\frac{1}{3}} \quad (11)$$

During operation, the magnetic field signals are measured by the triaxial magnetometer embedded within the SD, which functions in the magnetometer attitude coordinate system O-XYZ. The triaxial magnetometer data can be denoted as  $\mathbf{B}' = [B'_x \ B'_y \ B'_z]^T$ . Let  $\alpha$  denote the pitch angle of the magnetometer, respectively. The triaxial accelerometer data is denoted as  $\mathbf{A} = [A_x \ A_y \ A_z]^T$ . Therefore,  $\alpha$  can be expressed as follows:

$$\begin{cases} \alpha = \arctan\left(\frac{A_z}{A_x}\right), & a_x < 0 \\ \alpha = \arctan\left(\frac{A_z}{A_x}\right) + \pi, & a_x > 0 \end{cases} \quad (12)$$

The magnetic field vector  $\mathbf{B}$  in the magnetometer's horizontal coordinate system O-xyz can be obtained by transforming the magnetometer data  $\mathbf{B}'$  from the magnetometer attitude coordinate system O-XYZ using a rotation matrix  $\mathbf{R}$ . This transformation is expressed as:

$$\mathbf{R} = \begin{pmatrix} \cos\alpha & 0 & -\sin\alpha \\ 0 & 1 & 0 \\ \sin\alpha & 0 & \cos\alpha \end{pmatrix} \quad (13)$$

The magnetic field vector  $\mathbf{B}$  is calculated as follows:

$$\mathbf{B} = \mathbf{R} \mathbf{B}' \quad (14)$$

## 2.2. Position calculation of the SD in the world coordinate system

A positioning methodology based on dual magnetic base stations is proposed, as shown in Fig. 3. By deploying two rotating magnetic base stations operating at different angular velocities, time-varying magnetic fields with distinct frequencies are generated. The dual magnetic base stations are positioned on the ground surface to establish a world coordinate system  $O_w-x_w y_w z_w$ ; the midpoint between the two magnetic base stations serves as the origin  $O_w$ , the direction from rotating magnet 1 to rotating magnet 2 defines the positive  $x_w$  axis, the upward direction

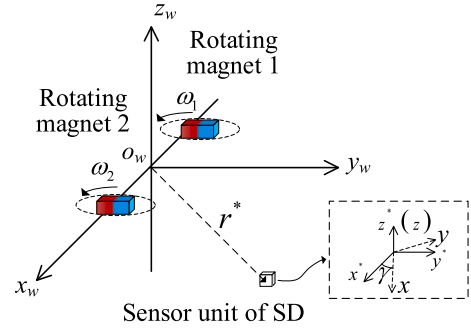


Fig. 3. Configuration schematic of dual rotating magnetic base stations.

(opposite to gravity) defines the positive  $z_w$  axis, and the  $y_w$  axis is determined according to the right-hand rule. Thus, a right-handed Cartesian coordinate system is established.

The specific SD positioning procedure is as follows:

(1) Initially, magnetometer data calibration is performed, followed by filtering and normalization of the tangential acceleration data.

(2) Based on Equation (8), the raw rotational magnetic field data are transformed into translational magnetic field data within the magnetometer horizontal coordinate system O-xyz. Subsequently, the Variational Mode Decomposition (VMD) algorithm is employed to extract magnetic field signals of distinct frequencies generated by the dual rotating magnetic base stations.

(3) Using Equations (4), (5) and (6), the positions of the two rotating magnetic base stations are calculated within the magnetometer horizontal coordinate system O-xyz. Subsequently, the position  $\mathbf{r}'$  of the world coordinate system origin  $O_w$  is determined relative to the magnetometer horizontal coordinate system O-xyz.

(4) A magnetometer orientation coordinate system  $O-x^*y^*z^*$  is established at the SD magnetometer position, where the  $x^*$ ,  $y^*$  and  $z^*$  axes are parallel to the corresponding axes of the world coordinate system. The coordinates of the world coordinate system origin  $O_w$  in the magnetometer horizontal coordinate system O-xyz are subsequently transformed to the coordinate system  $O-x^*y^*z^*$ . The transformation relationship is expressed as follows:

$$\mathbf{r}^* = \mathbf{R}_\gamma \mathbf{r}' \quad (15)$$

The rotation matrix  $\mathbf{R}_\gamma$  can be expressed as:

$$\mathbf{R}_\gamma = \begin{pmatrix} \cos\gamma & \sin\gamma & 0 \\ -\sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (16)$$

$\gamma$  represents the angular deviation between the baseline vector connecting the two base stations and the x-axis of the O-xyz coordinate system. Inverting  $\mathbf{r}^*$  yields the position of the SD sensor in the world coordinate system  $O_w-x_w y_w z_w$ .

The coordinated transformation process is shown in Fig. 4.

## 3. System design and development

The algorithmic workflow is illustrated in the Fig. 5. The core algorithmic workflow can be summarized as follows: First, the triaxial acceleration and magnetic field data of the SD are collected. The acceleration data undergoes filtering and normalization, while the magnetic field data has the geomagnetic bias removed. Subsequently, the pitch angle is calculated from the acceleration to construct a rotation matrix, transforming the magnetic field data into the horizontal coordinate system. The Variational Mode Decomposition (VMD) algorithm is then used to decompose and extract the characteristic magnetic field signals  $f_1$  and  $f_2$  from the dual base stations. Next, complex integration of the magnetic field components is performed for each base station signal.

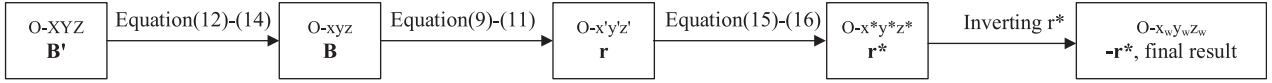


Fig. 4. Transformation process of each coordinate system.

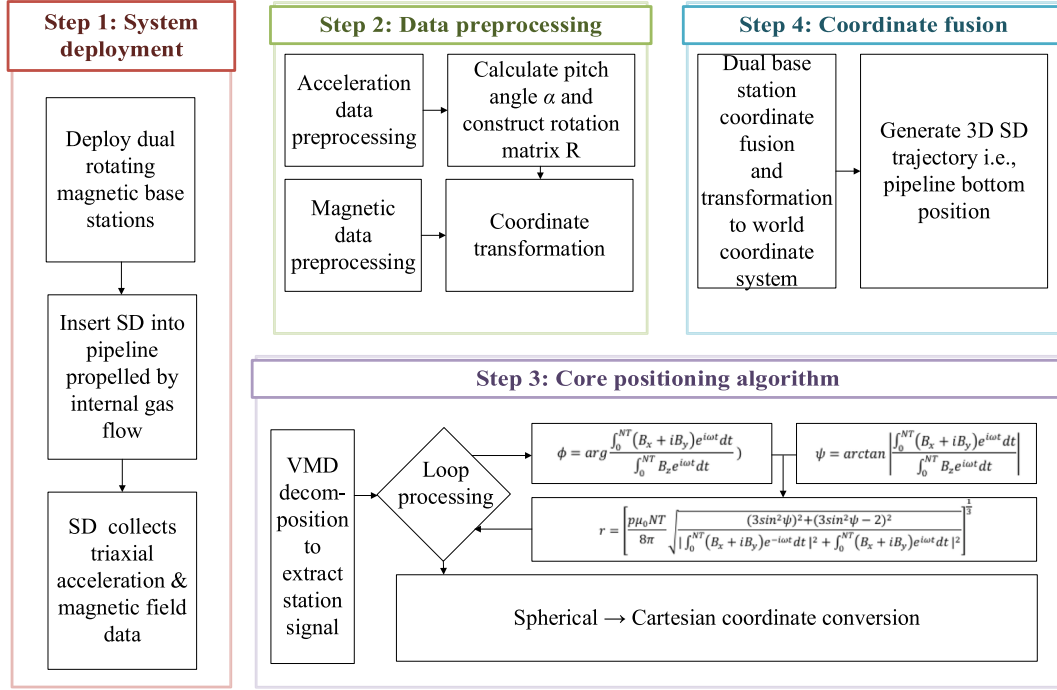


Fig. 5. Algorithm flowchart.

These results are substituted into Equations (9) and (10) to calculate the angular parameters  $\psi$  and  $\phi$ , and then the spatial distance  $r$  is solved using Equation (11). The spherical coordinates  $(\psi, \phi, r)$  are converted to Cartesian coordinates. Finally, the data from the dual base stations are processed iteratively. After coordinate fusion and transformation into the world coordinate system, the 3D trajectory of the SD is output as the 3D coordinates of the pipeline.

### 3.1. Rotating magnetic base station

The rotating magnetic base station is designed as illustrated in Fig. 6. The entire enclosure of the base station is made of aluminum alloy,

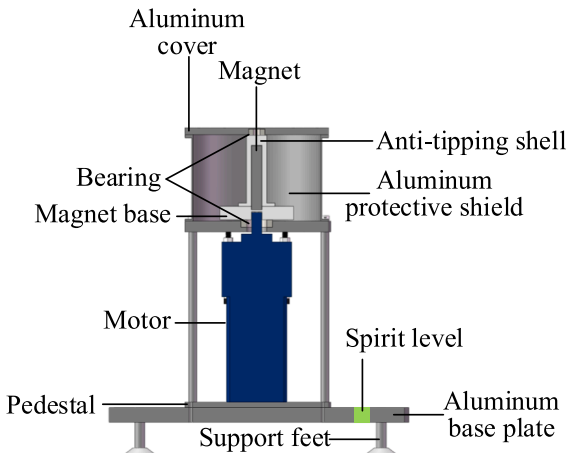


Fig. 6. Rotating magnetic base station.

including the cover, protective shield, pedestal and base plate. A neodymium-iron-boron (NdFeB) magnet with dimensions of 100 mm × 100 mm × 20 mm is rigidly connected to the magnet base through a 3D-printed anti-tipping shell. The drive system couples the magnet base to the shaft of a 24 V DC motor via a keyway connection, enabling precise rotational control. To minimize mechanical losses, ceramic flat bearings are installed between the magnet base and the enclosure, as well as between the anti-tipping shell and cover. System leveling is achieved through adjustable support feet and a spirit level, ensuring that the magnet rotates around the vertical axis.

### 3.2. SD

The SD structure is shown in Fig. 7. The SD consists of two 3D-printed hemispherical shells bonded together using UV adhesive. The outer shell is fabricated from white photosensitive resin with an outer diameter of 51 mm and a wall thickness of 2.5 mm. The internal components

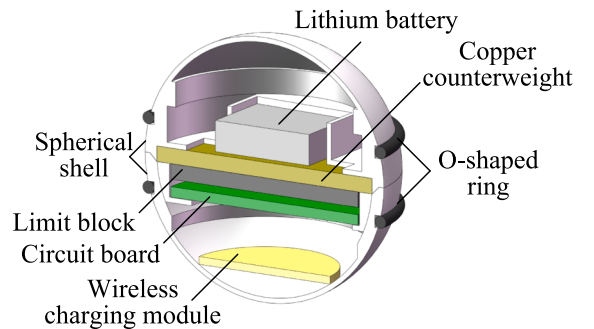


Fig. 7. SD.

primarily include the following:

- A lithium battery provides power to the system.
- A data acquisition circuit board records motion acceleration and magnetic field data.
- A wireless charging module enables charging through a coil mounted at the bottom.
- A limiting block secures the circuit board and balances the weight distribution.
- Counterweight blocks adjust the overall center of gravity.

To reduce rolling vibrations, two O-shaped rubber rings with an outer diameter of 52 mm and a wire diameter of 2.4 mm are installed on the surface of the casing. This structure ensures basic protection while achieving the functions of data acquisition and wireless charging.

Fig. 8 illustrates the data acquisition circuit, which comprises a microprocessor, magnetometer, accelerometer, power management chip, TF card, and their associated peripheral circuits. The magnetic sensor uses a 3-axis anisotropic magneto resistive (AMR) digital sensor. The power management chip regulates the charging and discharging of the lithium battery while supplying power to the microprocessor. The magnetometer and accelerometer communicate with the microprocessor via the I2C protocol, and the acquired data is stored on the TF card. After the measurement is completed and the SD is taken out from the pipeline, the microprocessor can wirelessly transmit the data stored on the TF card to the computer using the built-in Wi-Fi module.

According to the literature [18], when the moment of inertia ratio  $\eta$  is sufficiently large, the SD will roll stably around the axis with the maximum moment of inertia. As shown in Fig. 9, for a cylinder with radius  $r$  and height  $h$ , the moments of inertia are calculated as follows:

$$\begin{aligned} I_x = I_z &= \frac{1}{12}m(3r^2 + h^2) \\ I_y &= \frac{1}{2}mr^2 \end{aligned} \quad \# \quad (17)$$

The ratio  $\eta$  is as follows:

$$\eta = \frac{I_y}{I_x} = \frac{I_y}{I_z} = \frac{6r^2}{3r^2 + h^2} \quad \# \quad (18)$$

According to Equation (18), when  $r \gg h$ , the ratio  $\eta$  reaches its maximum value, with a maximum value of 2. To realize the fixed axis rolling of the SD, a cylindrical copper plate with a diameter of 46 mm and a thickness of 3 mm is embedded inside the SD. Using SolidWorks software, a 3D model of the SD structure shown in Fig. 6 is built. The software computes the moments of inertia about the three principal axes, and the results are  $I_x = 15.662 \text{ kg}\cdot\text{mm}^2$ ,  $I_z = 15.838 \text{ kg}\cdot\text{mm}^2$  and  $I_y = 24.571 \text{ kg}\cdot\text{mm}^2$ . The inertia ratio  $\eta$  is calculated and is 1.55 and 1.57. These results theoretically demonstrate the feasibility of fixed axis

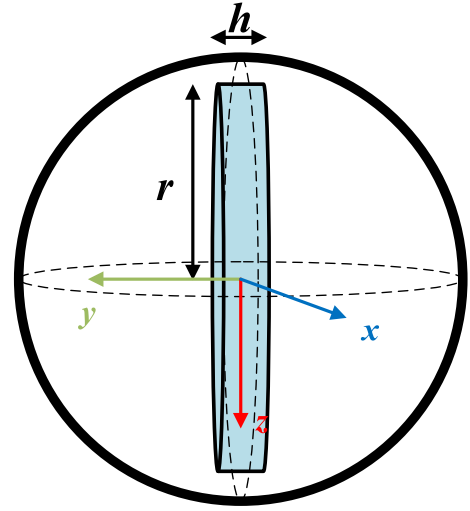


Fig. 9. Cylindrical counterweight block.

rolling for the SD.

## 4. Experiment results

### 4.1. Magnetic moment calibration of the station magnet

The magnetic moment  $p$  is one of the key parameters that affect the positioning result. To accurately obtain the magnetic moment  $p$  of the two magnetic base stations, the magnetic moment calibration experiment is conducted. A HMR2300 standard magnetometer is used to collect magnetic field data at distances of 0.6 m, 1.2 m, 1.8 m, 2.4 m, and 3.0 m from each base station, respectively. The geomagnetic bias at each measurement point is subtracted from the collected data. Using the lsqnonlin nonlinear least squares fitting toolbox in MATLAB, the collected data removing the geomagnetic bias are fitted according to the Equation (1). The results are shown in Fig. 10. To eliminate random errors, the average of the four experimental results is taken, yielding the magnetic moments of the two base stations as  $63.2242 \pm 3.2120 \text{ (A}\cdot\text{m}^2)$  and  $65.4447 \pm 0.4315 \text{ (A}\cdot\text{m}^2)$ , respectively.

### 4.2. Unobstructed straight pipe positioning experiment

A scaled-down pipeline positioning experiment is conducted, as shown in Fig. 11. A blower is used to provide airflow to the SD, simulating the airflow inside a gas PE pipeline, which pushes the SD to roll forward within the pipeline. Two rotating magnetic base stations are initially placed at  $(-0.3 \text{ m}, 0 \text{ m}, 0 \text{ m})$  and  $(0.3 \text{ m}, 0 \text{ m}, 0 \text{ m})$ . The pipeline is located at from  $(-1 \text{ m}, -0.6 \text{ m}, -0.48 \text{ m})$  to  $(1 \text{ m}, -0.6 \text{ m}, -0.48 \text{ m})$ , and from  $(-1 \text{ m}, -1.2 \text{ m}, -0.48 \text{ m})$  to  $(1 \text{ m}, -1.2 \text{ m}, -0.48 \text{ m})$ , respectively. The lateral distance between the pipeline and the station is  $\sqrt{0.6^2 + 0.48^2} = 0.77 \text{ m}$  and  $\sqrt{1.2^2 + 0.48^2} = 1.29 \text{ m}$ . Given that the low-frequency magnetic fields at 6 Hz and 8 Hz have extremely long wavelengths (tens of thousands of kilometers), they operate entirely within the quasi-static field at practical localization ranges, where the magnetic field pattern remains stable. Moreover, the exceptional penetration capability of these frequencies through geological strata helps to reduce the demands on the motor's driving capability [19].

Positioning results are shown in Fig. 12 and Fig. 13. To eliminate the influence of random errors, ten inspections are conducted. Measurement results are averaged at 0.2 m interval within each section. Following the calculation of averages for individual experiments, a final average is computed across all the ten experimental results. Positioning error percentage is shown in Table 1 and Table 2. When the lateral distance is 0.77 m, in the horizontal direction the maximum, minimum and mean

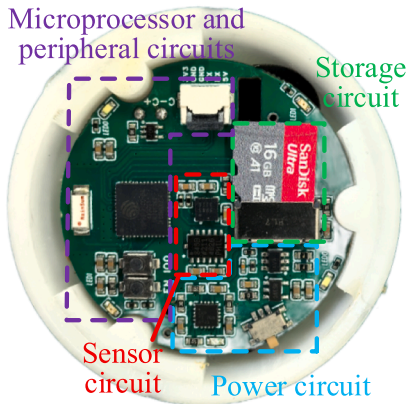


Fig. 8. Data acquisition circuit module.

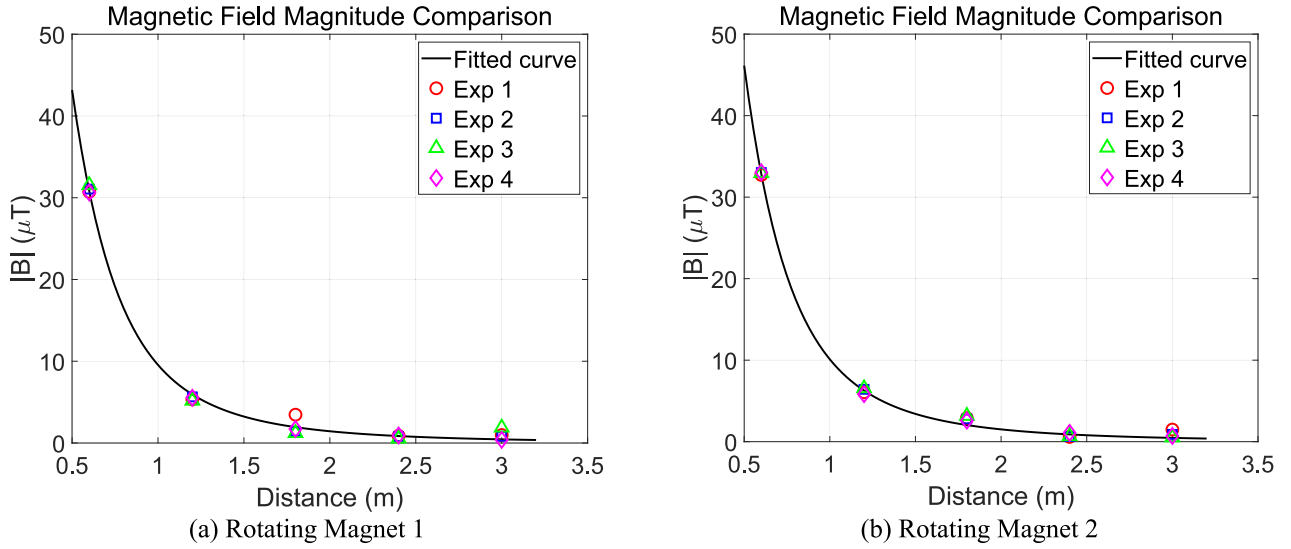


Fig. 10. Magnetic moment calibration experiment fitting curve.

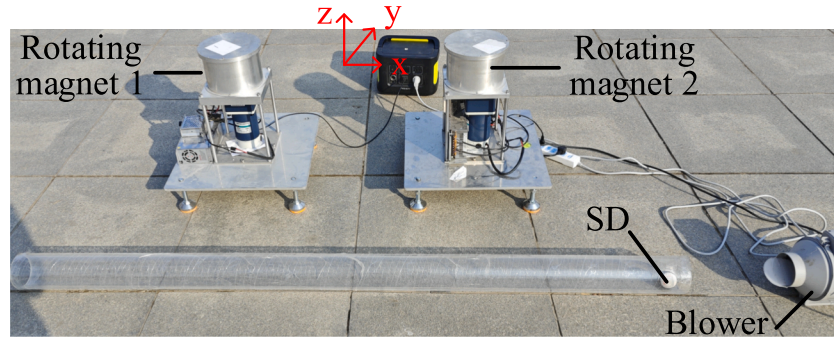
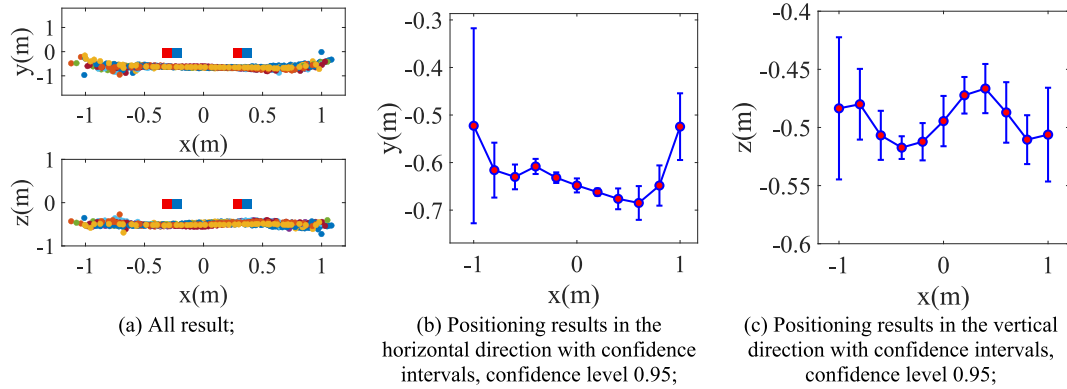


Fig. 11. Scaled-down pipe positioning experiment.

Fig. 12. Pipeline positioning results with  $y = -0.6$  m.

errors are 14.16%, 1.36% and 8.46%; in the vertical direction the maximum, minimum and mean errors are 7.78%, 0.005% and 3.78%. When the lateral distance is 1.29 m, in the horizontal direction the maximum, minimum and mean errors are 9.27%, 0.96% and 6.23%; in the vertical direction the maximum, minimum and mean errors are 11.14%, 1.62% and 6.15%. Error analysis can be found in [supplementary material](#).

#### 4.3. Pipeline positioning experiment with soil obstruction

In order to verify whether it is possible to locate the pipeline in a soil environment, a pipeline positioning experiment is conducted under the condition of soil obstruction. The position parameter is the same as the position when the pipeline is offset by 1.2 m. The shielding environment between the pipeline and the base stations is created using coir brick soaked in water, simulating a real moist soil environment. The field experiment setup is shown in Fig. 14, and the positioning results are shown in Fig. 15. A comparison of the positioning results in the

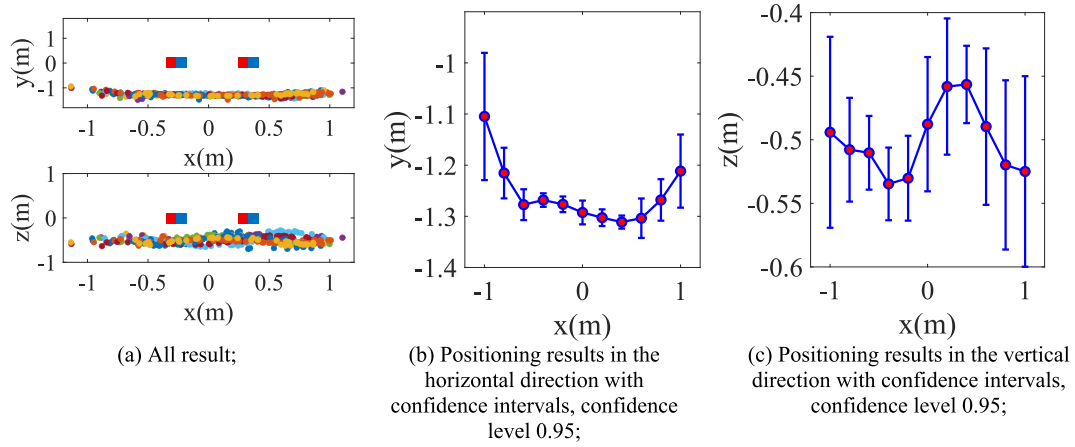
Fig. 13. Pipe positioning results with  $y = -1.2$  m.

**Table 1**  
Horizontal localization error without soil.

| Lateral distance | Maximum Error | Minimum Error | Mean Error | Absolute Error |
|------------------|---------------|---------------|------------|----------------|
| 0.77 m           | 14.16%        | 1.36%         | 8.46%      | 0.065 m        |
| 1.29 m           | 9.27%         | 0.96%         | 6.23%      | 0.080 m        |

**Table 2**  
Vertical localization error without soil.

| Lateral distance | Maximum Error | Minimum Error | Mean Error | Absolute Error |
|------------------|---------------|---------------|------------|----------------|
| 0.77 m           | 7.78%         | 0.005%        | 3.78%      | 0.029 m        |
| 1.29 m           | 11.4%         | 1.62%         | 6.15%      | 0.079 m        |

horizontal and vertical directions is presented in Table 3 and Table 4. When the pipe is covered by soil, in the horizontal direction the maximum, minimum, mean errors and absolute error are 11.41%, 2.05%, 7.66% and 0.099 m; in the vertical direction the maximum, minimum, mean errors and absolute error are 6.9%, 0.16%, 3.24% and 0.040 m. It can be observed that regardless of the presence of the soil environment, the mean positioning errors are within 10%, demonstrating good positioning performance.

#### 4.4. L-shaped Pipe positioning experiment

To verify the impact of this positioning method on pipelines with

bends, an L-shaped pipeline localization experiment is conducted. The localization experiment for the single-elbow L-shaped pipeline is conducted as shown in the Fig. 16(a) Results are shown in Fig. 16(b), (c) and (d). For the first straight pipeline section, the mean y-coordinate of the SD trajectory is  $-1.2526$  m with a deviation of 0.0526 m, and the mean z-coordinate is  $-0.5510$  m with a deviation of 0.0710 m. The ratio of the 3D positioning deviation to the positioning distance is 7.2%. For the second straight pipeline section, the mean x-coordinate of the SD trajectory is  $-0.6550$  m with a deviation of 0.055 m, and the mean z-coordinate is  $-0.4934$  m with a deviation of 0.0134 m. The ratio of the 3D positioning deviation to the positioning distance is 8.0%. The average error level is essentially the same as that for straight pipelines.

## 5. Discussion

### 5.1. Geometric constraints analysis

During the calculation of coordinate transformation, the angle  $\gamma$  used in Equation (16) plays a critical role in aligning the measurement coordinate system with the global reference coordinate system. Specifically,  $\gamma$  represents the angular deviation between the baseline vector connecting the two base stations and the x-axis of the O-xyz coordinate system. This angle  $\gamma$  is computed by determining the direction of the vector  $\mathbf{d} = \mathbf{p}_2 - \mathbf{p}_1$ , where  $\mathbf{p}_1$  and  $\mathbf{p}_2$  denote the estimated positions of base station 1 and base station 2, respectively. The angle  $\gamma$  is obtained via  $\gamma = \arccos(\mathbf{d} \cdot \mathbf{x} / \|\mathbf{d}\|)$ , where  $\mathbf{x}$  is the unit vector along the x-axis.

Although the theoretical value of  $\gamma$  is independent of the baseline length  $\|\mathbf{d}\|$ , the numerical stability of the angle estimation is



Fig. 14. Pipeline localization experiment photo with soil-shielded environment.

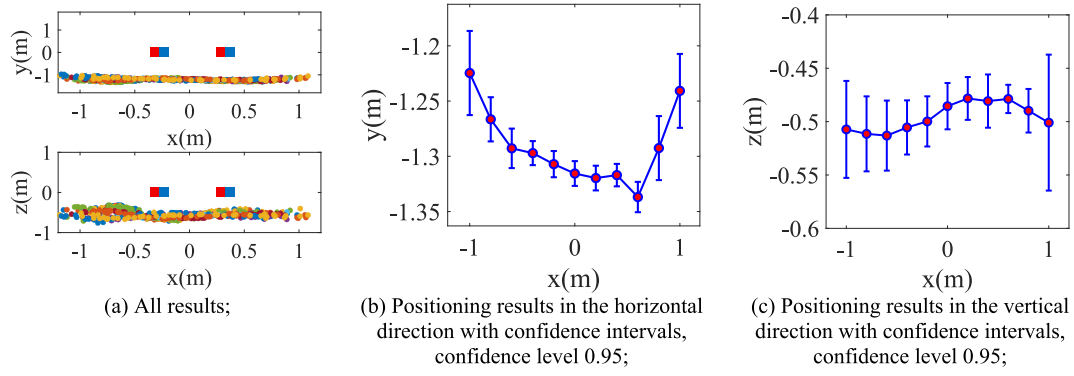


Fig. 15. Pipe positioning results with soil obstruction.

Table 3  
Horizontal localization error with soil.

|              | Maximum Error | Minimum Error | Mean Error | Absolute Error |
|--------------|---------------|---------------|------------|----------------|
| With soil    | 11.41%        | 2.05%         | 7.66%      | 0.099 m        |
| Without soil | 9.27%         | 0.96%         | 6.23%      | 0.080 m        |

Table 4  
Vertical localization error with soil.

|              | Maximum Error | Minimum Error | Mean Error | Absolute Error |
|--------------|---------------|---------------|------------|----------------|
| With soil    | 6.9%          | 0.16%         | 3.24%      | 0.040 m        |
| Without soil | 11.4%         | 1.62%         | 6.15%      | 0.079 m        |

significantly affected by the magnitude of  $\|d\|$ . When the baseline distance is small, measurement noise introduces substantial relative errors to the vector  $d$ , leading to significant fluctuations in the computed angle  $\gamma$ . This ill-conditioned situation amplifies angular uncertainty, which then propagates through the rotation matrix  $R(\gamma)$ , thereby degrading the accuracy of the final position estimate.

Conversely, an excessively large baseline separation also imposes limitations, as the SD detector must simultaneously resolve signals from both base stations to achieve positioning. When the two base stations are too far apart, signal attenuation increases with distance, leading to a reduced SNR at the SD. This decline in SNR directly degrades the quality of magnetic field measurements, thereby introducing greater errors in the estimation of  $p_1$  and  $p_2$ , and ultimately impairing positioning accuracy. Therefore, maintaining an optimal baseline interval between the two sensor base stations is crucial for balancing the numerical conditioning of angular calibration and the requirements of signal quality, particularly in environments with inherent measurement uncertainty.

To further verify the positioning performance at measurement points in different locations within a limited area, pipeline positioning experiments at different angles are conducted, as shown in the Fig. 17. The results indicate that the two base stations remain effective in positioning pipelines with different orientations, demonstrating that the method proposed in this paper achieves effective positioning for pipelines at various angles.

The positioning accuracy of the dual rotating magnetic base station system is significantly influenced by its geometric deployment, which is mainly reflected in two aspects: first, the baseline length between the two base stations; second, the relative angle between the line connecting the base stations and the pipeline orientation. An excessively short baseline length reduces the numerical stability of the angle  $\gamma$  calculation, amplifying the impact of measurement noise on coordinate transformation; conversely, an excessively long baseline leads to signal attenuation, lowers the signal-to-noise ratio, and similarly compromises

positioning accuracy. Therefore, an optimal baseline length must be sought to balance numerical stability and signal quality. On the other hand, experiments have demonstrated that the proposed method can achieve effective pipeline localization under various angle conditions, indicating that the system possesses good adaptability and robustness to changes in the spatial orientation of the pipeline. In summary, a rational geometric deployment design is crucial to ensure the stable and precise operation of the system in real-world complex scenarios.

## 5.2. Discussions for field application

When applying this method to actual field pipeline positioning, two problems need to be faced: (1) longer pipelines and (2) greater burial depth of pipelines. Given that this method is blind measurement, the first problem can be solved through segment-by-segment localization of long pipelines. In the proposed method, the pipeline position calculation does not use the two end's coordinates of each pipeline section, but only utilizes the magnetic data recorded by the SD and the coordinates and model of the rotating magnetic base station. The SD can determine its coordinates as long as it detects valid rotating magnetic signals while rolling inside the long pipeline. Therefore, the scaled-down experiment can be considered as the SD rolling in any small section of a long pipeline. There will also be no time-cumulative error for long pipelines.

The second problem may result in too weak magnetic signals to achieve pipeline localization but can be solved by increasing the volume of the magnet in the base station according to the burial depth of the pipeline. To evaluate the positioning error in the actual field application, an analysis of distance sensitivity to magnetic signals  $|dr/dB|$  is conducted, namely, the absolute value of the derivative of the distance between the rotating magnetic base station and the magnetometer with respect to the magnitude of the magnetic flux density. The simulation results are shown in the Fig. 18.

For the same magnetic signal-to-noise ratio (SNR) and  $|dr/dB|$ , the resulting positioning accuracy is expected to be the same. According to the conclusion of literature [20], the volume of the magnet is proportional to its magnetic moment. Assuming a 10 times increase in magnet's three dimensions, the magnetic moment  $p$  of the magnet increases by 1000 times. The detection distance can be improved from 1.29 m at point A to 7.25 m at point B as shown in Fig. 12 under the same resulting positioning accuracy, namely,  $\sqrt{(1.2 \cdot 6.23\%)^2 + (0.48 \cdot 6.15\%)^2} = 0.08$  m. When the positioning accuracy requirement is further relaxed to an allowable engineering limit, for example, 0.32 m that is 4 times the above accuracy, the positioning distance can reach 10.25 m at point C where  $|dr/dB|$  is 4 times that of point A or B. Most PE pipelines are buried at depths within 10 m, which satisfies most application scenarios. In practical inspection applications, the volume of the magnet can be adjusted according to the PE pipelines' approximate burial depth and positioning accuracy requirements. Since both rotating magnetic base stations and the SD are reusable, it is feasible to implement a two-stage

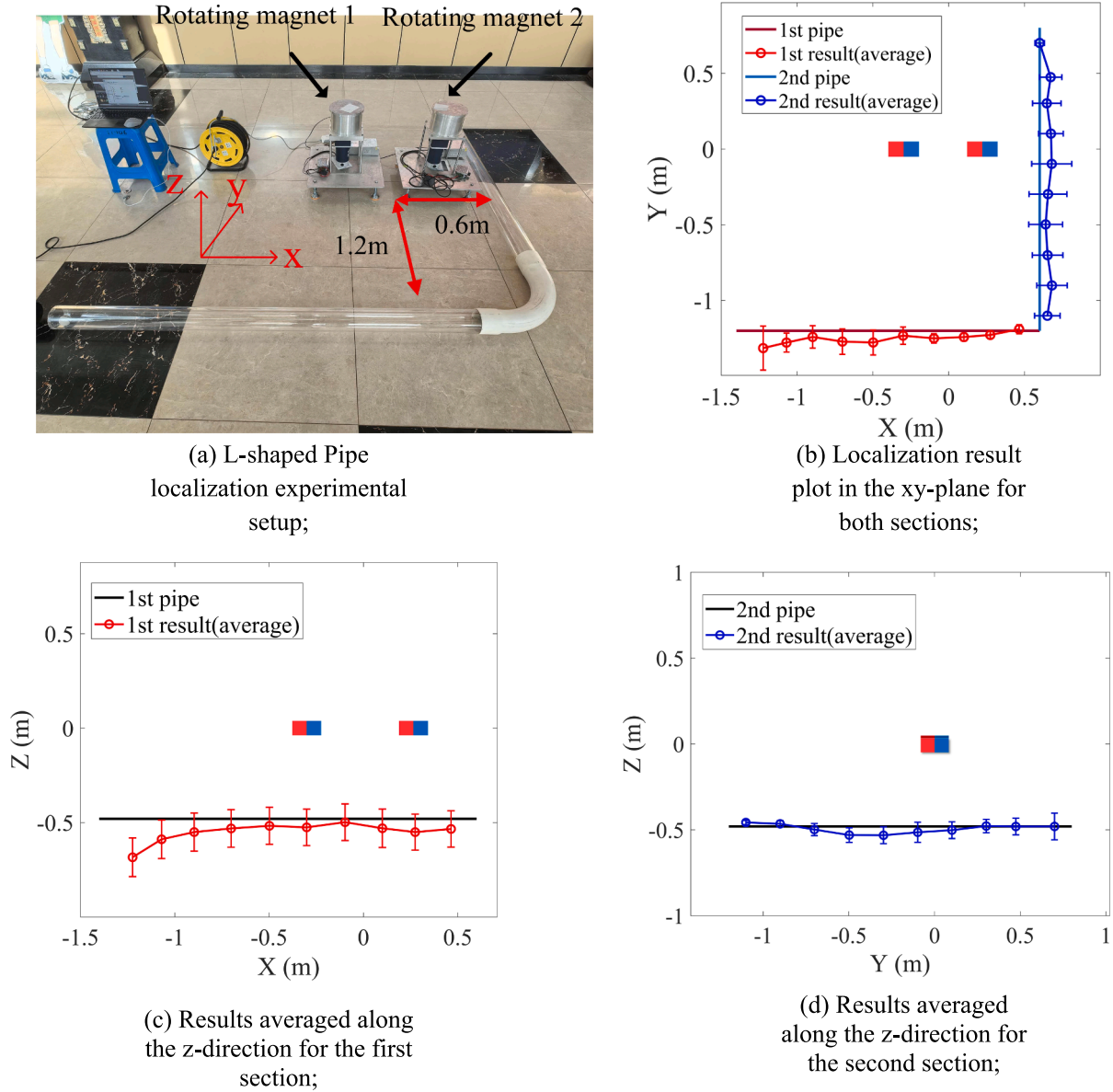


Fig. 16. Localization results of the L-shaped pipe.

detection approach. Initially, a preliminary detection can be performed to determine the pipeline location; in this case, the magnetic base stations may be too far away from the PE pipelines. Subsequently, based on the initial positioning results, the rotating magnetic base stations can be repositioned closer to the pipeline, and the detection process can be repeated to enhance overall detection accuracy and precision.

In field applications, there is infinite-length airflow within field pipelines, and the SD can roll more stably compared to inside short pipes used in this paper, which is more favorable for localization. Previous research [18] conducted measurements using a pipeline length of 12 m and recorded acceleration data of the SD at different launch angles. After careful design of the SD's mass distribution, stable fixed-axis rotation can be achieved. For SDs launched at different angles, stable rolling can be maintained after a certain period. In this paper, the pipeline is only 2 m long, and rolling instability occurs upon entering and exiting the pipeline. However, localization within the stable region remains effective. To validate practical applicability, positioning experiments are conducted using wet coir bricks to simulate moist soil conditions. The pipeline offset is maintained at 1.2 m for comparative analysis. The experimental setup and results are shown in Fig. 14 and Fig. 15, Table 3

and Table 4. Horizontal positioning achieved mean error of 7.66% (absolute: 0.099 m), while vertical positioning yielded 3.24% (absolute: 0.040 m). The superior vertical accuracy is attributed to the geometric configuration of dual base stations. Mean errors remain below 10% regardless of soil presence, confirming that extremely low-frequency magnetic fields effectively penetrate conductive soil, validating feasibility for buried PE pipeline localization.

## 6. Conclusion

This paper proposes a positioning method for in-service PE gas pipelines based on extremely low-frequency magnetic base stations and a lightweight SD. This method enables the localization of in-service PE gas pipelines without interfering with their normal operation.

(1) A method for calculating the relative position between a magnetometer in an arbitrary orientation and a single rotating magnetic base station is proposed. By integrating the data processing algorithm for magnetic field and acceleration signals, a PE pipeline positioning method based on dual rotating magnetic base stations is developed.

(2) A scaled-down pipeline positioning experiment with dual

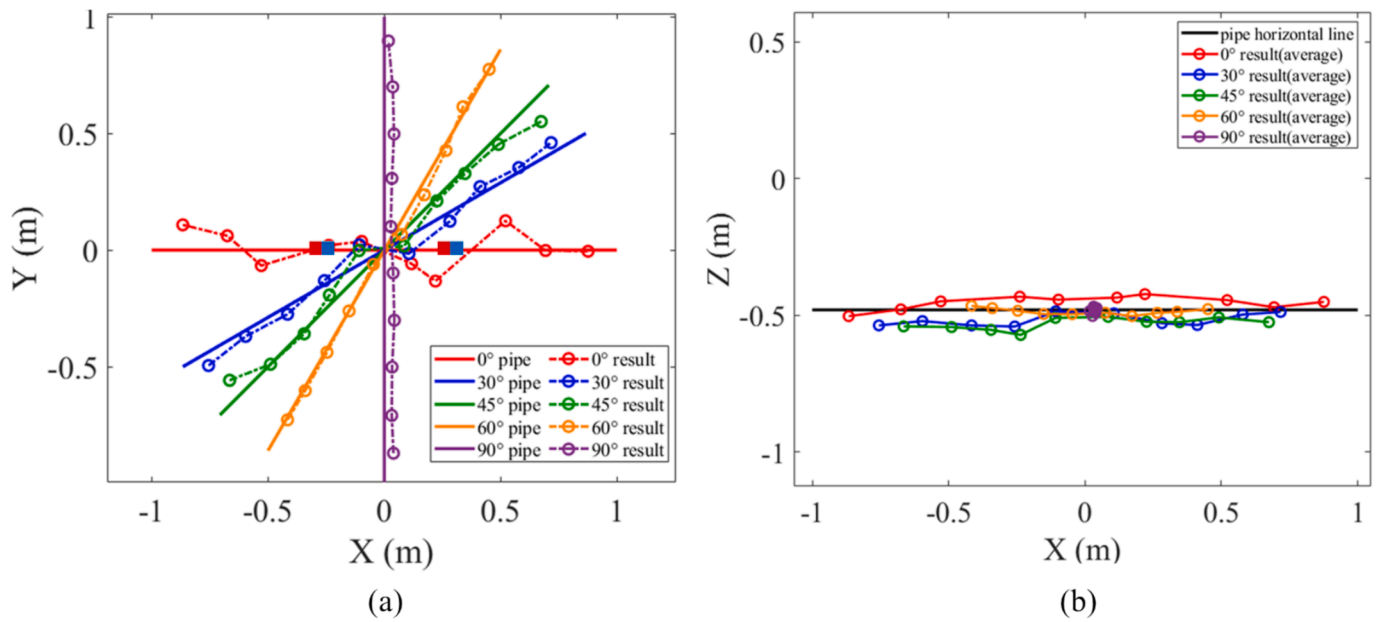


Fig. 17. Pipeline positioning experimental results at different angles. (a) top view; (b) side view.

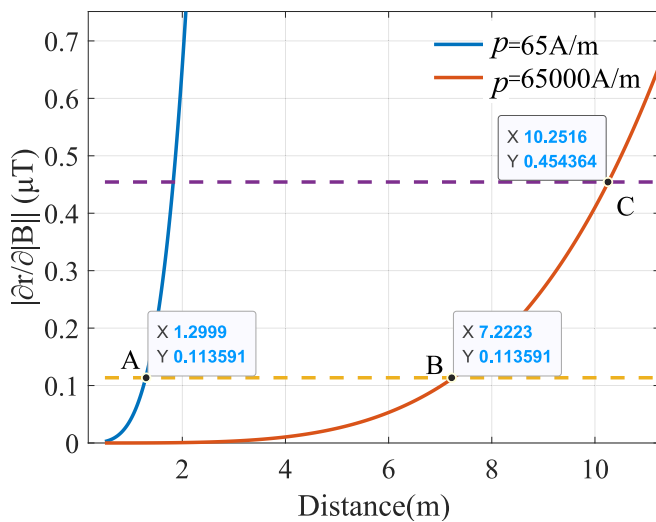


Fig. 18. Error analysis for different distances between the station and the measure point where the SD passes in the pipeline.

rotating magnetic base stations is conducted. When the lateral positioning distance is 1.29 m, the mean localization error in the horizontal and vertical directions are 6.23% and 6.15%. When the pipe is covered by soil, in the horizontal direction the maximum, minimum, mean errors and absolute error are 11.41%, 2.05%, 7.66% and 0.099 m; in the vertical direction the maximum, minimum, mean errors and absolute error are 6.9%, 0.16%, 3.24% and 0.040 m. It can be observed that regardless of the presence of the soil environment, the mean positioning errors are within 10%, demonstrating good positioning performance. An L-shaped pipeline localization experiment is conducted. The average error level is essentially the same as that for straight pipelines.

(3) For field applications, the magnet volume should be increased by 10 times in three dimensions to ensure the SD collects sufficiently strong magnetic signals, thereby achieving the same positioning accuracy for 10 m deep PE pipeline. As the current experiments are still in the laboratory validation phase, further evaluation of the positioning accuracy under field conditions is necessary. Future work will therefore involve

assessing the method's performance under actual in-service conditions.

#### CRediT authorship contribution statement

**Yuan Wang:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Formal analysis. **Mingrui Zhang:** Writing – original draft, Software, Formal analysis. **Jinyu Ma:** Supervision, Project administration, Conceptualization. **Feifan Jing:** Methodology, Data curation. **Yi Jin:** Validation, Supervision. **Xinjing Huang:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.measurement.2026.121038>.

#### Data availability

Data will be made available on request.

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