

3-D Localization of In-Service Deep-Buried PE Pipelines via ELF Magnetic Matching: System Design and Field Validation

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Abstract—The nonconductive and nonmagnetic properties of polyethylene (PE), combined with the severe attenuation of acoustic and electromagnetic waves by soil, render 3-D localization of deep-buried, in-service PE gas pipelines a significant challenge. This study presents a 3-D localization system based on extremely low frequency (ELF) magnetic field matching, consisting of a high-current ground magnetic station and a Φ 17-mm miniature spherical detector (SD). The station generates penetrative ELF fields through large wire loops, while the SD is deployed through existing purge valves without interrupting gas service. Trajectory reconstruction is achieved by matching the magnetic fields measured by the SD to a precomputed field map under kinematic constraints, rather than by relying on long-distance inertial dead reckoning. Furthermore, system scaling laws are established, demonstrating that localization uncertainty can be reduced by increasing wire loop current and employing large-scale wire loops to maintain deep-buried pipelines within the magnetic near-field region. In field tests on a 140-m PE pipeline buried at about 4.5-m depth, repeated localization experiments were conducted. The deviation between the mean of three repeated runs and the commercial strapdown inertial navigation system (SINS) results is 0.32 m, with a repeatability precision of 0.07 m. These results verify the system's effectiveness for high-precision, nondestructive localization of buried urban in-service PE gas pipelines.

Index Terms—Extremely low frequency (ELF), in-service pipeline localization, magnetic field matching, miniature spherical detector (SD), polyethylene (PE) pipelines.

I. INTRODUCTION

WITH the acceleration of urbanization, polyethylene (PE) pipelines have been widely adopted in urban low- and medium-pressure gas networks owing to their excellent corrosion resistance and high flexibility [1], [2]. However, due to the lack of as-built records or urban redevelopment, the precise locations of numerous in-service PE pipelines are difficult to trace. This results in frequent accidental punctures during excavation operations, posing significant safety risks

[3], [4], [5]. As PE pipelines are nonmetallic (i.e., nonconductive and nonmagnetic), conventional localization methods for metallic pipelines—including magnetic anomaly detection [6], electromagnetic induction [7], and pipeline current mapping [8]—cannot be applied. Therefore, high-precision localization of in-service deep-buried PE pipelines is of paramount importance. Any viable technique must operate on in-service pipelines without interrupting gas transmission or requiring high-risk pipe cutting, thereby enabling a truly nondestructive inspection workflow.

Localization technologies for underground nonmetallic pipelines can be broadly categorized into external and internal detection methods. External methods primarily include acoustic methods and ground-penetrating radar (GPR). Acoustic methods involve emitting sound waves from the ground surface, which propagate underground and are reflected by the target pipeline. Acoustic signals are then received at multiple surface points and processed via array signal processing to determine the pipeline location [9], [10], [11]. However, acoustic signals attenuate rapidly in complex soil media, and the acoustic receivers must maintain good contact with the ground. GPR employs the reflection of high-frequency electromagnetic waves from the target pipeline surface to achieve localization. Nevertheless, its performance degrades significantly in soil with high conductivity and is susceptible to clutter interference in complex underground environments [12], [13].

External detection methods like acoustic methods and GPR are inherently nondestructive. However, they both suffer from rapid signal attenuation in complex soil media, which limits their applicability in deep-buried targets. When stacked or intersecting pipes exist underground, upper layer pipes may shield those below, further reducing detection reliability. Furthermore, these methods require operators to scan the ground surface above the pipeline using handheld instruments or detection vehicles, resulting in low efficiency and susceptibility to surface environmental conditions. When there are obstacles on the ground, operators cannot easily access the site, making it impossible to perform continuous spatial coordinate measurement along the entire pipeline.

Internal detection methods rely on in-pipe robots equipped with various sensors to reconstruct pipeline trajectories in enclosed underground environments, and are mainly categorized into strapdown inertial navigation systems (SINSs) [14] and simultaneous localization and mapping (SLAM) [15]. For urban low- and medium-pressure gas pipelines, SINS typically adopts in-pipe robots with circumferentially distributed support wheels to align the robot's axis with the pipeline axis; each robot integrates a three-axis MEMS gyroscope, three-axis

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MEMS accelerometer, and odometer wheels [16], [17], [18]. The use of compact, low-cost MEMS inertial measurement units (IMUs) reduces cost, weight, and volume, ensuring smooth movement of the robot inside the narrow pipeline. However, inherent characteristics of MEMS IMUs—including zero-bias error, thermal drift, installation misalignment, and robot-induced vibration—can cause SINS positioning errors to accumulate and grow with travel distance, potentially leading to localization failure [14]. In recent years, various strategies have been proposed to improve the localization accuracy of in-pipe SINS, including round-trip repeated detection [17], improved odometers [19], multilevel information fusion [18], and the installation of additional external markers [20]. Currently, in-pipe SINS has achieved localization accuracy sufficient for excavation collision avoidance and has been widely applied in practical engineering.

In-pipe SLAM achieves precise self-localization, 3-D environment reconstruction, and accurate labeling of defect positions by equipping in-pipe robots with multisensor configurations (e.g., cameras and LiDAR in addition to MEMS IMUs) [21], [22], [23]. SLAM-based robots can autonomously navigate and turn within the pipeline, utilizing features such as elbows, tees, and valves, along with prior topological information, to locate themselves and reconstruct the 3-D shape of the pipeline. This approach is better suited for localized pipe networks with complex spatial geometries. However, in long regular straight pipes, SLAM often suffers from “longitudinal degradation,” leading to a complete failure of localization [24].

Because the support wheels of SINS robots must maintain tight contact with the pipe wall, the robots require careful placement and alignment inside the pipeline as well as traction via a safety tether [18], [19], which necessitates pipeline excavation, cutting, purging, and rewelding, resulting in gas supply interruption, significant economic losses, and safety risks. Although in-pipe SLAM robots offer greater flexibility, their substantial volume and weight—required to accommodate multiple complex sensors, real-time computing units, and large-capacity batteries—also necessitate pipe cutting and depressurization for careful deployment. Therefore, both in-pipe SINS and SLAM methods are currently only suitable for newly built pipelines and remain difficult to deploy directly in in-service PE gas pipelines, as the robot deployment inevitably requires pipeline excavation and pipe cutting.

In-service PE gas pipelines are typically equipped with block valves and paired purge valves at regular intervals, used to isolate the pipeline and purge methane during emergency repairs. The diameter of purge valves is generally small, ranging from 18 to 25 mm. To deploy a detector through such narrow openings, the in-pipe device must be extremely compact, which severely restricts the variety and performance of onboard sensors. Under these constraints, a viable localization approach requires an external signal source mounted on the ground surface that can penetrate both the soil and pipe walls, as well as the fusion of internal and external information to achieve localization of in-service PE gas pipelines.

Extremely low frequency (ELF) magnetic fields can penetrate soil, water, and rock layers, and have been widely applied in through-the-Earth localization and ultralong-distance communication [25], [26], [27], [28], making them

a highly suitable auxiliary signal source. Existing magnetic beacon-based positioning systems could be categorized into two types according to their transmitter-receiver configurations.

1) Rotating permanent magnet beacons [29], [30], [31], [32], [33], [34]. These systems generate time-varying magnetic fields by mechanically rotating a permanent magnet. They offer strong penetration and immunity to environmental noise, but suffer from complex mechanical structures and stringent motor control requirements. Moreover, the magnetic dipole model limits their effective range: field strength decays as $1/r^3$, so achieving deep-buried localization would demand impractically large magnets, raising unresolved issues of power consumption and operational safety.

2) Low-frequency current-carrying coils beacons [35], [36], [37], [38], [39]. Compared to rotating magnets, these systems generate time-varying magnetic fields via alternating current (AC) or switched-DC excitation of stationary coils, offering higher controllability and simpler mechanical structures. While representative studies have achieved impressive accuracies—ranging from subcentimeter errors at short distances [35], [37] to approximately 0.1 m within 10–15-m indoor workspaces [36]—their effective coverage remains restricted by the rapid attenuation of the magnetic field and the environmental sensitivity of the magnetometer receivers.

Despite these achievements, the effective coverage of both rotating-magnet and current-loop systems is fundamentally limited by the intrinsic $1/r^3$ attenuation of magnetic fields. In typical configurations, high-precision results are often confined to extremely localized volumes, such as the 30-cm cube in Ferrigno et al. [40] or the 2-m ranges in Chen et al. [33]. Even in larger scale indoor tests, errors tend to scale unfavorably with distance, as seen in the 0.3–1.0-m deviations reported by Pasku et al. [41] and Kusche et al. [29] as the range approaches 10 m.

For underground pipeline applications, although preliminary attempts [34], [42] have demonstrated decimeter-level accuracy, they are primarily tailored for shallow burial or short-range scenarios. A significant research gap persists in achieving robust, high-precision localization for deep-buried (e.g., 5 m) and long-distance (e.g., >100 m) urban gas infrastructure. This motivates the proposed method, which transitions from conventional dipole-type sources to large near-field wire-loop stations to overcome the severe distance penalty associated with existing ELF approaches.

To bridge this gap, this study proposes a 3-D localization method for in-service PE gas pipelines using a ground-based ELF magnetic station and an in-pipe spherical detector (SD). The station comprises a large rectangular wire loop deployed on the ground to generate a standard spatial magnetic field, while the miniature SD rolls forward inside the pipeline driven by gas flow. The trajectories of both the SD and the pipeline are reconstructed by matching the recorded magnetic data to the precomputed field. The methodological novelty lies not in generic preprocessing or attitude estimation modules, but in combining measured loop geometry, an absolute magnetic map, direct observation-to-map matching, and multiconstraint ambiguity suppression into a localization framework that remains effective for deep-buried, in-service,

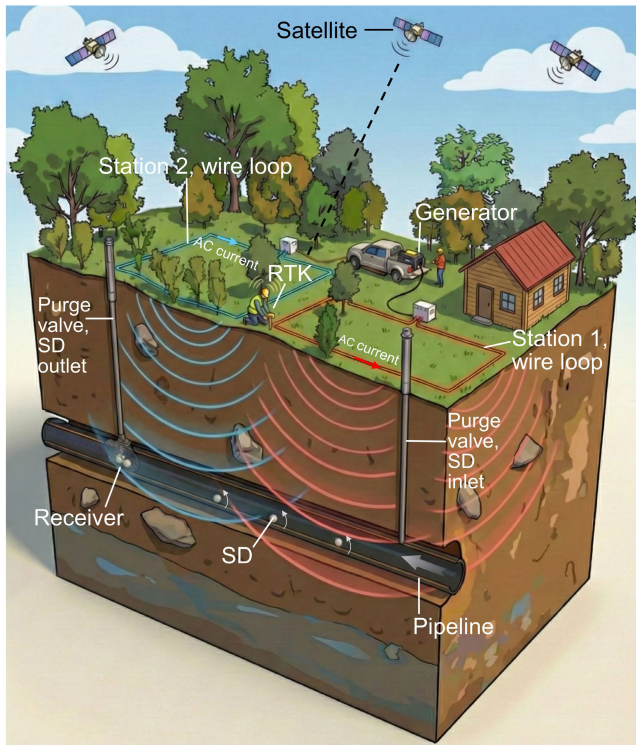


Fig. 1. Schematic of pipeline localization based on an ELF magnetic station and an SD.

- 1) *Enhanced Penetration and Anti-Interference Capability:* The developed ELF magnetic source achieves deep soil penetration, is insensitive to soil moisture and electromagnetic interference, and provides extensive spatial coverage.
- 2) *Long-Distance, Nondestructive In-Service Inspection:* By combining the 17-mm SD deployable through purge valves with movable or phase-synchronized ground stations, the proposed system supports segmented localization over long in-service pipeline sections without pipe cutting, methane purging, or interrupting gas transmission.
- 3) *Absolute-Map-Based Trajectory Reconstruction:* Instead of relying on inertial recursion, the method constructs an absolute standard magnetic field map from the measured loop geometry and directly matches each observation to that map, while distance, azimuth, and depth constraints shrink the feasible set to suppress ambiguous solutions; as a result, the method avoids the continuously diverging cumulative drift typical of long-distance inertial integration. It removes the requirement for repetitive ground surface scanning and enables highly efficient blind detection.

II. METHODOLOGY

A. Localization Principle

As illustrated in Fig. 1, the proposed method proceeds as follows. A current-carrying wire-loop-based magnetic station is deployed on the ground surface above the pipeline segment to be measured, and the world coordinates of the wire nodes

are measured using a real-time kinematic (RTK) satellite positioning system. An ELF sinusoidal AC is injected into the wire to generate a standard magnetic field with a known spatial distribution, covering the target buried pipeline. A miniature SD is deployed into the in-service pipeline through the inherent purge valves and rolls forward driven by the internal gas flow. The SD continuously records acceleration and magnetic data along its path and is subsequently retrieved at the next purge valve using a prepositioned collection net. RTK measurements are used to determine the world coordinates and precise geometry of the wire, thereby enabling computation of a standard magnetic field throughout the space beneath the base station. The magnetic data collected by the SD are transformed and matched against the standard field to determine the spatial position of the SD relative to the base station, which corresponds to the coordinates of the pipeline bottom centerline. This method enables high-precision 3-D localization of buried pipelines in the world coordinate system without excavation, pipe cutting, gas service interruption, or methane purging.

The magnetic data $\mathbf{B}_h^{meas}(t_k)$ collected by the SD at time t_k is matched with the standard magnetic field $\mathbf{B}_w^{map}(\mathbf{p}^{(i)})$ at each grid point $\mathbf{p}^{(i)} = [x^{(i)}, y^{(i)}, z^{(i)}]^T \in \Omega_{grid}$ beneath the wire loop. The objective is to minimize the difference between the two while satisfying multiple kinematic constraints. This localization problem can be modeled as a constrained nonlinear optimization problem, as expressed in the following equation:

$$\min_{\mathbf{p}^{(i)}} J(\mathbf{p}^{(i)}) = \|\mathbf{B}_h^{\text{meas}}(t_k) - \mathbf{B}_w^{\text{map}}(\mathbf{p}^{(i)})\| \quad (1a)$$

$$\text{s.t. } \mathbf{p}^{(i)} = [x^{(i)}, y^{(i)}, z^{(i)}]^T \in \Omega_{\text{grid}} \quad (1b)$$

$$||\mathbf{p}^{(i)} - \hat{\mathbf{p}}_{k-1}|| - \Delta s_k| < \epsilon_s \quad (1c)$$

$$|\tan^{-1}\left(\frac{y^{(i)} - \hat{y}_{k-1}}{x^{(i)} - \hat{x}_{k-1}}\right) - \varphi_k| < \epsilon_\varphi \quad (1d)$$

$$|z^{(i)} - \bar{z}| < \epsilon_z \quad (1e)$$

where $\hat{p}_{k-1} = [\hat{x}_{k-1}, \hat{y}_{k-1}, \hat{z}_{k-1}]^T \in \Omega_{grid}$ is the matched solution obtained using the magnetic data recorded by the SD at time t_{k-1} .

B. Definition of Coordinate Frames

- 1) *Body Frame* ($O_b - X_b Y_b Z_b$): It is fixed to the center of the SD. The axes X_b , Y_b , and Z_b correspond to the three axes of the sensors. The SD is assumed to roll specifically around the Y_b axis. The raw magnetic data recorded at time t is denoted as $\mathbf{B}_b^{meas}(t)$.
- 2) *Horizontal Frame* ($O_h - X_h Y_h Z_h$): Its Origin Coincides With the Center of the SD. The Z_h Axis Is Perpendicular to the Ground Surface (opposite to gravity), and the X_h and Y_h Axes Are Parallel to the Horizontal Plane. The Magnetic Data in This Frame Is Denoted as $\mathbf{B}_h^{meas}(t)$.
- 3) *World Frame* ($O_w - X_w Y_w Z_w$): The east-north-up (ENU) system is adopted to describe the absolute coordinates of the pipeline. The magnetic field at each grid point beneath the current-carrying wire in this frame is denoted as $\mathbf{B}_w^{map}(\mathbf{p}^{(i)})$.

C. Calculation of $\mathbf{B}_w^{\text{Map}}(\mathbf{p})$

A sinusoidal AC $i(t) = I_0 \cos(2\pi ft)$ is injected into the rectangular wire loop, where I_0 is the current amplitude.

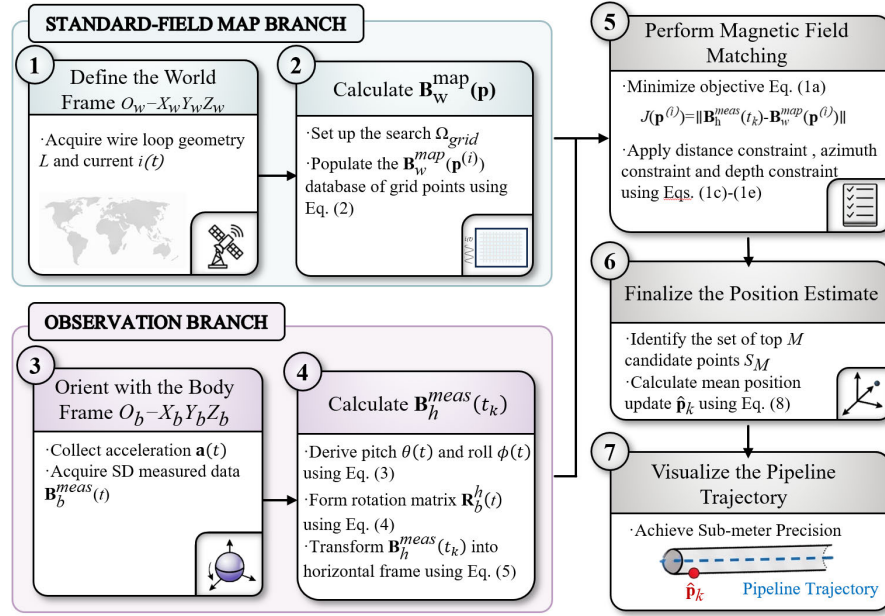


Fig. 2. Workflow of the proposed localization algorithm.

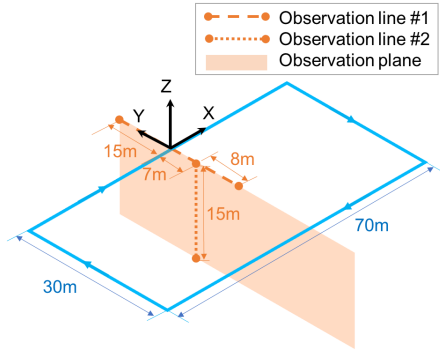


Fig. 3. Schematic of the simulated wire loop.

The standard magnetic field $\mathbf{B}_w^{map}(\mathbf{p})$ at any point $\mathbf{p}$ in the space beneath the wire is the vector superposition of the magnetic fields generated by all differential elements $d\mathbf{l}$ along the wire loop L . Based on the quasi-static approximation [43], the magnetic flux density vector $\mathbf{B}_w^{map}(\mathbf{p})$ and the current amplitude I_0 satisfy the Biot-Savart Law [44]. In practice, the wire is discretized into N finite-length segments, and the spatial magnetic field is calculated using a Riemann sum approximation as follows:

$$\mathbf{B}_w^{map}(\mathbf{p}) \approx \frac{\mu_0 I_0}{4\pi} \sum_{j=1}^N \Delta l_j \times (\mathbf{p} - \mathbf{r}_j) / \|\mathbf{p} - \mathbf{r}_j\|^3 \quad (2)$$

where μ_0 is the vacuum permeability and $\mathbf{r}_j$ is the midpoint of the j th wire segment. The space beneath the base station is discretized into a set of grid points Ω_{grid} . The magnetic field $\mathbf{B}_w^{map}(\mathbf{p}^{(i)})$ at each grid point is precalculated using (2) to establish the standard magnetic field database.

D. Calculation of $\mathbf{B}_h^{meas}$

The pitch angle $\theta(t)$ and roll angle $\phi(t)$ of the SD are calculated using the recorded acceleration data

$$\mathbf{a}(t) = [a_x(t), a_y(t), a_z(t)]^T$$

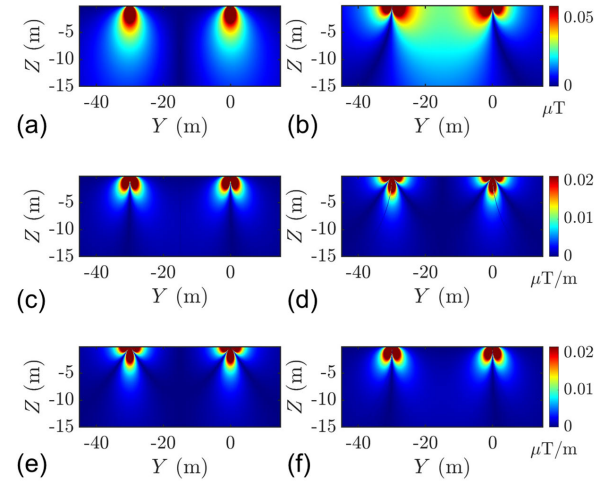


Fig. 4. Magnetic field amplitude and gradient generated by a 1-A current on the YZ measurement plane. (a) $(B_x^2 + B_y^2)^{1/2}$, (b) $|B_z|$, (c) $\partial(B_x^2 + B_y^2)/\partial Y$, (d) $\partial B_z/\partial Y$, (e) $\partial B_z/\partial Z$, and (f) $\partial |B_z|/\partial Z$.

$$\begin{aligned} \theta(t) &= \tan^{-1}(a_y(t)/a_z(t)) \\ \phi(t) &= \tan^{-1}(-a_x(t) / \sqrt{a_y^2(t) + a_z^2(t)}) \end{aligned} \quad (3)$$

A rotation matrix $\mathbf{R}_b^h(t)$ from the body frame to the horizontal frame is constructed using $\theta(t)$ and $\phi(t)$

$$\begin{aligned} \mathbf{R}_b^h(t) &= \mathbf{R}_y(\phi) \mathbf{R}_x(\theta) \\ &= \begin{bmatrix} \cos \phi(t) & 0 & \sin \phi(t) \\ 0 & 1 & 0 \\ -\sin \phi(t) & 0 & \cos \phi(t) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta(t) & -\sin \theta(t) \\ 0 & \sin \theta(t) & \cos \theta(t) \end{bmatrix} \end{aligned} \quad (4)$$

This matrix transforms the rotational magnetic field $\mathbf{B}_b^{meas}(t)$ measured in the body frame into the translational magnetic field $\mathbf{B}_h^{meas}(t)$ in the horizontal frame

$$\mathbf{B}_h^{meas}(t) = \mathbf{R}_b^h(t) \mathbf{B}_b^{meas}(t). \quad (5)$$

Since both the Z_h axis of the horizontal frame and the Z_w axis of the world frame are vertical, the two frames differ by a rotational deviation about the vertical axis. Consequently, when evaluating the magnetic field deviation in (1a), magnetic field matching is performed using the vertical and horizontal components rather than all three components.

E. Multiple Kinematic Constraints

Due to the existence of points around the wire where the magnetic field magnitude and direction are identical, magnetic field matching may yield multiple solutions. Constraints including azimuth, mileage, and depth are introduced to eliminate these ambiguities.

- 1) *Distance Constraint*: The SD is designed with a precise counterweight to ensure stable rolling about the Y_b axis driven by the gas flow. The rolling distance s is calculated as follows:

$$s(t) = \int_0^t \frac{1}{2} D_b \theta(t) dt. \quad (6)$$

The Euclidean distance between the candidate point $\mathbf{p}^{(i)}$ at time t_k and the previously estimated point $\hat{\mathbf{p}}_{k-1}$ must be consistent with the mileage increment $\Delta s_k = s_k - s_{k-1}$ calculated using (6), satisfying the constraint in (1c), where ϵ_s is the allowable distance error.

- 2) *Azimuth Constraint*: The yaw $\varphi(t)$ of the SD's forward axis (i.e., the pipeline axis) can be calculated from the projection of $\mathbf{B}_h(t)$ onto the horizontal plane relative to magnetic north

$$\varphi(t) = \varphi_0 - \tan^{-1} (B_{h,y}(t) / B_{h,x}(t)). \quad (7)$$

The deviation between the azimuth of the line connecting $\mathbf{p}^{(i)} = [x^{(i)}, y^{(i)}, z^{(i)}]^T \in \Omega_{grid}$ and $\hat{\mathbf{p}}_{k-1}$ and the calculated azimuth φ_k must satisfy (1d), where ϵ_φ is the allowable azimuth error.

- 3) *Depth Constraint*: Given the continuity and smoothness of the pipeline, the vertical coordinate $z_k^{(i)}$ of the candidate point is constrained by the local average depth $\bar{z}$ of the historical trajectory, satisfying (1e), where ϵ_z is the allowable depth error.

The final position estimate $\hat{\mathbf{p}}_k$ at time $\hat{t}_k$ is taken as the mean of the top M candidate points in the set S_M that minimize the objective function $J(x)$ and satisfy all constraints

$$\hat{\mathbf{p}}_k = \frac{1}{M} \sum_{m=1}^M \mathbf{p}_k^{(m)}, \mathbf{p}_k^{(m)} \in S_M \subset \Omega_{grid}. \quad (8)$$

The whole workflow is shown in Fig. 2.

III. SYSTEM SCALING LAW AND DETECTION OPTIMIZATION

A. Localization Uncertainty Scaling Law

The magnetic field gradient characteristics of the current-carrying wire loop directly determine the system's localization resolution. The relationship between the localization uncertainty δp , the magnetic sensor resolution δB , and the standard field gradient ∇B_w^{map} satisfies as follows:

$$\delta p = \delta B / \|\nabla B_w^{map}\|. \quad (9)$$

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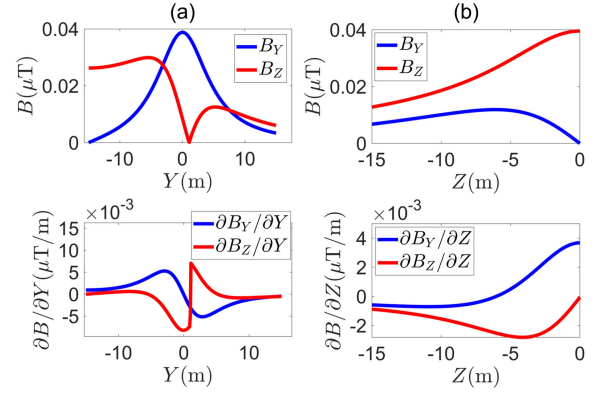


Fig. 5. Magnetic field amplitude and gradient generated by a 1-A current on the measurement lines. (a) Observation line #1. (b) Observation line #2.

For a rectangular base station ($a \times b$), when the detection distance $R \gg a, b$, the field behaves as a far-field magnetic dipole. From (2), the approximate far-field amplitude is derived as follows:

$$B_{w,far}^{map} = \|\mathbf{B}_{w,far}^{map}\| = \frac{\mu_0 I_0 ab}{4\pi} \cdot \frac{\sqrt{1+3\cos^2\beta}}{R^3} \propto 1/R^3 \quad (10)$$

where R is the distance to the wire loop center, and β is the magnetic moment angle. In this region, the gradient $\nabla B_{w,far}^{map} \propto 1/R^4$ leads to a localization uncertainty $\delta p \propto R^4$, causing detection blind zones for deep pipelines.

Conversely, when $R \ll a, b$, the pipeline resides in the “near-field region” dominated by the nearest wire segment. The near-field approximation (11) can be derived from (2)

$$B_{w,near}^{map} = \|\mathbf{B}_{w,near}^{map}\| = \frac{\mu_0 I_0}{2\pi} \cdot \frac{1}{d} \propto 1/d \quad (11)$$

where d is the perpendicular distance to the wire. Since $\nabla B_{w,near}^{map} \propto 1/d^2$, the uncertainty $\delta p \propto d^2$ increases slowly, offering higher signal-to-noise ratios for deep detection. These relationships are summarized by the universal scaling law as follows:

$$\delta p \propto \delta B \cdot R^N / I_0 \quad (12)$$

where $N = 2$ for the near-field and $N = 4$ for the far-field. To ensure high precision, this study adopts large-scale rectangular base stations laid along the pipeline to maximize near-field coverage while increasing excitation current I_0 to minimize δp .

B. Magnetic Field Distribution of Wire Loop and Its Optimized Layout

Numerical calculations are performed for the magnetic field distribution in the space surrounding the current-carrying rectangular wire loop. The magnitude and gradient of the magnetic flux density are calculated along the two lines and one plane shown in Fig. 3 to analyze localization uncertainty in the horizontal and depth directions. As shown in the measurement plane and lines (Figs. 4 and 5), horizontal and vertical components are strongest near the wire segments rather than beneath the center of the wire loop. Positioning the pipeline inside the wire loop provides simultaneous access to large amplitudes and gradients of magnetic flux density. Higher excitation currents can expand the high-precision localization

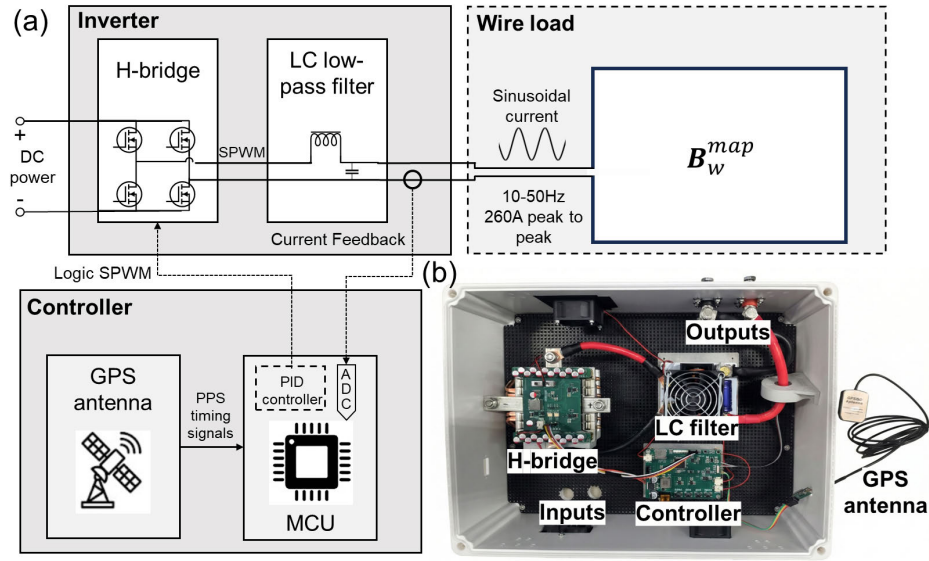


Fig. 6. ELF magnetic base station. (a) System block diagram. (b) Physical photograph.

zone, allowing the wire loop to be deployed approximately above the pipeline guided by known endpoint coordinates.

Furthermore, to resolve pseudosolutions where different positions share identical field vectors, the multiple kinematic constraints defined in (1c)–(1e) are utilized to confine the 3-D search range and ensure robust trajectory reconstruction.

IV. DESIGN AND DEVELOPMENT

A. ELF Magnetic Base Station

A high-performance ELF magnetic base station (Fig. 6) is developed to generate strong magnetic fields via large current injection. The system utilizes an MCU-controlled H-bridge and an LC low-pass filter to produce 10–49-Hz sinusoidal currents at up to 260-A peak-to-peak. Real-time closed-loop control ensures constant field amplitudes by dynamically adjusting the SPWM modulation depth. For long-distance inspections, GPS pulse-per-second (PPS) signals synchronize multiple stations to prevent irregular field superposition, thereby supporting phase-synchronized segmented localization over long pipelines.

Harmonic suppression and closed-loop control performance of the station were evaluated using a 200-m, 16-mm² wire. Operating at 40-Hz and 240-A peak-to-peak (~2300 W) for 1 h, the system demonstrated excellent long-term stability. Performance metrics, including current waveforms and sine-fitting goodness, are detailed in Fig. 7 and Table I.

B. Miniature SD

In-service PE gas pipelines feature block valves at specific intervals, with small branch pipes (purge valves) located on two sides of the block valve. The inner diameter of these branch pipes typically ranges from 18 to 25 mm. For on-site localization, a miniature SD is deployed into the main pipe through one branch pipe, as illustrated in Fig. 8(a), and retrieved from another branch pipe downstream, ensuring that normal gas transmission is not disrupted.

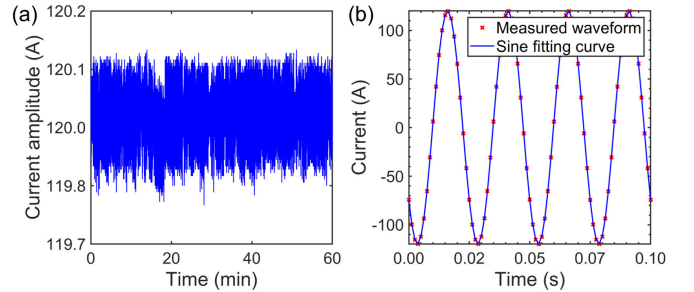


Fig. 7. Current output capability test of the magnetic base station. (a) Long-term stability of current amplitude. (b) Sine fitting of the current waveform.

TABLE I
STATISTICS OF AMPLITUDE FLUCTUATION AND SINE
GOODNESS-OF-FIT FOR THE OUTPUT CURRENT

Time(min)	Fluctuation	R ²
0	0.24%	0.999979
10	0.25%	0.999977
20	0.25%	0.999973
30	0.26%	0.999974
40	0.28%	0.999971
50	0.25%	0.999974
60	0.22%	0.999979

To accommodate the purge valves of the vast majority of pipelines, the outer diameter of the SD is designed to be 17 mm, with a weight of approximately 3.4 g, as shown in Fig. 8(b) and (c). The SD is composed of a spherical shell, a circuit board, a tungsten counterweight, and a rechargeable battery. The circuit board is a six-layer board with a diameter of 11 mm. Both the circuit board and the annular tungsten weight are located on the equatorial plane of the SD. Through precise counterweight design, the center of mass is aligned with the geometric center of the SD. The moment of inertia of the SD around the rolling axis is significantly larger than that around other axes, enabling it to maintain fixed-axis rolling driven by the gas flow within the pipeline [45]. Furthermore, a dedicated integrated charging and communication module for

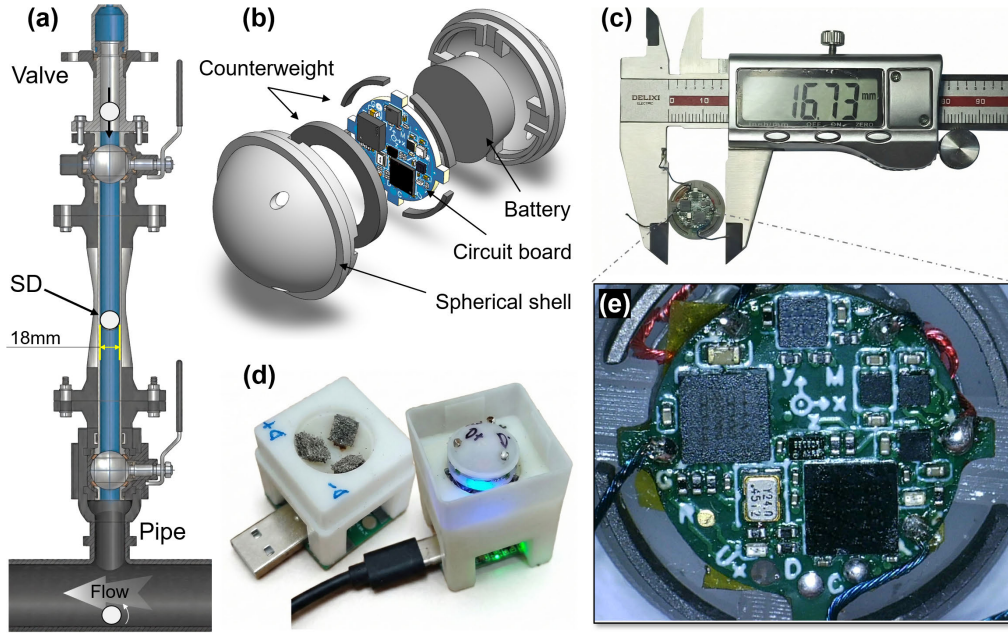


Fig. 8. SD. (a) Schematic of SD deployment through the pipeline purge valve. (b) Internal structure of the SD. (c) Measurement of SD dimensions. (d) Integrated charging and data transmission module. (e) Main circuit board.

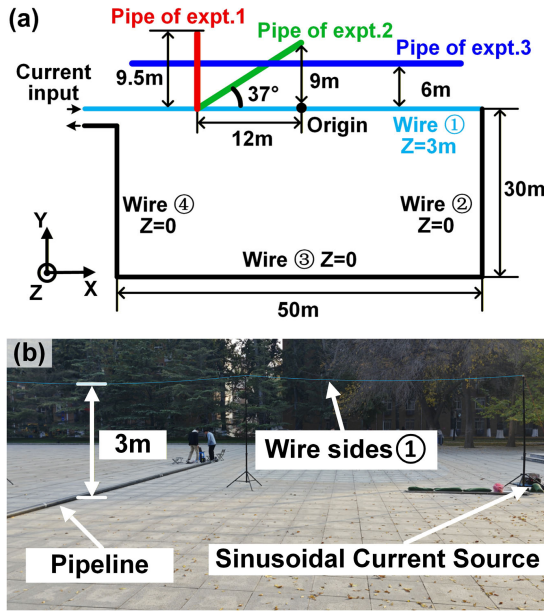


Fig. 9. Ground pipeline localization experiments. (a) Positional relationship between the pipeline under test and the wire loop. (b) Photograph of the experiment. (Expt. 1–3).

the SD is developed to facilitate on-site operations, as shown in Fig. 8(d).

V. EXPERIMENTS

A. Ground Validation Experiments

To evaluate the localization performance, three groups of PE pipelines with distinct orientations and known coordinates were sequentially deployed on the ground for testing. As illustrated in Fig. 9(a), the wire was arranged as a rectangular loop with dimensions of 50×30 m. The angles between the pipeline under test and side ① of the wire loop in the three experiments were 90° , 37° , and 0° , respectively.

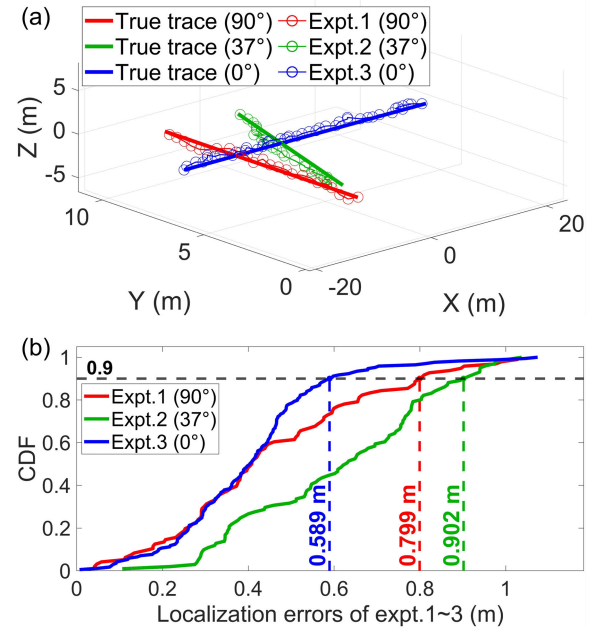


Fig. 10. Results of ground pipeline localization experiments. (a) 3-D view. (b) CDF statistics of the localization error norm.

For safety considerations regarding the elevated setup, a 10-mm^2 lightweight thin wire was used. Constrained by its safe current-carrying capacity, the peak-to-peak value of the excitation current was set to 80 A at 40 Hz. To simulate the actual scenario of buried pipelines, side ① was elevated by 3 m using tripods, as shown in Fig. 9(b), while the wires on the other three sides were laid on the ground. The cumulative distribution function (cdf) of the localization error was adopted to evaluate localization performance.

The experimental results demonstrate (Fig. 10) that the system successfully localized pipelines with three different

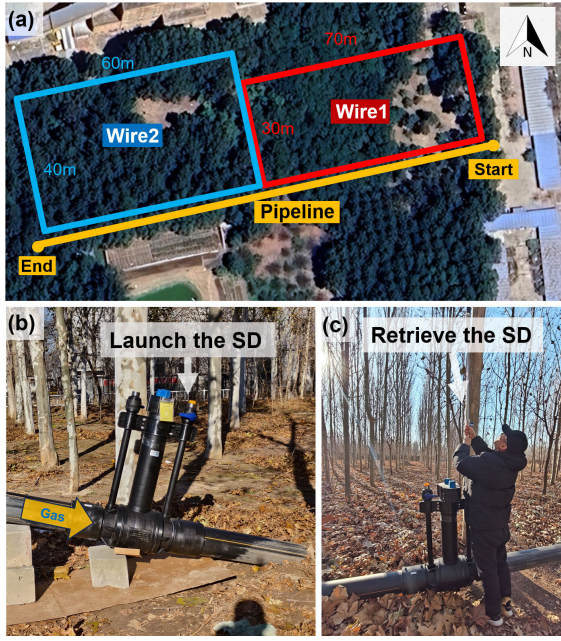


Fig. 11. (a) Wiring schematic of the field buried pipeline experiment (Expt. 4), and photographs of (b) SD launching and (c) retrieval process.

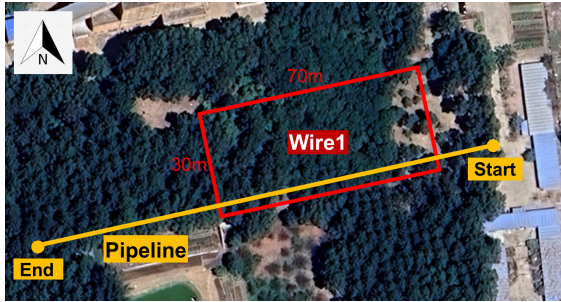


Fig. 12. Schematic of the field experiment (Expt. 5) with the pipeline located inside the rectangular wire loop.

orientations. The localization errors at $\text{cdf} = 90\%$ for the three groups are 0.6, 0.8, and 0.9 m, respectively. The highest localization accuracy is achieved when the pipeline is nearly parallel to the wire. Under conditions of a horizontal distance within 9 m and a vertical height difference of 3 m, the ratio of the average localization deviation to the detection distance is less than 8.3%, preliminarily validating the feasibility of the magnetic field matching method. Since the excitation current is only one-third of the rated value used in actual field operations, there remains significant room for improvement in localization accuracy.

B. Field Experiments on In-Service Pipelines

The field PE pipeline had a total length of approximately 140 m, a burial depth of about 4.5 m, and a diameter of DN200. Two sets of experiments, designated as Expt. 4 and Expt. 5, were conducted on this pipeline. The reference trajectory of the field pipeline was primarily provided by a commercial in-pipe SINS survey used by the construction contractor and the project sponsor. According to both the in-pipe SINS literature cited in Section I and the performance report of the commercial SINS used in this project, the cumu-

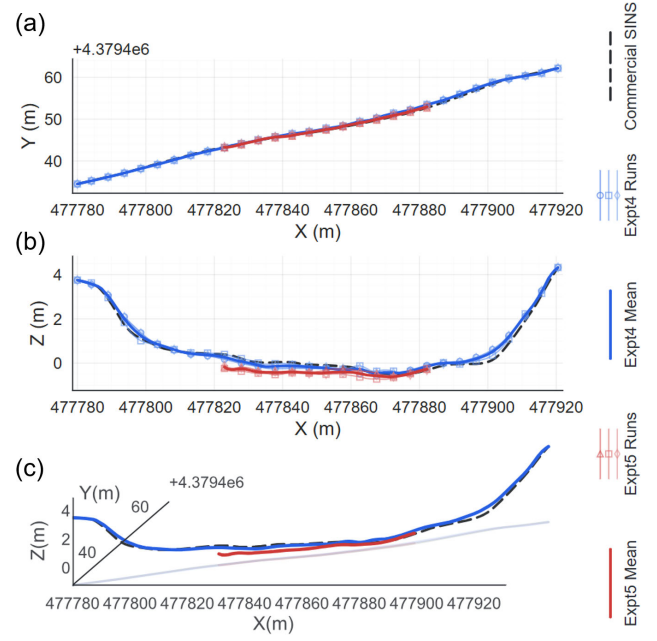


Fig. 13. Reference trajectory and the mean trajectories obtained from three repeated runs in Expt. 4 and Expt. 5. (a) X-Y projection. (b) X-Z projection. (c) 3-D projected view.

lative positioning error is typically about 0.1%–0.2% of the traveled distance. For the approximately 140-m pipeline tested here, this corresponds to an uncertainty of about 0.14–0.28 m, i.e., about 0.2 m and still at a submeter level suitable for excavation collision avoidance and is about 1/3 the errors of the proposed method. Accordingly, the comparisons reported below are described as deviations relative to the commercial SINS reference trajectory rather than strict ground-truth errors.

The setup for Expt. 4 is illustrated in Fig. 11(a). Two sets of phase-synchronized base stations (60×40 m and 70×30 m) were deployed to cover the entire line. The pipeline was located approximately 5.5 m outside the wire loops. A 16-mm^2 wire was employed and injected with an ELF current peak-to-peak value of 240 A at 40 Hz. An RTK system was used to measure the WGS84 world coordinates of the wire loops, based on which the magnetic field distribution beneath the wire was calculated. To achieve nondestructive in-service measurement of gas pipelines, the SD was launched and retrieved through 18-mm diameter purge valves. At the retrieval point, a specialized retrieval device captured the SD using a net. Photographs of the launching and retrieval process are presented in Fig. 11(b) and (c).

Then, Wire 2 was removed, and Wire 1 was shifted such that the projection of the first half of the pipeline on the horizontal plane lay within the interior of the rectangular wire loop. The relative position between the rectangular wire and the pipeline is illustrated in Fig. 12. The dimensions of the rectangular wire were 70×30 m. The ELF current injected into the wire had a peak-to-peak value of 240 A and a frequency of 40 Hz.

To evaluate both localization accuracy and repeatability under field conditions, Expt. 4 and Expt. 5 were each repeated three times. Fig. 13 shows the commercial SINS reference trajectory together with the mean trajectories from the three runs under the two field configurations. In the coordinate system

TABLE II
PERFORMANCE COMPARISON OF LOCALIZATION TECHNOLOGIES

Method	Acoustic	GPR	SINS	SLAM	ELF(rotating magnet)	ELF(coils)	Proposed Method
Nondestructiveness	Yes	Yes	No	No	Yes	Yes	Yes
Long-distance drift	No	No	Yes	Yes	No	No	No
Environment Dependence	High	High	None	None	Low	Low	Low
Max Depth	1.5m ^[10]	3m ^[12]	∞	∞	1.29m ^[34]	1.6m ^[38]	>10m
Accuracy	>0.13m ^[10]	>0.04m ^[12]	0.1% ^[17]	0.8% ^[20]	0.1m ^[34]	0.1m ^[38]	0.32m

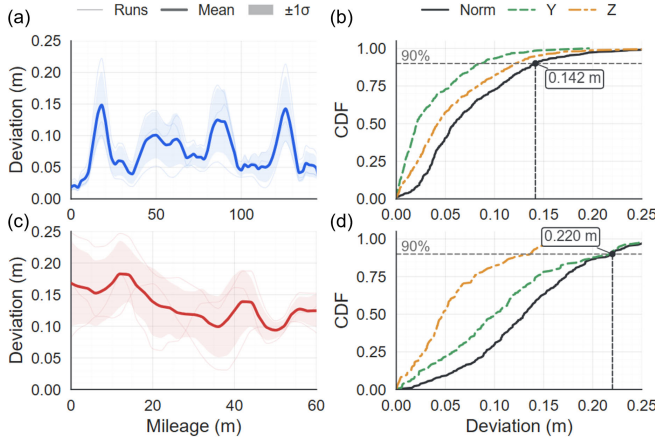


Fig. 14. Repeatability comparison of three repeated runs in Expt. 4 and Expt. 5. (a) Mileage-deviation curves and fluctuation band for Expt. 4. (b) CDF of repeatability deviation for Expt. 4. (c) Mileage-deviation curves and fluctuation band for Expt. 5. (d) CDF of repeatability deviation for Expt. 5.

defined above, the positive X -direction points east and the positive Y -direction points north. Relative to the commercial SINS reference, the mean total deviation is 0.32 m for Expt. 4 and 0.37 m for Expt. 5, with corresponding maximum deviations of 0.76 and 0.66 m relative to the commercial SINS results. Given that the reference itself has an uncertainty of about 0.2 m over the tested distance, these mean-trajectory results indicate that the proposed method achieves engineering-level localization accuracy without excavation, pipe cutting, or gas service interruption. Fig. 14 summarizes the repeatability of the three runs under each field configuration. The mean repeatability deviation is 0.07 m (90% CDF 0.14 m, maximum 0.28 m) for Expt. 4 and 0.13 m (90% CDF 0.22 m, maximum 0.28 m) for Expt. 5 relative to the commercial SINS results. The dominant fluctuations occur in the Y - and Z -directions, while variation along X remains small. These results show that repeated runs stay tightly clustered around the corresponding mean trajectories under field conditions.

A comparison between the ground validation experiments and the field experiments reveals that increasing the peak-to-peak current from 80 to 240 A results in a significant improvement in localization performance. This outcome corroborates the analytical conclusion presented in Section III: localization accuracy increases as the excitation current increases. Under both field configurations, the repeated runs

remain clustered around their respective mean trajectories, and the mean trajectories stay within submeter deviation relative to the commercial SINS reference. This indicates stable field performance under different loop-to-pipeline geometries.

VI. DISCUSSION

To achieve nondestructive localization of in-service gas pipelines, this article adopts a strategy of deploying a miniature SD through purge valves, working in conjunction with a ground ELF magnetic base station. Since the in-pipe SD is constrained to carry compact, commonly used MEMS magnetometers with limited precision, a breakthrough must instead be sought in the deployment of the ground magnetic base station. The universal scaling law for localization uncertainty in (12) provides the key guidance for this design choice.

First, by employing a large-scale rectangular wire loop, the pipeline segment under test is kept within the magnetic “near-field” region. This reduces the attenuation rate of the magnetic field gradient from $1/R^4$ in the traditional magnetic dipole model to $1/R^2$, thereby significantly extending the detectable depth.

Second, a high-current magnetic base station capable of outputting a peak-to-peak current of 260 A is developed and used to ensure that the system maintains a sufficient signal-to-noise ratio margin even in deep-burial scenarios. Given the favorable $1/R^2$ scaling and the precision margin demonstrated here, the method shows potential for submeter localization at greater depths when stronger excitation currents and stacked wire-loop stations are available, rather than proving such performance unconditionally at 10 m or beyond.

Third, it should be noted that the objective function in (1a) is evaluated directly against the absolute magnetic field map in the world frame, which serves as the primary anchor for position estimation at each time step. By contrast, the previous estimate introduced in (1c)–(1e) is used only to constrain the local search region and reject remote pseudosolutions caused by field ambiguity, rather than to propagate position through time integration. Therefore, unlike SINS-type methods, the proposed method does not exhibit continuously diverging cumulative drift as its dominant error mode over travel distance. Furthermore, the incorporation of multiple kinematic constraints has demonstrated strong robustness in eliminating multiple solutions arising from magnetic field matching, enabling effective localization with a single wire loop station.

Fourth, the proposed method exhibits excellent resistance to magnetic and electromagnetic interference. Based on the quasistatic electromagnetic field attenuation theoretical formulas, when a 40-Hz electromagnetic field propagates in dry and very wet soil whose conductivity is 0.001 and 0.04 S/m, 1% attenuation occurs at 25.31 and 4.00 m. The ELF magnetic field emitted by ground magnetic base stations is not shielded by soil. Therefore, for a 4.5-m burial depth in the experiment, geometric distance dominates over soil absorption under rain-free conditions. By extracting the specific 40-Hz magnetic component of the magnetic station, the system is inherently immune to static background magnetic interference caused by buried iron or steel targets in common urban areas.

To objectively evaluate the performance of the proposed method, Table II compares it with current mainstream non-metallic pipeline localization technologies. The proposed solution, comprising a ground-based large-loop ELF magnetic base station and an in-pipe miniature SD, not only addresses the challenge of in-service localization for PE gas pipelines but also extends its applicability to PVC water supply pipes, concrete drainage pipes, and various industrial nonmetallic transport pipelines. Provided that these pipelines possess miniature access points analogous to purge valves, fire hydrants, or maintenance manholes, the nondestructive deployment and retrieval of the miniature SD can be realized. By leveraging the superior soil penetration capability of ELF magnetic fields and the absolute-map-based matching algorithm that avoids long-distance inertial drift as the dominant error source, the proposed system overcomes the physical limitations imposed by the nonmagnetic and nonconductive characteristics of nonmetallic materials. In practical deployment, the ground loop need not remain a perfect rectangle because (2) is evaluated from discretized wire segments; irregular polygonal layouts can also be modeled as long as the coordinates of wire vertices are accurately measured, for example by RTK. This flexibility allows the loop to bypass buildings, landscaped areas, or roadside obstacles, and the nondestructive nature of the method further permits off-peak or nighttime deployment to reduce interference with urban traffic. Consequently, it establishes a novel technical foundation for the digital mapping and safe operation and maintenance of urban underground PE pipeline infrastructure.

VII. CONCLUSION

Unlike previous studies that emphasize localization accuracy alone, this work addresses both in-service deployability and submeter precision for deep-buried PE gas pipelines. A 17-mm miniature SD and a high-current ELF magnetic base station with a peak-to-peak output of 260 A were developed and deployed without pipe cutting or service interruption. The proposed Biot-Savart-based magnetic matching algorithm combines absolute-map matching with multiple kinematic constraints to suppress field ambiguity, without relying on long-distance inertial recursion as the primary localization mechanism. The scaling analysis shows that higher excitation current and large wire loops that keep the target segment in the magnetic near-field region are effective ways to improve localization accuracy for deep-buried pipelines. Field experiments on a 140-m PE pipeline buried at about 4.5 m show

mean-trajectory deviations of 0.32 m relative to a commercial SINS reference, with corresponding maximum deviations of 0.76 m and corresponding mean repeatability deviations of 0.07 m across three repeated runs. These results demonstrate the practical value of the proposed method for excavation collision avoidance and digital management of urban PE pipeline networks.

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