Study of Pipeline Robot’s Localization Technology Based on Ultra-Low Frequency Electromagnetic Wave

H M Qi, H J Chen, X H Zhang, Y N Zhao and Y B Guo
Department of Electrical Engineering and Automation, Harbin Institute of Technology, Harbin, Heilongjiang, 150001, China
E-mail: qhm0318@126.com

Abstract. Aimed at the various problems existing in the process of pipeline transportation for seabed petroleum, many kinds of pipeline robots are used in the pipe’s scheduled detection and maintenance. This paper mainly presents an effective tracing and localization technology for robots inside pipe based on ultra-low frequency electromagnetic wave. Magnetic dipole transmitting model and double-peak & single valley localization model are built. This method can solve the weakness in traditional technique, for example, harmful radiation, finite energy, signal shielding and cable winding etc. The localization accuracy and error are also analyzed in the paper. At last, this technique is verified by practical application.

1. Introduction
Now seabed petroleum is mainly conveyed by pipelines buried under seawater, and pipe-robot plays an important role in the process of pipe defect inspection. The localization robot outside is the key technology during its practical application. At present, counter wheel, CCD optical technology, static magnetic field, and radiation are the main localization method. X-ray based pipe-robot has been used in welding line defect inspection [1, 2]. JME Company has produced creeping plant JME10/60, driven by engine. It uses isotope 137Cs and ray-receiver to realize localization in the pipe for robot itself. Operator controls its action outside, and it can reach a long distance without cable. However, the engine will fail when it reaches the deep area of pipe for lack of oxygen. Zongquan Deng developed an X-ray robot with CCD sensor and inner power [3], but it needs cable to communicate with outside. And its position is also unknown to operator outside.

This paper presents a remote localization strategy by means of Ultra-Low Frequency (ULF) electromagnetic wave (23HZ) as communication medium, which is powerful in penetration capacity through metal, soil and seawater. This method can avoid damages to sea ecological environment and human body, and resolves the shielding problem for usual electromagnetic wave in metal pipe. And it also realizes the robot’s wireless working mode, which improves its working distance.

Based on the transmission character of ULF electromagnetic wave, a magnetic-dipole model is developed [4], and its distribution regularity along the pipeline is numerically analyzed. Consequently, a Double-Peak & Valley (DP&V) localization method is presented based on this character. Electromagnetic signal is received by antenna array which is equidistant in space, and the position information is derived from data fusion of multi-sensors. Prior-Database and Constraint Satisfaction

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methods are applied in localization algorithm. The way of choosing the interval between two antennas is studied, and an error-compensation method is presented to improve the localization accuracy.

2. Magnetic-dipole model
Definition: As shown in Figure 1, a thin lead cirque, with radius \( a(a << \lambda) \), \( \lambda \) is the wavelength), and carrying alternating current \( i = I_m \cos(\omega t + \phi) \). If the perimeter of cirque is far less than the wavelength, it can be considered that current at any part of the cirque has the same amplitude and phase. Then we call the cirque magnetic dipole.

![Figure 1. Magnetic dipole model.](image1)

From magnetic potential’s vector expression [5]

\[
A(r) = \frac{\mu I}{4\pi} \frac{e^{-jk\rho}}{R} \frac{d\rho}{\rho} = \frac{\mu I}{4\pi} \frac{e^{-jk|\rho-\rho'|}}{|\rho-\rho'|} d\rho'
\]

And \( H = \nabla \times A \), we can get the distribution of magnetic dipole’s magnetic field as

\[
H_r = \frac{IS}{2\pi} \cos\theta \left( \frac{1}{r^3} + \frac{jk}{r^2} \right) e^{-jkr}
\]

\[
H_\theta = \frac{IS}{2\pi} \sin\theta \left( \frac{1}{r^3} + \frac{jk}{r^2} - \frac{k_r}{r} \right) e^{-jkr}
\]

\[
H_\phi = 0
\]

Where \( I = I_m e^{j\phi} \), \( S = \pi a^2 \), \( k = 2\pi / \lambda \). Only consider the near magnetic field region \( (k_r<<1) \), and decompose the sphere-coordinate. Then the magnetic intensity in \( z \) direction \( (|H_z| \sin\theta - |H_0| \cos\theta) \) should be expressed as

\[
H_z = \frac{I_m S}{4\pi} \frac{3xz}{(x^2 + z^2)^{3/2}}
\]  

As shown in Figure 2, transmission antenna can be seen as combination of infinite magnetic dipoles in \( x \) direction. So, the magnetic intensity in \( y \) direction is the coactions of all magnetic dipoles. It can be expressed as

\[
H_z = \sum_i H_{zi} = \int L/2_{-L/2} H_{zi} dl = K \left( \left( x^2 - Lx + L^2 / 4 + z^2 \right)^{-3/2} - \left( x^2 + Lx + L^2 / 4 + z^2 \right)^{-3/2} \right)
\]

where \( K = zI_m S / 4\pi \). If we only consider the absolute amplitude of \( H_z \), the relation between \( |H_z| \) and \( x \) is shown in Figure 3.
3. Localization model of antenna array

Fix the transmission antenna, and keep it normal to the receiver. Figure 4 shows the system’s working environment. Transmission antenna is inside the pipe, and the receiving ones are outside, just overhead the pipe. When the car is pushed from one end of the pipe to the other, the relation curve between $|H_z|$ and $x$ is emerged, that is double peak and single valley (DP&V). From the curve, it is known that the pipe robot will be searched outside. We can use single receiving antenna, move along the pipe, get the whole curve, and then find the point with the lowest signal value. It is seen that this method is low efficiency and accuracy. So the paper presents a three-equidistant-antenna receiving mode to improve.

3.1. Localization algorithm

3.1.1. Prior-Database. Prior-Database is also called look-up-in-table (LUT). Before localization, get the necessary information, including contain position, signal amplitude for the three receivers, and sampling interval $\Delta d$. The practical curve is shown in Figure 5. These samplings are taken as the reference of localization. As the curve is DP&V distribution, one signal value corresponds to more position. This phenomenon leads to position redundancy problem. How to select the correct position is the key technology, and it is also the reason that three receiving antennas are applied.

![Figure 3](image3.png)  
**Figure 3.** The relation curve between $|H_z|$ and $x$.

![Figure 4](image4.png)  
**Figure 4.** System’s working process.

![Figure 5](image5.png)  
**Figure 5.** Practical DP&V curve.
3.1.2. CSP algorithm. CSP algorithm is simple and suitable for solving nonparametric problem [6]. In this system, permeability of pipe wall and magnetic interference of surroundings are unknown. So, the distribution equation (4) can’t be used directly. However, there are some constraint relations among the system. For example, the antenna interval is constant, that is
\[
\begin{align*}
    x_2 - x_1 &= d \pm \hat{\delta}d \\
    x_3 - x_2 &= d \pm \hat{\delta}d \\
    x_3 - x_1 &= 2(d \pm \hat{\delta}d)
\end{align*}
\]
(5)

Where, \(x_1, x_2, x_3\) are the LUT results for three receiving systems, and \(\hat{\delta}d\) is the position error produced from magnetic interference.

Define the characteristic matrix for antenna \(S_n\), \((n=1,2,3)\) as
\[
M_n = \begin{bmatrix}
    x_n^0 & x_n^1 & x_n^0 & x_n^0 \\
    x_n^1 & x_n^1 & x_n^1 & x_n^0 \\
    x_n^2 & x_n^2 & x_n^2 & x_n^2 \\
    x_n^3 & x_n^3 & x_n^3 & x_n^3
\end{bmatrix}
\]
(6)

Where \(x_n^0, x_n^1, x_n^2, x_n^3\) are the LUT results for \(S_n\). Notice, if the number of LUT results is less than four, just fill with zero. And error matrix is defined as
\[
\hat{D}_{mn} = D_{mn} - M_n^T = \{d_{ij}\}_{i,j=\{1,2,3,4\}}, m,n = \{1,2,3\}, m > n
\]
(7)

Then normalize error matrix \(D_{mn}\) to \(A_{mn}\) as followed,
\[
a_{ij} = \begin{cases} 
    0 & d_{ij} \notin (m-n)\left[d - \hat{\delta}d, d + \hat{\delta}d\right] \\
    1 & d_{ij} \in (m-n)\left[d - \hat{\delta}d, d + \hat{\delta}d\right]
\end{cases}
\]
(8)

Where \(d_{ij}\) is the element of \(D_{mn}\), and \(a_{ij}\) is the element of \(A_{mn}\).

So, the position \((x_1^i, x_2^j, x_3^k)\) selected from \((x_1^0, x_1^1, x_1^2, x_1^3), (x_2^0, x_2^1, x_2^2, x_2^3), (x_3^0, x_3^1, x_3^2, x_3^3)\) is the correct position for pipe robot, if only the constraint condition is satisfied as (9).
\[
\begin{align*}
    a_{ij} &= 1, \quad a \in A_{S_1} \\
    a_{ij} &= 1, \quad a \in A_{S_2} \\
    a_{ij} &= 1, \quad a \in A_{S_3}
\end{align*}
\]
(9)

Then the distance between receiver and transmission antenna can be expressed as \(x=(x_1^i+x_2^j+x_3^k)/3\).

3.2. Localization error analysis

3.2.1. Selection of \(\hat{\delta}d\). As \(\hat{\delta}d\) plays an important role in the process of localization, the localization accuracy is improved with small error when \(\hat{\delta}d\) is small, but it is sensitive to the magnetic interference. However, if \(\hat{\delta}d\) is large, then system has a low localization accuracy, and position redundancy problem may be produced, for error allowance domain is also large. \(\hat{\delta}d\) is consists of two parts:
- \(\hat{\delta}d_1\), produced in LUT. As the sampling interval is \(\Delta d\), and interpolation method is applied in LUT, then position error may be brought in this process, and \(\hat{\delta}d_{1\text{max}}=\Delta d/2\).
- \(\hat{\delta}d_2\), produced by magnetic interference. An interference with amplitude \(dv\) will produce position error \(\hat{\delta}d_2\). And it is known that \(\hat{\delta}d_{2\text{max}}=K\cdot\Delta v\), where \(1/K\) is the slope coefficient of the gentle part on the curve. \(\Delta v\) is the maximum error of signal value, among data samplings of many times, in the same position.

Then, we can get \(\hat{\delta}d=\hat{\delta}d_1+\hat{\delta}d_2=\Delta d/2+K\cdot\Delta v\).

3.2.2. Determine the antenna interval \(d\). Three-antenna mode is presented to solve the weakness in single antenna mode, but it also brings position redundancy problem. The error compensation method
can help to solve this problem. But it is not sufficient. Antenna interval \( d \) also infects the localization result. It is clear that, if \( d \) is small, three antennas will get little information. Then it is adverse for position selection. Usually, we select \( \Delta d / d \leq 15\% \), namely \( d \geq 15\Delta d \).

4. Experiment results

In the experiment, the antenna interval is 80cm, and the distance between receiver and transmitting antenna is 160cm. The length of pipe is 300cm, and the pipe is 9mm in thickness. The sampling interval is 5cm, and 5 groups of data are collected as reference. Then \( \Delta v = 0.05 \cdot K = (x_1 - x_2) / (v_1 - v_2) = 124.8 \text{cm} / \text{s} \), and \( \Delta d = \Delta d / 2 + K \cdot \Delta v = 8.7 \text{cm} \). Signals are transmitted to PC with an ART USB 2000A collection card, and the localization algorithm is programmed with Borland C++ Builder language. Table 1 shows the practical position, the calculating position, and localization error. It can be seen that both the localization error and the fault probability is reasonable for application.

| Group | Practical position (cm) | Calculated position (cm) | Error (cm) |
|-------|------------------------|--------------------------|------------|
| 1     | 7                      | 87                       | 167        |
| 2     | 27                     | 107                      | 187        |
| 3     | 34                     | 114                      | 194        |
| 4     | 42                     | 122                      | 202        |
| 5     | 62                     | 142                      | 222        |
| 6     | 98                     | 178                      | 258        |
| 7     | 122                    | 202                      | 282        |
| 8     | 157                    | 237                      | 317        |

5. Conclusion

This paper presents a magnetic dipole distribution model and a DP&V localization model. Prior-Database algorithm and CSP algorithm are applied to select the only position that satisfies the constraint conditions. The experiment results show that the localization accuracy is suitable for the pipeline robot application.

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