

A New Magnetic Model for Distinguishing Between UXO and Non-UXO

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Abstract—The traditional magnetic measurement method is based on the magnetic dipole model that is a point model, and the shape information of the target cannot be determined, resulting in high false alarm rate and low detection efficiency. In this paper, a magnetic multi-order pole expansion model is proposed, target recognition is based on the relationship between the magnetic quadrupole field and the symmetry of the target. In addition, the Euler deconvolution method can be used to determine the decay rate of the magnetic poles of each order and realize the separation of magnetic anomalies of different polar poles from the total magnetic field. A numerical simulation experiment based on the Ansoft Maxwell software verifies that the algorithm can effectively distinguish different targets and can be applied to the distinction between UXO and non-UXO.

Keywords—magnetic multi-order pole expansion; euler deconvolution; levenberg marquardt optimization; target recognition; magnetic detection

I. INTRODUCTION

Whether it is war years or peaceful times, unexploded ordnance (UXO) has potential harm to human survival [1]-[2], [6]. The detection methods for UXO mainly include magnetic method, electromagnetic method, and ground penetrating radar. The magnetic measurement is a passive detection method, which has the advantages of good concealment, low cost and fast detection. However, how to distinguish between UXO and non-UXO (magnetic clutter, underground pipeline, debris) targets is one of the key issues in magnetic measurement technology [1], [3]. The traditional point-like magnetic dipole model is based on the fact that when the detection distance is greater than three times the target, the abnormal target is considered as a point with three-component magnetic moment, ignoring the shape information, resulting in the traditional method unable to distinguish the shape feature of the target and increasing the false alarm rate.

To approach this dearth of distinguishing between UXO and clutter, the work of this paper is to extend the traditional pointlike magnetic dipole model, and build a complex high-order magnetic pole model to simulate anomalous targets, combined with the characteristics of the high-order magnetic moment, determining the shape information of the target. The magnetic anomaly field generated by any abnormal target is equivalent to the superposition of magnetic fields generated by magnetic order poles (n=1, magnetic dipole; n=2, magnetic quadrupole; n=3, magnetic octapole, n=4, magnetic hexadecapole; ...). The magnitude of the magnetic moment of each order is related to the material, shape, and posture of the target. In particular, when the shape of the target has a three-axis (x, y, z) symmetry, the magnetic moments of the magnetic quadrupoles are all zero. For UXO, its shape is generally a cylinder or a spheroid, which can be approximated as a three-axis symmetric target, so its corresponding fourth-order pole is zero; on the other hand, for non-UXO, the shape is generally irregular, and its fourth-order pole is not zero. According to this, the distinction between UXO and fragmentation targets can be achieved by the high-order magnetic pole model.

II. METHOLOGY

This section presents the target recognition algorithm using the multipole model, including the following three parts, the multi-order pole expansion model, the various pole magnetic field separation method and the target recognition process.

A. Multi-order Pole Expansion Model

An anomalous target produces the magnetic anomaly field under the magnetization of the earth's magnetic field, which can be approximated by magnetic multi-order pole filed, i.e. "magnetic dipole field + magnetic quadrupole field + magnetic octapole field +... +Magnetic high-order polar field". Considering that the high-order polar field is attenuated with distance severely, higher-order polar fields above magnetic octapole field can be ignored. That is, the abnormal field generated by any target is equivalent to the sum of the magnetic dipole field, the magnetic quadrupole field and the magnetic octapole field.

The magnetic moment and magnetic field corresponding to each order of poles are calculated as follows:

The magnetic moment of dipole (n=1):

$$m_{\alpha}^{(1)} = \int_{S'} x_{\alpha}' \vec{M} \cdot d\vec{s'}$$
(1)

The magnetic moment of quadrupole (n=2):

$$m_{\alpha\beta}^{(2)} = \int_{S'} x'_{\alpha} x'_{\beta} \vec{M} \cdot d\vec{s'}$$
(2)

The magnetic moment of octapole (n=3):



$$m_{\alpha\beta\gamma}^{(3)} = \int_{S'} x'_{\alpha} x'_{\beta} x'_{\gamma} \vec{M} \cdot d\vec{s'}$$
(3)

The magnetic potential of magnetic poles (n = 1, 2, 3, ...):

$$\phi^{(2^n)} = \frac{m^{(n)}_{\alpha\beta\dots}}{4\pi n!} \frac{\partial^n}{\partial x'_\alpha \partial x'_{\beta\dots}} \left(\frac{1}{r''}\right) \tag{4}$$

The magnetic anomaly field of magnetic poles (n=1, 2, 3, ...):

$$B^{(2^n)} = -\nabla \phi^{(2^n)}$$
(5)

A special case where the magnetic quadrupolar (n=2) moment is an all-zero second-order tensor if the target having three-axis symmetry.

B. The Spearation of Magnetic Field

In the actual measurement, the scalar or vector magnetic sensor can be used to measure the total magnetic field in a point. Separating the anomalous fields of each order from the total magnetic field is based on the different decay rate with distance. The magnetic dipole field decays with the cubic of the distance, the magnetic quadrupole field attenuates with the fourth power of the distance, and the magnetic octapole field decays with the fifth power of the distance. The attenuation coefficient of the magnetic anomaly field can be determined by the Euler deconvolution method.

The measured height is h1 (h1 > 3L, L is the maximum size of the target), and the magnetic field at each point in space is d_{h1}^{obs} . Since the magnetic anomaly of high-order poles decays fast, the total magnetic field at h1is generated by magnetic dipole only, using traditional magnetic dipole positioning method, position and magnetic moment of dipole is identified.

$$\min \sum_{i=1}^{N} \left| d_{h1}^{obs} - f_i (m_x, m_y, m_z, x_0, y_0, z_0) \right|^2$$

$$f_i (m_x, m_y, m_z, x_0, y_0, z_0) = \frac{\mu_0}{4\pi} \left(\frac{3(\vec{m} \cdot \vec{r})\vec{r}}{r^5} - \frac{\vec{m}}{r^3} \right)$$
(6)

Where, i=1...N denotes the samples at h1.

The measured height is h2 (h2 < 3L), and the magnetic field at each point in space is d_{h2}^{obs} . According to the dipole moment and position, B_{dip}^{h2} is the magnetic dipole field extends down to h2. The high-order polar anomaly field B_{res}^{h2} is equal to the observation field d_{h2}^{obs} . subtracts the magnetic dipole extension field B_{dip}^{h2} .

$$B_{dip}^{h2} = \frac{\mu_0}{4\pi} \left(\frac{3(\vec{m}\cdot\vec{r})\vec{r}}{r^5} - \frac{\vec{m}}{r^3} \right) B_{res}^{h2} = d_{h2}^{obs} - B_{dip}^{h2}$$
(7)

After that, the Euler deconvolution method calculates the attenuation coefficient of the high-order polar subfield [5], [7]. The attenuation coefficient is used to determine whether the high-order polar subfield is a magnetic quadrupole field or a magnetic octapole field.



FIGURE I. THE FLOW CHART OF TARGET RECOGNITION (UXO AND NON-UXO) ALGORITHM.

$$\begin{cases} f = B_{res}^{h2} \\ \frac{\partial f}{\partial x}(x - x_0) + \frac{\partial f}{\partial y}(y - y_0) + \frac{\partial f}{\partial z}(z - z_0) \\ = -Nf(x - x_0, y - y_0, z - z_0) \end{cases}$$
(8)

Where, (x,y,z) denotes the position of observation points, N denotes the attenuation coefficient of the high-order polar field.

By using the attenuation coefficient N, it can be determined that the high-order polar field is a magnetic quadrupole field or a magnetic octapole field, thereby realizing the separation of the polar fields of each order.

C. Target Recognition Process

The target process depends on the characteristics of each order pole. For a target with three-axis symmetry, such as a cylinder, a sphere, etc., any component of the magnetic quadrupole moment is zero, that is, the abnormal field generated by the magnetic quadrupole is zero. Whether the magnetic quadrupole field is zero not can determine whether the target has symmetry to achieve target shape recognition. The flow chart of the proposed algorithm is shown in Fig. 1.





FIGURE II. THE EXPERIMETN TEST SCENARIO



FIGURE III. THE MAGNETIC ANOMALY FIELD AT H1=0.4 M (UNIT: NT)

III. NUMERICAL EXPERIMENT

The experimental scene is illustrated in the Fig. 2. A cylindrical hollow steel tube target generates an abnormal field under the magnetization of the earth's magnetic field. The earth's magnetic field has a modulus of 55000 nT with geomagnetic inclination 55°, and geomagnetic declination of 5°. The cylindrical steel tube is 20 cm in diameter and 80 cm in length, simulating the UXO target. The magnetic field is measured at different heights by the Ansoft Maxwell.

Based on the magnetic field data at a height of 4 m, given in Fig. 3., the target position and dipole moment are inverted by the Levenberg Marquardt algorithm [4]. The results are as follows:

$$\vec{m} = (m_x, m_y, m_z) = (0.7036, 0.0615, 4.1065)Am^2$$

 $\vec{r} = (x_0, y_0, z_0) = (0.0001, 0.0001, 0.29999)m$



FIGURE IV. THE SEPARATION OF EACH POLES MAGNETIC FIELD

The magnetic dipole field (five lines) is extended down to H2 = 0.5 m, and the magnetic dipole anomaly field at H2 = 0.5 m is presented in Fig. 4 (b). Therefore, the magnetic higher order polar field (five lines) at H2 = 0.5m is determined by subtracting the magnetic dipole extension field from the observation field, and the result is shown in Fig. 4 (d).

Within the entire measurement range (H2 = 0.5 m), the attenuation coefficient N of the magnetic higher order polar field is identified by the Euler deconvolution method in Fig. 5. The attenuation coefficient fluctuates around 4.8, indicating that the high-order polar field is the magnetic octapole field. The magnetic quadrupole field is zero, and the target has three-axis symmetry, which can be considered as a UXO.

- (A) THE DIPOLE MAGNETIC FIELD AT H1=0.4 M.
- (B) THE DIPOLE FIELD DOWNWARD EXTENSION TO H2=0.5 M.
- (C) THE TOTAL ANOMALY FIELD AT H2=0.5 M.
- (D) THE RESIDUAL HIGH-ORDER POLAR MAGNETIC FIELD AT H2=0.5 M.



FIGURE V. THE ATTENUATIOIN COEFFICIENT N OF HIGH-ORDER POLAR FIELD



IV. CONCLUSION

The model proposed in this paper extends the traditional magnetic dipole model to the multi-order pole expansion model. The magnetic field produced by an anomalous body equals to the superposition of anomalous fields generated by the magnetic dipole, the magnetic quadrupole, and the magnetic octapole. Based on the relationship between the magnetic quadrupole field and the target symmetry, the shape characteristics of the target can be determined, realizing the distinction between UXO and non-UXO. This target recognition algorithm fills the gap that the traditional magnetic measurement cannot distinguish the target shape.

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