Letter

Underwater Cable Localization Method Based on Beetle Swarm Optimization Algorithm

Wenchao Huang, Zhijun Pan, and Zhezhuang Xu

Dear Editor,

This letter concerns the localization of three-core underwater cables which are widely deployed for offshore energy transmission. It is a non-trivial problem, since the external magnetic field of three-core underwater cables is variable which reduces the accuracy of localization. To solve this problem, in this letter, an approximate equation is firstly derived to formulate the external magnetic field of a three-core armored underwater cable by considering the seafloor environments and the structure of three-core cables. Then, a new underwater cable localization method is proposed based on dual three-axis magnetic sensor array and the beetle swarm optimization (BSO) algorithm. The method constructs a fitness function based on the magnetic flux density amplitude and replaces the existing analytical geometry method with an optimization algorithm to achieve underwater cable localization with higher accuracy.

With the rapid development of the offshore wind power industry, the maintenance of underwater cables becomes important in offshore energy transmission [1], [2]. The underwater cable works in a complex environment, and its location can be changed by water flows and underwater geological activity. Therefore, it is difficult to locate the underwater cable during the maintenance [3]–[5]. To reduce the loss caused by underwater cable downtime, it is important to localize the cables and update their location with high efficiency.

Some research works have been proposed for the underwater cable localization, including acoustic, optical, and magnetic based methods [6]–[9]. The performance of acoustic methods [6] is unreliable with the impacts of sediments and complex seafloor environments. Optical methods require higher quality images of underwater cables in the actual underwater environment. Nevertheless, underwater cables may be buried and underwater photography is susceptible to water quality, currents and other factors [7].

Magnetic based methods are popular for underwater cable localization due to their high efficiency and low cost [8], [9]. The method proposed in [8] achieves cable localization by repeatedly moving a three-axis magnetic sensor over the cable to find the peak point or slotting point, which is easy to implement with low cost. To improve the efficiency of localization, the methods based on dual three-axis magnetic sensor array are proposed in [9]. It resolves the location of the underwater cable based on the magnetic components detected by each sensor and the geometry of the array.

In this letter, we consider the localization of three-core underwater cables which are widely deployed for offshore energy transmission. The external magnetic field of three-core underwater cables is variable due to three-phase currents and the complex structure of the cable. To the best of our knowledge, the existing magnetic based methods have not considered these characteristics in the cable localization, and thus can not provide sufficient localization accuracy in three-core underwater cable localization.

To solve this problem, this letter proposes a new method for localizing three-core underwater cables. The main contributions of this letter include: 1) An approximate equation is derived to formulate the external magnetic field of a three-core armored underwater cable by considering the structure of cables, such as the armor layer and the shielding layer. 2) We propose an underwater cable localization method based on dual three-axis magnetic sensor array and the BSO algorithm. The method constructs a fitness function based on the magnetic flux density amplitude and then obtain the location of the cable with an optimization algorithm. Theoretical analysis is provided to prove the effectiveness of the proposed method, and experimental results also prove that the proposed method has higher localization accuracy compared with the existing method.

Modeling the magnetic field of three-core underwater cable: The formula for the external magnetic flux density of three-phase lines with the same phase-to-phase distance and balanced three-phase currents has been presented in [10], [11]. Three-core underwater cable meets the above requirements, but there are structures such as lead sheath and armor layer besides the conductor, as shown in Fig. 1. These structures have a magnetic shielding effect, which makes the external magnetic field of the three-core underwater cable smaller than that generated by the three conductors.

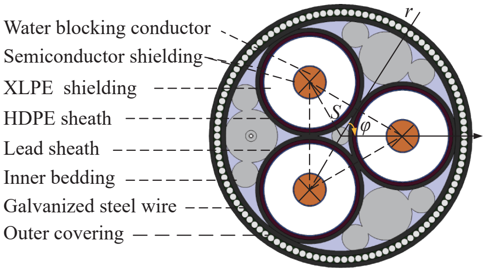


Fig. 1. The structure of the three-core underwater cable.

Therefore, we propose an approximate formula for the external magnetic flux density of three-core underwater cables based on [10]. As shown in Fig. 1, if we choose the center of the underwater cable as the origin of the polar coordinate system. The amplitude B of the magnetic flux density at an angle φ with the horizontal axis, at a distance r from the origin, can be expressed as

$$B(r)=\frac{3M\mu I}{2\sqrt{2}\pi}\sqrt{\frac{s^4+s^2r^2}{r^6-2s^3r^3\cos(3\varphi)+s^6}}+c \tag{1}$$

where μ is the vacuum permeability. I is the amplitude of the conductor current. s is the distance from each phase to the center. M, c are two correction factors, which are obtained by curve fitting. In this paper, $M=0.745$, $c=-1.0\times10^{-8}$.

To verify the accuracy of this model, we simulated the external magnetic field of a common 220 kV underwater cable in COMSOL. As shown in Fig. 2, the results obtained by (1) are very close to the simulation results. For comparison, Fig. 2(c) plots the variation of magnetic flux density with the horizontal distance between the measured point and the cable, at a certain height Y above the cable. Compared with the equation described in [10], (1) is more applicable to calculate the external flux density of a three-core underwater cable.

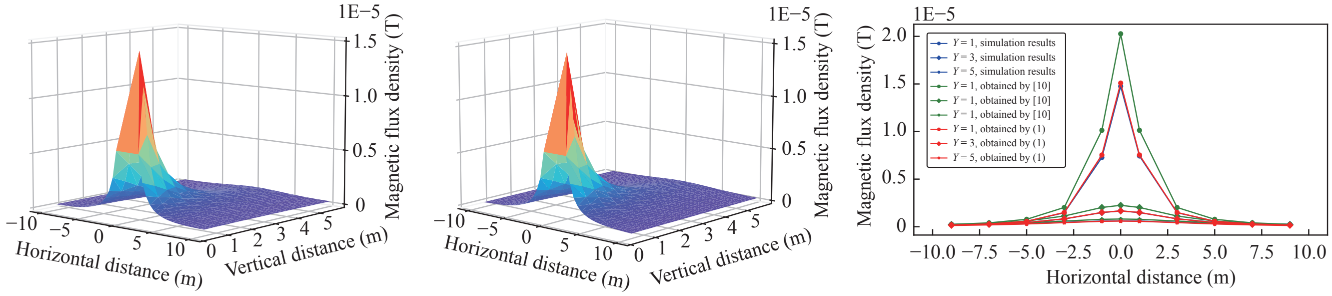
Underwater cable localization method based on BSO algorithm: The underwater cable's external magnetic field frequency is correlated with the current frequency it loads, which allows us to filter the signal of the underwater cable from the marine environment with filtering and spectral analysis. With the above magnetic field analysis, we designed a localization method using an underwater robot with a dual three-axis magnetic sensor array, as shown in Fig. 3. According to the magnetic component relationship sensed by the horizontal axial sensor, the robot's heading can be adjusted so that the robot moves along the direction of the underwater cable. The robot will execute the localization algorithm at fixed intervals. According to Ampere's law, the magnetic signal of the underwater cable detected by the two sensors comes from the small section of the cable in the vertical plane (i.e., the effective detection plane in Fig. 3).

Corresponding author: Zhezhuang Xu.

Citation: W. C. Huang, Z. J. Pan, and Z. Z. Xu, "Underwater cable localization method based on beetle swarm optimization algorithm," *IEEE/CAA J. Autom. Sinica*, vol. 10, no. 9, pp. 1893–1895, Sept. 2023.

The authors are with the College of Electrical Engineering and Automation, Fuzhou University, Fuzhou 350108, China (e-mail: ehwenc@fzu.edu.cn; zhijun.pan@foxmail.com; zzxu@fzu.edu.cn).

Digital Object Identifier 10.1109/JAS.2022.106073



(a) Simulation results (b) The results of (1) (c) Projection of magnetic flux density in the *x*-*z* plane

Fig. 2. Comparison of magnetic field models.

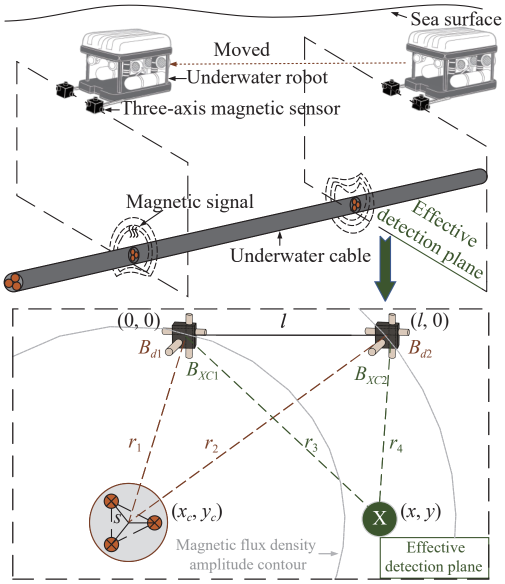


Fig. 3. The underwater cable location method.

Therefore, we can explore the problem of localizing underwater cables in the two-dimensional plane.

Assumption 1: The structure and current-carrying capacity of the underwater cable are known and the cable is located under the array. The two sensors of the array are horizontal. The distance r between the underwater cable and the sensor satisfies $r >> s$.

The description of Assumption 1 can be seen in Fig. 3. In general, the underwater cable is laid on the seabed and s is very small usually only a few centimeters. Thus, Assumption 1 is easily satisfied.

Theorem 1: Under Assumption 1, suppose $X_c(x_c, y_c)$ is the actual coordinate point of the underwater cable and $X(x, y)$ is arbitrary point in the effective detection plane of the array, the magnetic flux density amplitude of X_c and X at the two sensors are B_{d1}, B_{d2} and B_{XC1}, B_{XC2}, respectively. Let

$$f(X) = \sqrt{(B_{XC1} - B_{d1})^2 + (B_{XC2} - B_{d2})^2} \tag{2}$$

then, the coordinates of X_c and X satisfies $X \to X_c$, if $f(X) \to 0$.

Proof: Set the coordinates of the two sensors as $(0, 0)$ and $(l, 0)$ respectively. According to Assumption 1, the coordinate of $X_c(x_c, y_c)$ is below the sensors. By $r >> s$, the approximate expression of (1) can be formulated as

$$B(r) = \frac{3M\mu I}{2\sqrt{2}\pi} \cdot \frac{s}{r^2} + c. \tag{3}$$

From (3), we have

$$B_{d1} = B(\sqrt{x_c^2 + y_c^2}), \ \ B_{d2} = B(\sqrt{(l - x_c)^2 + y_c^2})$$

$$B_{XC1} = B(\sqrt{x^2 + y^2}), \ \ B_{XC2} = B(\sqrt{(l - x)^2 + y^2}).$$

If $B_{XC1} \to B_{d1}$ and $B_{XC2} \to B_{d2}$ can be simultaneously met, it is easy to obtain that $x \to x_c$, $y \to y_c$ or $x \to x_c$, $y \to -y_c$. Since the point $(x_c, -y_c)$ is above the sensors, which violates the condition of Assumption 1, it means $x \to x_c$, $y \to -y_c$ is impossible. Furthermore, $B_{XC1} \to B_{d1}$ and $B_{XC2} \to B_{d2}$ are equivalent to $f(X) \to 0$, thus, if $f(X) \to 0$, we have $X \to X_c$. ■

Remark 1: In the actual localization process, B_{d1}, B_{d2} can be detected by the sensors and B_{XC1}, B_{XC2} are calculated by proposed model. Limited by negative factors such as the measurement accuracy of the sensor, signal interference, parameters precision, errors are inevitable. Theorem 1 does not use analytical method to determine the exact coordinate of the underwater cable, but transforms the localization issue into an optimalization problem of $f(X)$, which potentially reduces the effect of calculation accuracy.

Based on the above analysis, we can localize the underwater cable by finding the point in the effective detection plane that minimizes (2). In this letter, we use the BSO algorithm to achieve the objective.

The BSO algorithm introduces a tentacle search mechanism, which reduces the probability of the population falling into a local optimum and improves the convergence speed [12]. It is suitable for underwater cable localization problems that need to consider timeliness. If we assume that there are several hypothetical underwater cable locations within the effective detection range of the sensor array and regard them as a swarm of beetles. Regard the actual underwater cable location as food, and the food odor concentration can be characterized by (2). We can achieve underwater cable localization by imitating beetle foraging, as shown in Fig. 4. The detailed process is as follows.

1) Initialize the locations of the beetle swarm as $X = (X_1, X_2, \ldots, X_n)$. where n is the number of beetles.

2) Beetle's head orientation when detecting an unknown environment is random, and the orientation and distance of its right tentacle, relative to its left is also random, modeled as follows:

$$X_{li}^{k+1} = X_{li}^{k} - V_i^k \cdot d^k/2, \qquad X_{ri}^{k+1} = X_{ri}^{k} + V_i^k \cdot d^k/2 \tag{4}$$

where k is the current number of iterations. X_{li}^k, X_{ri}^k are the locations of the left and right tentacles of the ith beetle respectively. V_i^k is transfer speed. d^k is the distance between two tentacles. $d^k = \delta^k/a$. V_i^k modeled as follows:

$$V_i^{k+1} = \omega^k V_i^k + C_1 R_1 \left(P_i^k - X_i^k\right) + C_2 R_2 \left(P_g^k - X_i^k\right) \tag{5}$$

where δ^k indicates step size, updated by (6) to speed up the iterative process. a, C_1, C_2 are adjustable constants. R_1, R_2 are random num-

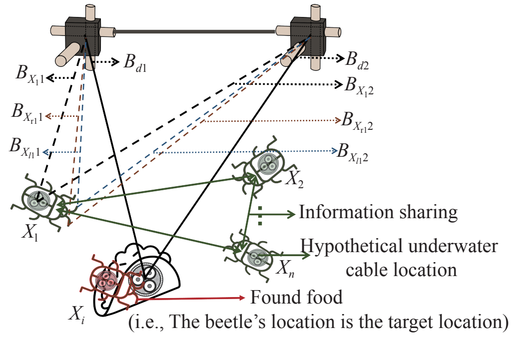


Fig. 4. Localization method based on BSO algorithm.

bers between 0 and 1. P_i^k denotes the optimal value of the current individual beetle. P_g^k denotes the group optimal value. ω^k is the current inertia weighting factor which can be obtained by (7).

$$\delta^{k+1} = \delta^k \times \eta \tag{6}$$

$$\omega^k = \omega_{\max} - (\omega_{\max} - \omega_{\min}) \cdot k/K \tag{7}$$

where η is the contraction factor. K is the maximum number of iterations. $\omega_{\max}$, $\omega_{\min}$ are the set values of the maximum and minimum inertia weights, respectively.

3) The beetle shifts its location according to the concentration of scent detected by its own left and right tentacles and the information shared by the group. The process is modeled as follows:

$$X_i^{k+1} = X_i^k + (1-\lambda)V_i^k + \lambda\xi_i^k \tag{8}$$

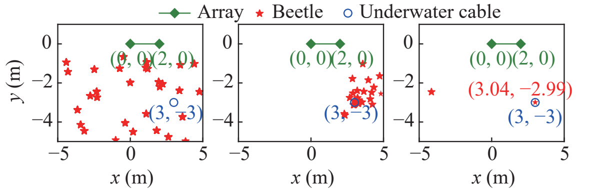
where λ is a random number between 0 and 1. ξ_i^k refers to the displacement increment of the beetle is given by the following:

$$\xi_i^k = \delta^k \cdot V_i^k \cdot \mathrm{sign}\left(f\left(X_{li}^k\right) - f\left(X_{ri}^k\right)\right) \tag{9}$$

where sign(·) is the sign function. $f\left(X_{li}^k\right)$ and $f\left(X_{ri}^k\right)$ denote the current adaptation values of the left and right tentacles of the beetle calculated by (2), respectively.

Experiment: The experiments use an Intel(R) Core (TM) i5-4200H CPU @ 2.80 GHz and Windows 10 64bit. We use Python 3.7 to realize the localization algorithm and use the underwater cable simulated in COMSOL as the localization target. The detection value of the sensor is replaced by the value simulated in COMSOL.

Firstly, to prove the effectiveness of the method, within the effective detection plane, we set the underwater cable is located on (3, −3) and the two sensors of the array are (0, 0) and (2, 0). The simulation results are shown in Fig. 5. As the iterative process of the algorithm progresses, the initial assumed underwater cable locations eventually converge to (3.04, −2.99) less than 150 iterations. The error with the actual location is less than 5 cm. The whole process runs less than 2 seconds. Then we tested the method by taking random points within the effective detection plane as the location of the underwater cable. As shown in Table 1, our method always achieves accurate underwater cable localization with an error less than 8 cm.



(a) The 0th interation (b) The 50th interation (c) The 150th interation

Fig. 5. Iterative process of the localization algorithm.

Table 1. Test Results

Underwater cable coordinates	Algorithm derived coordinates	Coordinate deviation (m) $\sqrt{\Delta x^2 + \Delta y^2}$
(−1, −4)	(−0.93, −3.98)	0.073
(1, −4)	(1.00, −3.97)	0.03
(3, −4)	(2.97, −3.97)	0.042
(0, −3)	(0.00, −3.00)	0
(2, −3)	(2.04, −3.00)	0.04
(3, −3)	(3.04, −2.99)	0.041

Secondly, assume that (0.5, −2, −3), (0.5, 0, −3.5), and (0.5, 2, −2.5) are the three coordinate points on the underwater cable. Compare the localization effect of the method proposed in this letter with the method proposed in [9]. As shown in Fig. 6, the results obtained by the method of this letter are almost identical to the set underwater cable locations, while the other one have a large error.

Simulation results show that our method has higher localization accuracy compared to the method proposed in [9]. The method resolves the location of the underwater cables based on the magnetic components sensed by each sensor and the geometry of the array itself. However, this method has large error when the magnetic field of the cable is variable. In this letter, we use the magnetic flux density magnitude as the basis for localization and use the optimization-seeking algorithm instead of the resolution method to achieve underwater cable localization, which improves the localization accuracy.

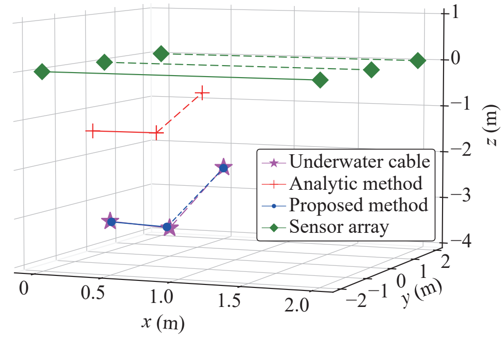


Fig. 6. Comparison of localization accuracy.

Conclusion: In this letter, an approximate equation for the external magnetic flux density of a three-core underwater cable is proposed, by considering the influence of the cable's structure. Then an underwater cable localization method based on BSO algorithm is proposed. Simulation results show that the method has higher localization accuracy compared with the existing method based on dual three-axis magnetic sensor array. With the equation proposed in this paper, the magnitude of the magnetic field around the three-core underwater cable can be calculated, which helps to evaluate its impact on the sea area it lies in. The localization method proposed in this paper is expected to shorten the maintenance time of underwater cables.

Acknowledgments: This work was supported by the National Natural Science Foundation of China (61973085).

References

[1] J.-A. Pérez-Rúa, M. Stolpe, K. Das, and N. A. Cutululis, "Global optimization of offshore wind farm collection systems," *IEEE Trans. Power Syst.*, vol. 35, no. 3, pp. 2256–2267, 2020.

[2] B. Finn, "Underwater cables," *Proc. IEEE*, vol. 101, no. 5, pp. 1253–1259, 2013.

[3] M. Bawart, M. Marzinotto, and G. Mazzanti, "Diagnosis and location of faults in submarine power cables," *IEEE Electr. Insul. Mag.*, vol. 32, no. 4, pp. 24–37, 2016.

[4] H. Zhao, J. Yan, X. Luo, and X. Guan, "Privacy preserving solution for the asynchronous localization of underwater sensor networks," *IEEE/CAA J. Autom. Sinica*, vol. 7, no. 6, pp. 1511–1527, 2020.

[5] Y. Li, B. Li, W. Yu, S. Zhu, and X. Guan, "Cooperative localization based multi-auv trajectory planning for target approaching in anchor-free environments," *IEEE Trans. Veh. Technol.*, vol. 71, no. 3, pp. 3092–3107, 2022.

[6] K. Brown, C. Capus, Y. Pailhas, Y. Petillot, and D. Lane, "The application of bioinspired sonar to cable tracking on the seafloor," *EURASIP J. Adv. Signal Process.*, vol. 2011, pp. 1–18, 2011.

[7] K. Yang, L. Yu, M. Xia, T. Xu, and W. Li, "Nonlinear ransac with crossline correction: An algorithm for vision-based curved cable detection system," *Opt. Lasers Eng.*, vol. 141, p. 106417, 2021.

[8] X. Huang, W. Wang, Z. Lv, Y. Meng, C. Yuan, and J. Feng, "Precise positioning of the underground power cable by magnetic field detectio," in *Proc. Annu. Rep. Conf. Electr. Insul. Dielectr. Phenom,* Richland, USA, Oct. 2019, pp. 702–705.

[9] X. Xiang, C. Yu, Z. Niu, and Q. Zhang, "Subsea cable tracking by autonomous underwater vehicle with magnetic sensing guidance," *Sensors*, vol. 16, no. 8, p. 1335, 2016.

[10] F. Moro and R. Turri, "Fast analytical computation of power-line magnetic fields by complex vector method," *IEEE Trans. Power Delivery*, vol. 23, no. 2, pp. 1042–1048, 2008.

[11] G. Filippopoulos and D. Tsanakas, "Analytical calculation of the magnetic field produced by electric power lines," *IEEE Trans. Power Delivery*, vol. 20, no. 2, pp. 1474–1482, 2005.

[12] T. Wang, L. Yang, and Q. Liu, "Beetle swarm optimization algorithm: Theory and application," *Filomat*, vol. 34, no. 15, pp. 5121–5137, 2020.