Improving the detection of underwater metal-containing objects by fusion of ferromagnetic sensors data with vehicle’s navigational data

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Abstract. Currently, the task of developing the Arctic shelf is relevant, because there are proven reserves of minerals – oil and gas. Undoubtedly, researchers and engineers, after installing the appropriate underwater infrastructure, will face the task of maintenance and repair of communications. For this purpose, autonomous unmanned underwater vehicles (AUV) can be used, with e.g. the task of inspecting pipelines. The article describes the processing algorithm for the signal from passive ferromagnetic sensors mounted on an AUV carrier used to search for metal-containing objects at the sea bottom. A scheme for such a measurement is proposed - the installation of two sensors at opposite ends of the carrier. This allows to measure the gradient of magnetic field between the sensors. The characteristic form of such a signal and the dependence of the signal on the motion parameters of the vehicle and external factors are determined. To eliminate false positives, filters are used based on the readings of the position, speed and orientation sensors of the navigation system. Using data on the motion parameters of the device allows to generate a reference signal, which is used to validate the detection of an object using the cross-correlation method. The use of data on orientation angles makes it possible to compensate for the influence of the orientation of the device in the Earth’s magnetic field.

1. Introduction

Arctic is a promising region with large mineral reserves. Recently, there has been an active study and planning of the necessary infrastructure for the mining of mineral resources on the Arctic shelf [1]. In the course of repairing or replacing undersea infrastructure objects passing along the sea bottom, there are problems of their detection and assessment of their length. To solve the problems of detecting metal-containing objects (gas pipelines, etc.) there exist two main types of electromagnetic sensors: active and passive. For an active detection method, additional energy is required for irradiation of the scanning signal into the surrounding space. At the same time, the active detection principle is characterized by resistance to external sources of magnetic fields (MF), both environmental and created by the carrier of the magnetic sensor. On the experimental AUV electromagnetic sensors of the passive type were installed. In contrast to the active, the passive sensors require compensation for the effects of external magnetic fields, which can have a significant impact on the readings of the probes. To search for metal-containing objects, it is proposed to use two passive three-component ferromagnetic probes mounted on the bow and stern of the vehicle. The presence of two probes separated by a known distance from each other allows to calculate the gradient of the magnetic field between the probes by simply subtracting the
readings of the sensors. Calculation of the gradient compensates the influence of external magnetic fields, the impact of which on each of the sensors is the same. When crossing a metal-containing object, it is firstly registered by the bow sensor, and then on the stern one. In this case, a characteristic pattern is observed in the gradient signal — the alternation of the maximum and minimum (minimum and maximum) of the gradient. The presence of such a pair of extremes is a necessary condition for the detection.

2. Detection algorithm

2.1. Initial signal processing

![Detection Algorithm Diagram](image)

The algorithm for detecting an extended metal-containing object is based on the detection of the intersection of a metal-containing object by the vehicle. For this, the pre-filtered and corrected signal is compared with the reference signal using the cross-correlation method. To reduce the computational load, the signal before the cross-correlation is pre-tested for compliance with the necessary criteria. The scheme of the algorithm is shown in Fig.1.

To compensate for the influence of the orientation of the apparatus in the Earth’s magnetic field, the coefficients of dependence of sensor readings on course, roll and trim angles were determined using the linear regression method. The dependence on heel and trim was linear, and on the heading it was harmonic. In the bare signal from a passive ferromagnetic sensor with a sampling frequency of 50 Hz, a constant harmonic component with a frequency of 4 Hz was also detected, for filtering of which a low-pass filter is used. To smooth the signal and eliminate sharp outliers, a median filter is applied to the signal. The filtering results are presented on Fig.2. After orientation compensation, all values are given in arbitrary units.
Then, calculating the difference between the readings of the bow and stern sensor, we obtain a signal that has the meaning of the gradient of the magnitude of the magnetic field along the vehicle. The signal of the gradient on passing over a metal-containing object has a characteristic shape - two alternating extrema. After that the local extrema of the received signal are searched for. Local extrema are filtered by the width of the peaks that they form. Fig. 3 shows the result of a search for local extrema of the gradient of the magnetic field along the vehicle. The local maxima are marked with the red circles and the local minima with blue. To filter such a pair of extrema, it is assumed that the time between them should be approximately equal to the speed of the AUV (it is assumed that it is constant) multiplied by the distance between the bow and stern ferrosonde.

To filter by the intersection of the mean value criteria, a similar pair of points described earlier is taken. For each such pair of points, a check is made on the intersection of the mean gradient value by...
the line connecting this pair of points. A pair of points for which this condition is not fulfilled is eliminated. Then, for each pair of extrema found, validation is performed.

2.2. Validation

The task of searching for a signal of a known form in time series arises in many areas of knowledge. In medicine such is the task of identifying complexes in signals of various vital indicators, for example, a QRS complex in a cardiogram [2], or patterns in an electroencephalogram [3], and in modern physics this problem was solved in experiments that recorded gravitational wave signals [4]. This problem can be solved in different ways: using filter combinations [5, 6], using wavelet transform [7, 8], using machine learning methods and neural networks [9, 10]. We have chosen a matched filter for our purpose for its incomplexity and fast implementation.

The matched filter is used to search for a known sequence (template) in the signal by correlating the template with the signal being studied. The maximum of the cross-correlation function then marks the point in time that corresponds to the appearance of the template signal in the analyzed one. With the appropriate normalization, it is not necessary for the sample and template signal to have equal magnitude, since the cross-correlation function will always have values in the -1: 1 range, but it is necessary that the pattern and the signal under study have the same sampling frequency. In this case, false detections can be filtered by setting the threshold of the cross-correlation function at the maximum, which is determined experimentally.

![Fig. 4. A template signal (green) and a real one (red)](image)

As a result of analyzing the experimental data from the device, a hypothesis was put forward about the shape of the sample signal: the signal from each sensor must be proportional to 1 / r, where r is the distance to the object, and the template signal is the difference of such functions. The template is defined by two dynamic parameters — the speed of movement and the impact parameter (height above the sea bottom), and one static parameter — the distance between the sensors. An example of such a generated signal is shown in Fig. 4, in this case, the vehicle speed was 0.62 m/s and the distance to the sea bottom was 1.34 m. At the time of receiving the information about the speed and position of the device from the navigation system, the metal-containing object detection system changes the template signal accordingly, which allows filtering out external noise that does not fit the shape.

3. Experiments

We performed 23 experiments in which the vehicle moved uniformly and rectilinearly, with an average speed of about 0.5 m/s and at a distance of 1.0–2.5 meters above the sea bottom. The metal pipe and the other metal objects were placed on the sea bottom. The sea bottom was also filmed by a video camera, which made possible the markup of the data to count the number of true detections, the number of false positives and the number of false negatives. The presence of a cross-correlation maximum with a value greater than the threshold value 0.7 was considered the detection for the algorithm with validation. The choice of threshold value was performed heuristically, based partly on the uncertainties in the readings.
of the navigational system. The detection without validation was considered to be the result of the work of the candidate selection algorithm in Fig.1. Since the output of the algorithm without validation is a pair of extrema and several pairs can be found on the true signal, then each pair of extrema was taken as a detection, and not the fact of the presence of at least one pair. This allowed to correctly account for the false detected pairs of extrema. The comparison involved 4 different combinations of candidate selection and analysis algorithms, the results are presented in Table 1.

**Table 1.** Results of experiments with various algorithms: algorithm without orientation correction and form validation (1), algorithm without orientation correction with form validation (2), algorithm with orientation correction without form validation (3), and algorithm with orientation correction and form validation (4).

| Algorithm | True positive | False positives | False negative | True / all detections, (%) |
|-----------|---------------|-----------------|----------------|---------------------------|
| 1         | 67            | 85              | 0              | 44.1                      |
| 2         | 27            | 9               | 5              | 65.9                      |
| 3         | 63            | 60              | 0              | 51.2                      |
| 4         | 31            | 5               | 2              | 81.6                      |

4. Conclusions
The paper proposed a measurement scheme and a signal processing algorithm for determining the presence of metal-containing objects at the sea bottom. The characteristic features of the signal to identify it in the data of ferromagnetic sensors were described. According to the results of the experiments, we can conclude that the algorithm for finding pairs of extrema and filtering them by distance and amplitude is not sufficient for the qualitative detection of an object, and for determining the time of its intersection by the vehicle. Using a matched filter allows to determine the point in time at which the template signal arrives in the data and helps to reduce the number of false detections significantly.

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