Three-dimensional Acoustic Target Surface Reconstruction Method Based on Marching Cubes

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Abstract. Marching Cubes is an isosurface reconstruction algorithm based on volume data. In order to solve the problems of low resolution, rough surface, insufficient texture and stereo sense in the process of three-dimensional acoustic target’s visualization, a method based on Marching Cubes is used to reconstruct the surface of three-dimensional acoustic target in this paper. By constructing the minimal cube in acoustic data field, determining the connection mode, vertex coordinates and normal vectors of triangle elements in the cube where the target contour lies, we establish the target’s three-dimensional surface model, and the reconstruction of three-dimensional acoustic target is realized. The performance and validity of the method are validated by the sea trial data from three-dimensional imaging sonar, and the performance of the method is tested by multi-resolution data, and a three-dimensional surface model of buried target is constructed based on the sea trial data. The results show that the surface reconstruction technology of three-dimensional acoustic target based on marching cubes algorithm has the advantages of simple structure and less computation, and the time-consuming of the algorithm is proportional to the number of sampling points. In the process of three-dimensional acoustic image visualization, surface reconstruction technology can effectively improve the stereo sense and recognition of buried targets.

1. Introduction

Underwater acoustic imaging technology is an important means to detect marine resources. With the development of computer technology and image processing technology, underwater acoustic imaging technology has gradually expanded from traditional two-dimensional imaging to three-dimensional imaging[1,2]. The high dimensionality of imaging data makes it difficult for traditional two-dimensional image to express such a large amount of information. It is urgent to find a new representation method of high-dimensional underwater acoustic data. Three-dimensional visualization is a kind of computer technology which can reproduce three-dimensional objects, express the complex information of three-dimensional objects and make them have real-time interactive ability[3]. It has been widely used in medicine, geophysics, geology, meteorology, geographic information and other fields[4]. Applying the visualization technology of three-dimensional data to the field of underwater acoustic imaging is conducive to improving the accuracy and intuition of three-dimensional acoustic image display.

Three-dimensional acoustic images are usually collected by three-dimensional imaging sonar based on area array synthetic aperture technology, which has the characteristics of low frequency penetration and full coverage. Compared with the optical image, the physical characteristics of sonar determine that the acoustic image has the characteristics of low resolution, less pixels in target, and rough edges...
of target, which make it difficult to distinguish the buried target from the background image due to the insufficient texture and stereo sense of the target in the visualization process of the three-dimensional acoustic image. In view of the above problems, we can learn from the field of medical image visualization where reconstructing the internal organs and bone three-dimensional model to assist the diagnosis of the disease[4], and use computer technology to reconstruct the three-dimensional surface of the target, and display it in the form of surface shape, so as to provide users with a more realistic three-dimensional object model for the observation and analysis of the target.

At present, the widely used three-dimensional surface reconstruction algorithms are Delaunay Triangle and Marching Cubes. This paper focuses on target surface model reconstruction method based on Marching Cubes in three-dimensional acoustic image. Marching Cubes is an algorithm for three-dimensional isosurface extraction, proposed by Lorensen in 1987, which constructs a cube from three-dimensional discrete regular data field, compares the gradient value of each cube with the value of the isosurface to find the cube containing this value, and finally uses the interpolation algorithm to get the surface model[7,8].

2. Acoustic Target Reconstruction Method

Three-dimensional imaging sonar generates three-dimensional acoustic data in alongtrack-crosstrack-depth arrangement. As shown in Fig.1, the sampling points in the far field of three-dimensional acoustic data can be approximately regarded as a cube consisting of eight adjacent points corresponding to two adjacent slices in a cubic grid system.

![Fig.1 Three-dimensional imaging sonar technology scheme](image)

The basic idea of three-dimensional acoustic target reconstruction based on Marching Cubes is to process cubes in data field one by one according to the target threshold. First, we get the cube containing the target contour, and calculate the intersection points between the cube edge and the target contour. Then, we connect the intersection points into triangular elements in a certain way, so as to be approximate representation on the target surface in the cube. After all the cubes in the data field are processed, the surface of the three-dimensional object the approximate representation of triangular elements on is formed as a whole. The overall flow chart of the method is shown in Fig.2.
2.1. Constructing Cubes
Three-dimensional acoustic data are imported into memory, and eight adjacent pixels of two adjacent slices in three-dimensional acoustic data field are formed into a cube model. As shown in Fig.3, each cube contains 12 edges, 8 vertices, and the coordinates of each vertex are: $P_{ijk}$, $P_{ijk+1}$, $P_{i+1j+k}$, $P_{i+1j+k+1}$, $P_{i+1j+k+1}$, $P_{i+1j+k}$, $P_{i+1j+k+1}$, and $P_{i+1j+k+1}$.

2.2. Determining the Connection Mode of Triangular Elements
In the cube, the gray value of eight vertices is compared with the threshold of the target to determine whether the cube contains the contour of the target. If the gray value of each vertex is greater than the threshold value, it will be marked; if it is less than the threshold value, it will not be marked. The eight vertices of the cube are marked and unmarked. The cube has $2^8 = 256$ states. The vertex state of a cube has antisymmetry and rotational symmetry, that is, the rotation of the cube and the inversion of
the vertex state will not change the connection mode of the inner triangle elements. According to these two symmetries, 256 states of the cube can be simplified to 15 configurations, as shown in Fig.4.

![Fig.4 Fifteen basic topological configurations of cubes](image)

According to the marking state of vertices, index is established for each cube state. As shown in Fig.5, the vertex state of a cube is represented by an 8-bit binary number, and each bit represents the marking state of a vertex. Similar to the vertex marking method, edge states can also be divided into two kinds: intersecting with the target contour and not intersecting with the target contour. A 12-bit binary value is used to represent the state of the cube edge, and each bit represents the state of one edge.

The connection relationship of triangle elements is obtained by querying the index table of triangle elements, which gives 256 fractal triangle element combination patterns. The cube configuration contains at most five triangles, so that each item in the index table of triangle elements is 16 numbers, and each three number of its sequential combination represents the edge of the cube where the three vertices of a triangle are located, and the remaining number is -1.

![Fig.5 Vertex and edge distribution of cubes](image)

2.3. Obtaining the Intersection Point between the Target Surface and the Cube Boundary
After determining the connection mode of triangle elements in the cube, it is necessary to calculate the vertex coordinates of triangle elements, that is, the intersection point between the target surface and the cube boundary. When the density of three-dimensional acoustic data field is high and the size of each cube is very small, it can be assumed that the data value changes linearly along the cube boundary. The intersection point between the target surface and the cube boundary can be obtained by
linear interpolation of the data at both ends of the cube boundary. The calculation formulas are as follows:

\[ P = P_1 + (V_{iso} - V_1)(P_2 - P_1) / (V_2 - V_1) \]

Among them, \( P \) represents the coordinates of nodes on the target surface, \( P_1, P_2 \) represent the coordinates of two endpoints, \( V_1, V_2 \) represent the gray values of two endpoints, \( V_{iso} \) represent the target threshold.

If the density of the three-dimensional acoustic data field is high enough, the intersection point between the target surface and the cube can be obtained by the midpoint selection method. The intersection point between the target contour and the cube boundary can be expressed by the midpoint of the boundary. The calculation formula is as follows:

\[ P = (P_1 + P_2) / 2 \]

After calculating the intersection point between the target surface and the cube, the triangle element is formed according to the connection mode of triangle element in the cube, which is a part of the target surface model.

2.4. Calculating Normal Vector of Target Surface Model

In order to render the three-dimensional target realistically, the normal vectors of each triangle that constitutes the surface model of the target must be calculated. For each sampling point on the target contour, the gradient component along the tangent direction of the contour should be zero, and the direction of the gradient vector of the point represents the normal vector of the target surface at that point. Acoustic target surface is the interface between two substances with different densities, so its gradient vector is not zero, which can be expressed as:

\[ g(x, y, z) = \nabla f(x, y, z) \]

With the help of Godello model, the whole triangle can be drawn concisely by using the gradient vectors of the triangle’s three vertices. Assuming that the value of a sampling point in a three-dimensional acoustic data field is \( f(x, y, z) \), the calculation formula of gradient vector \( g(x, y, z) \) of the point is as follows:

\[
\begin{align*}
    g_x(x, y, z) &= \frac{f(x+1, y, z) - f(x-1, y, z)}{2\Delta x} \\
    g_y(x, y, z) &= \frac{f(x, y+1, z) - f(x, y-1, z)}{2\Delta y} \\
    g_z(x, y, z) &= \frac{f(x, y, z+1) - f(x, y, z-1)}{2\Delta z}
\end{align*}
\]

Among them \( \Delta x, \Delta y, \Delta z \) is the sampling distance along the \( x, y \) and \( z \) axis of the sampling point, that is, the edge length of the cube.

3. Test and Verification

The experimental algorithm is implemented with C Language and OpenGL three-dimensional image engine, and is programmed and tested on VS2010 development platform. The experimental platform is HP Z670 graphics workstation and the CPU is Intel Xeon E5. The experimental image is derived from the sea trial data of the three-dimensional imaging sonar based on the area array synthetic aperture technology developed by our institute. The size of the experimental image is 800 in alongtrack samples, 81 in crosstrack samples and 2048 in depth samples. As shown in Fig.6, the burial target is a self-made mine-like target (cylinder 2 meters long and 0.5 meters in diameter) buried deeper than 1.5 meters in the stratum.
The original image is processed before reconstructing the three-dimensional surface model of the target. The preprocessing includes image denoising, target enhancement and target segmentation. Fig.7(a) is the original image, (b) the denoised image, (c) the enhanced image for the buried target, (d) the segmented image for the buried target.

After pretreatment, the three-dimensional image with buried target is extracted and the cubes in the image are constructed. The number of sampling points of the experimental image is 800*81*2048, and the number of constructed cubes is 799*80*2047. According to the acoustic characteristics of buried target, the threshold of buried target surface in the image is set. According to the above method, the connection relation of triangle elements in a single cube, the intersection point between triangle elements and cube boundary, and the normal vector of triangle elements are obtained. By analogy, triangular element attributes in all cubes are obtained. The three-dimensional reconstruction model of buried targets is formed by combining all the triangular elements. Finally, it is rendered by OpenGL image engine.

The visualization effect of buried target's three-dimensional image is shown in Fig.8. The image has the characteristics of less pixels and rough edges. The rendering map of the target surface model
obtained by the target surface reconstruction method is shown in Fig.9. Compared with Fig.8, it can be seen that the target surface reconstruction method can effectively reduce the rough edge of the target, improve the stereo sense and recognition of the target, and help to distinguish the target from the background image.

The image around the buried target is intercepted from the experimental image. The number of sampling points is 100*81*600, the number of alongtrack sampling is 100, the number of crosstrack sampling is 81, and the number of depth sampling is 600. Seven images with different alongtrack sampling numbers are obtained by linear interpolation of 1 to 7 times in the alongtrack of the intercepted image. The crosstrack sampling number, depth sampling number and buried target information in the seven images are the same. In this paper, the acoustic target reconstruction algorithm is used to extract the same buried targets from the above seven images. The time-consuming algorithm is shown in Tab.1. The relationship between the time-consuming of the algorithm and the sampling number in alongtrack is shown in Fig.10. Experiments show that time-consuming of the algorithm is proportional to the number of image sampling points.

| alongtrack sampling number | 100 | 200 | 300 | 400 | 500 | 600 | 700 |
|----------------------------|-----|-----|-----|-----|-----|-----|-----|
| time-consuming (ms)        | 586 | 672 | 977 | 1256| 1666| 1927| 2263|
4. Conclusion
The progress of underwater acoustic technology and computer technology promotes the development of three-dimensional imaging sonar technology. Visualization of three-dimensional acoustic images, as an important part of it, has attracted more and more attention. In order to solve the problems of low resolution, rough surface, insufficient texture and stereo sense in the process of three-dimensional acoustic image visualization, this paper proposes a method reconstructing three-dimensional target’s surface model based on moving cube method to improve the stereo sense and expressiveness of target.

In order to verify the correctness and validity of the acoustic target reconstruction method, a three-dimensional surface model of buried mine by sea trial three-dimensional sonar data are established in this paper. The processing results show that the acoustic target reconstruction method based on Marching Cubes has the advantages of simple structure and small computation. It can realize establishing three-dimensional surface model of target in three-dimensional acoustic images, and the method’s consuming time and sampling points are proportional to each other. In the process of three-dimensional acoustic image visualization, reconstructing three-dimensional model of buried targets or other key targets easily occluded can effectively improve the stereo sense and recognition of targets.

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Fig. 10 Relation between algorithm’s time-consuming and image sampling points