Research on the Ocean Environment Implementation Methods for Digital AUV Platform

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Abstract—For the purpose of building a robust AUV controller, which could be used to handle complex ocean environment, a method of obtaining benthos terrain based on Electronic Chart is presented. Firstly, some terrain conversion algorithms for development of the benthos terrain, such as nearest neighbor interpolation, linear interpolation, cubic interpolation and v4-interpolation are compared; Secondly, a new terrain conversion algorithm for development of the benthos terrain DTTCSFD (Delaunay Triangle-based Terrain Considering of Grid, Sparse, Feature Data) is introduced. This method consider the data not only distance constant grid data, sparse data, but also feature data with the terrain data, such as fathom line etc; In the end, two kinds of current implement methods are presented; The result, which is of importance in the AUV research of terrain matching navigation, path planning and obstacle avoidance strategy, has been applied to the research work of our digital AUV platform.

Index Terms—AUV; DED; Digital AUV Platform; Delaunay trigonometry; Electronic Chart.

I. INTRODUCTION

At present, AUV (Autonomous Underwater Vehicles) plays an important role not only in the civil sector but also in underwater warfare. The development of a robust autonomous underwater vehicle is not a simple task. Besides the mechanical and electrical issues, the vehicle needs intelligent software architecture responsible for driving the vehicle during the mission. This software must be able to deal with unstructured and uncertain environments in real time. In order to build this kind of software, an intensive set of experiments in an exhaustive number of ocean environments are necessary. Nevertheless, testing in real environment is expensive in both resources and man-hours. Hence, there exists the following problem: (1) obtaining the ideal ocean scene for experiments is not simple; (2) testing in real environment is expensive in both resources and man-hours; (3) The number of real experiments must be reduced while at the same time intensive experimentation should be carried out; (4) eventually, almost any engineer involved in the software development of an AUV has experienced frustration due to a simple mistake in the software. For reasons above, a semi-physical virtual reality system implementing the virtual vehicle swimming in the virtual ocean world is desirable tools for research. In our laboratory we have designed digital AUV platform in such a way that it can distinctly deal with the real vehicle or the virtual one.

More and more attentions and focus on the development graphical simulators and virtual worlds are growing daily in the AUV community. The necessity of these kinds of tools was clearly shown by D. P. Brutzman who implemented an integrated simulator for the NPS AUV in 1994 [1]. In 1991, Pappas etc developed the first hardware in loop system. S. K. Choi and J. Yu etc. presented a distributed virtual environment collaborative simulator for underwater vehicles ODIN etc [2][3]. The ocean environments above system more or less is considered, But it is so simple that it is difficult to build a robust controller. In China, Fengju Kang etc designed a semi-physical system for underwater vehicle so much as they didn’t consider the ocean environments, such as benthos terrain, temperature, current, salinity, obstacle and so on [4].

In this paper, after the architecture of digital AUV platform is introduced, some common terrain conversion algorithms (such as nearest neighbor interpolation, linear interpolation, cubic interpolation, v4-interpolation) for development of the benthos terrain are compared. Later, a DTTCSFD (Delaunay Triangle-based Terrain Considering of Grid, Sparse, Feature Data) terrain conversion algorithm is introduced step by step: (1) Coordinate change from the map projection to geography coordinate; (2) According to the Delaunay trigonometry rule, the sparse depth data and discrete isobaths data are divided into groups; (3) The grid DEM data needed were generated in order to adopt the float2ded method provided by VR package; (4) Because the DED (Digital Elevation Data) format in our virtual reality software package are in big endian (Sun or Motorola) byte order, it is necessary to convert the data to little endian (PC or Intel) byte order; (5) The DED (Digital Elevation Data) file
can be obtained by using float2ded method in the last step. At last the conclusion is drawn and the further work is given.

The advantages of this semi-physical virtual reality system include that: (1) the vehicle software can be simulated in the laboratory before real experiments taking place, (2) the merit and demerit of some novel path planning, obstacle avoidance and terrain matching navigation algorithms can be verified, (3) Moreover intensive testing is easy and its cost is not too expensive.

II. ARCHITECTURE OF THE WHOLE SYSTEM

The system we developed is a semi-physical virtual reality platform aiming at testing AUV software. It is composed of four modules (see Fig.1): autopilot node, virtual node, visualization node and AUV CR02 (see Table I). Because the interface of virtual node just the same as real AUV CR02, this system can be work in virtual mode and real mode [5].

![Diagram of the system](image)

**Figure 1. Overview of the system**

<table>
<thead>
<tr>
<th>TABLE I MAIN FEATURES OF THE AUV CR02</th>
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<tbody>
<tr>
<td>Main Features</td>
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<td>----------------</td>
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<tr>
<td>Depth</td>
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<td>Endurance</td>
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<td>Speed</td>
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<td>Diameter</td>
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<td>Simulator</td>
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</table>

The functions of the autopilot node include: (1) mission planning and task planning according to demand; (2) controlling AUV’s motion in the ocean; (3) planning the optimal path according to Electronic Chart. (4) avoiding obstacles as occasion require.

The functions of the virtual node include: (1) calculate the dynamic model of AUV CR02, so that the posture of the vehicle can be obtained; (2) receive command from the autopilot node and pass the all of the information to the visualization node and all kinds of sensors; (3) make virtual sensors such as GPS, Doppler, sonar, TCM2, permanent magnetic motor, propeller and depth gauge, altimeter etc.

The functions of the visualization node include: (1) receive posture data of AUV calculated by virtual node and display its motion in the three-dimension ocean environment; (2) provide the obstacle avoidance sonar data and altitude data for virtual node; (3) create the ocean environment such as ocean terrain, current, temperature field, salinity field etc according to Electronic Chart.

The system software flowchart is as the following Fig. 2.

![Diagram of the software system](image)

**Figure 2. Flowchart of the software system**

III. METHODS COMPARING FOR GENERATING BENTHOS TERRAIN

There are many kinds of interpolation algorithm for two dimensions, which can be used for generating benthos terrain.

A. Nearest neighbor interpolation

If the interpolation method is the nearest neighbor, i.e. the point $i$ meets $\min (dist(s,i))$, then we take the value of the nearest point $i$ as the point $s$:

$$y(s) = y_i$$  \hspace{1cm} (1)

The result can be seen from the following Fig. 3.

![Diagram of the result](image)

**Figure 3. Result of nearest neighbor interpolation**

B. Linear interpolation

If we assume that the function that underlies our points is continuous, the nearest neighbor interpolation would be poor, because its value would abruptly change at the centers between the sample points.

For a linear interpolation, therefore, we use the attested
values on both sides (left and right) of $s$:

$$y(s) = y_1 + (s - s_i) \cdot (y_i - y_1) / (s_r - s_l)$$  \hspace{1cm} (2)

where floor ($x$) computes the greatest integer not greater than $x$. This interpolation is continuous (See Fig.4).

![Figure 4. Result of linear interpolation](image)

C. Cubic interpolation

If we assume that the function that underlies our points is smooth, i.e. its derivative is defined for every $x$, linear interpolation would probably be poor, because the derivative of the interpolated function would abruptly change at every sample point.

The next higher interpolation (Cubic interpolation), therefore, is differentiable at sample points. To enforce this, we define the derivatives $y_1'$ and $y_i'$ at the left and right sample points on the basis of their immediate neighbors, perhaps by a parabolic interpolation through these three points. A parabolic interpolation has the advantage that the extremum will be computed correctly, if the underlying function can be approximated by a parabola near its extremes (See Fig.5).

![Figure 5. Result of cubic interpolation](image)

D. V4- interpolation

Sandwell (1987) elegantly and concisely derives details of bi-harmonic spline interpolation that he applies to satellite altimetry data in two dimensions. Bi-harmonic splines satisfy the bi-harmonic equation:

$$\nabla^4 w(x) = \sum_{j=1}^{N} \alpha_j \delta(x - x_j)$$  \hspace{1cm} (3)

where $\nabla^4$ is the bi-harmonic operator, $x$ represents a location in a space of $m$ dimensions, $\delta$ is the Dirac delta function, and $j$ indicates $N$ data. The solutions to this equation are bi-harmonic Green’s function $\phi_m(x)$: that is,

$$w(x) = \sum_{j=1}^{K} \alpha_k \phi_m(x_i - x_k)$$  \hspace{1cm} (4)

which in two (m=2) and three (m= 3) dimensions has the forms

$$\phi_2(x) = |x|^2 (\ln |x| - 1)$$  \hspace{1cm} (5)

and

$$\phi_3(x) = |x|$$  \hspace{1cm} (6)

where $x = x_i - x_k$ and $i = 1, 2, ..., N$ represent data, while $k = 1, 2, ..., K$ represents specified nodal locations. Both $K$ and the nodal locations $x_i$ are arbitrary (as long as $x_i \neq x_k$). That is, for $K<<N$, solutions can be fitted by using the method of least squares (See Fig.6).

![Figure 6. Result of v4- interpolation](image)

The uniform data levels are then transferred from the discrete geographic data-collection-locations onto the uniform grid mentioned above. The cubic interpolation and v4-interpolation methods produce smooth surfaces while linear interpolation and nearest neighbor interpolation have discontinuities in the first and zero-th derivative respectively. All the methods except v4-interpolation are based on a Delaunay triangulation of the data.

IV. DTTGSFD METHOD OF CREATING OCEAN TERRAIN

Ocean terrain is of significance in the research of AUV obstacle avoidance, path planning and terrain matching navigation. The flow chart of generating ocean terrain is as the following Fig.7:

A. Projections transform

Projection is the process of transforming coordinates from the round spherical coordinate system to flat Cartesian coordinates. The basic assumption of most projections in this paper is that latitudes and longitudes map to x- and y-coordinates.

Mercator Projection is adopted in this paper, which is a projection with parallel spacing calculated to maintain
conformability. It is not equal-area, equidistant, or perspective.

![Diagram of Delaunay triangulation]

Figure 7. Steps of generating ocean terrain

Scale is true along the standard parallels and constant between two parallels equidistant from the Equator. It is also constant in all directions near any given point. Scale becomes infinite at the poles. The appearance of the Mercator projection is unaffected by the selection of standard parallels, they serve only to define the latitude of true scale. The Mercator, which may be the most famous of all projections, has the special feature that all rhumb lines, or loxodromes (lines that make equal angles with all meridians, i.e., lines of constant heading), are straight lines. This makes it an excellent projection for navigational purposes.

B. Transform Electronic Chart data into Delaunay trigonometry.

Digital Evaluation Modal (DEM) is widely used in topography, finite element analysis, GIS and others fields. Given a set of data points, the Delaunay triangulation is a set of lines connecting each point to its natural neighbors. Although there are many kinds of method triangle decompose, Delaunay in 1934 proved that there exists one and the only one kind of triangle decompose method, which makes the sum of all the minimum angle the most. The Delaunay triangulation is related to the Voronoi diagram—the circle circumscribed about a Delaunay triangle has its center at the vertex of a Voronoi polygon, their relation is shown in Fig.8.

In order to increase the fidelity of the ocean terrain, the data used should not only those sparse depth data in Electronic Chart, but also specialty data such as isolaths. So the first step should interpolate some data between polygon vertexes. The next step should add these data into the sparse data set for Delaunay triangulation together.

C. Grid DEM Generating

Generally speaking, the method of generating Grid DEM data can be classified as the following: whole interpolation, local interpolation, and point interpolation. Some methods such as spine interpolation, trend interpolation, moving curved surface, have been fallen into disuse for large memory or long CPU time, so these methods like least square method, weighted average method, bi linear interpolation method. Kriging spatial interpolation is very popular in DEM data processing.

Least square method and bilinear interpolation based on triangulation method [6] will be adopted here considering memory necessary and CPU time. We will find that there is some relation between these methods step by step. After Delaunay trigonometry generated, any point \(P_i(x_i, y_i)\) will lie in the \(\Delta 123\). Let’s assume that the three points are: \(P_1(x_1, y_1, z_1), P_2(x_2, y_2, z_2), P_3(x_3, y_3, z_3)\), then the \(z_y\) of point can be obtain by the following equation:

\[
Z = X^T A
\]

where \(Z = [z_1, z_2, z_3]^T\), \(A = [a_{ij}], a_{ij}\), and

\[
X = \begin{bmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ 1 & x_3 & y_3 \end{bmatrix}
\]

If \(|X^T X| \neq 0\), the undetermined coefficient matrix \(A\) can be obtained according to space analytical geometry:

\[
A = (X^T X)^{-1} X^T Z
\]

Equation (9) is the known least square method. Which is common in disposal experiment data.

Let’s consider this problem further, and if \(|X| \neq 0\), which is equivalence that

\[
\begin{bmatrix} x_2 - x_1 \\ y_2 - y_1 \\ x_3 - x_1 \end{bmatrix} \neq 0
\]

and (10) means that the three points are not in the same line. We can prove that the undetermined coefficient matrix can be direct obtained by Eq. (11):

\[
A = X^{-1} Z
\]

Equation (11) is the known bilinear interpolation method. Compared (10) and (11), the conclusion can be drawn that (1)
for large area, linear interpolation method is usually adopted; (2)
if the points are in the same line, least square method is often
used, otherwise blinear interpolation method is often adopted;
(3) for the same depth points, least square method will spend
more time on the two matrix multiply operation.

In this way, all the altitude can be obtained in the grid point
of \( P(y, y_0) \). This method proves high convergence speed and
high accuracy. The result can be seen in the following Fig.9
(3D plot).

![Figure 9. Ocean terrain of some place](image)

**D. Data format conversion**

The grid data cannot be made use of by the terrain
conversion tools directly since the data byte order exists
difference in different computer hardware or software system
[7][8]. The integers and double-precision floating-point
numbers that make up the depth data are in little endian (PC or
Intel) byte order. While the integers and double-precision
floating-point numbers used in the terrain conversion tools are
in big endian (Sun or Motorola) byte order. The TransEndian
method is adopted in the data format conversion module. Its
principle is as the following (see Fig.10):

```
31 ........ 24 | 23 ........ 16 | 15 ........ 8 | 7 ........ 0

7 ........ 0 | 15 ........ 8 | 23 ........ 16 | 31 ........ 24
```

![Figure 10. Principle of TransEndian module](image)

**E. Generating DED file**

The making of Electronic Chart is far more difficult than
general land map, since it cost great financial and man-hour. It
is well known that sonar is the most capable measure
instrument for the separate of seawater. Although the terrain
conversion tool has the following four method [9][10]: (1)
generating DED from NIMA DTED; (2) generating DED from
USGS; (3) generating DED from RGB image; (4) generating
DED from grid floating-point number, only the last method we
can use for generating the true ocean terrain and it is the main
reason that we adopt the steps of above.

There are four terrain conversion algorithms available with
the VR software package: Polymesh, Delaunay, TCT (Terrain
Culture Triangulation), and CAT (Continuous Adaptive
Terrain). Each algorithm has its advantages: (1) Polymesh
creates a terrain database consisting of a uniform, rectilinear
grid of triangles. This algorithm is ideal for image generators
that use Binary Separating Planes (BSPs). (2) Delaunay creates
a terrain database of triangular polygons. This method is best
suited for hardware Z-buffering because polygon count and
maximize terrain accuracy can be controlled by creating more
polygons in rough terrain areas and fewer in flatter areas. (3)
Terrain Culture Triangulation (TCT) processes feature data
with the terrain data. Features such as roads, rivers, lakes, and
streams, become a part of the terrain skin, rather than lying on
top of it. (4) Continuous Adaptive Terrain (CAT) provides
solutions to some of the traditional problems of terrain LOD
management. CAT allows terrain to morph smoothly from one
LOD to another. The CAT hierarchy is based on a triangular
area, which results in more efficient culling than with Delaunay
or Polymesh. According to the necessary of real-time system,
the result of the ocean terrain was generated and its experiment
in the digital AUV platform is shown in the following Fig.11.

![Figure 11. Ocean terrain for experiment](image)

**V. CURRENT IMPLEMENT METHOD**

The motion of ocean current is very complex in practice,
since the effects of the ocean circumfluence, surface air
circumfluence, typhoon, and density etc [11], further more; the
motion of AUV will affect its surrounding current. So the real
situation is: the law of the magnitude and the direction of the
current somewhere in the determinate ocean terrain are
determined by its position and time: AUV swims in the current
somewhere, and its motion affect the motion of surrounding
current, later, AUV continues to swim in the mixed current,
and current continue to affect the motion of AUV, and so on. But
the relationship between AUV and current can not resolve in
real time at present, and the level of computer calculate and
hydrodynamics need make further more progress.

The motion of current not only affects the posture of AUV,
but also its temperature, salinity and other factors affect the
sensors installed on the AUV. If the motion of current is
directional in the ocean, the conductor of this current may result
in large error of sensors on AUV [12]. Two kinds of methods
were adopted in the digital AUV platform as the following:
A. Current database

In order to implement the motion of current, database need built based on the history statistical current data. Since the magnitude and direction exist large differences in the surface layer, middle layer and bottom layer, only the data of middle layer current are stored in the database. The horizontal current of XOY plane can be obtained by the method of bivariate interpolation based on grid data. Assume the n*m coordinates in the XOY plane are:

\[ x_0 < x_1 < \cdots < x_{n-1}, \quad y_0 < y_1 < \cdots < y_{m-1} \]  

and their corresponding current values are:

\[ z_{ij} = z(x_i, y_j) \]

where \( i = 0,1, \cdots, n-1 \), \( j = 0,1, \cdots, m-1 \). The approximation value in the point \((u,v)\) can be obtained by the following (14):

\[ z(u,v) = \sum_{i=0}^{n-1} \sum_{j=0}^{m-1} z_{ij} \frac{(u-x_i)(v-y_j)}{(x_{i+1}-x_i)(y_{j+1}-y_j)} \]  

And the method in the vertical direction adopts piecewise linear approximation according to history statistical current data. In this way, the current of any point in the ocean can be implemented. The method of temperature and the salinity of the ocean are implemented in the same way.

The method above is appropriate for in possession of mass data of the ocean current. If current data of region concerned cannot be obtained, two methods can be used, one is experiential, and the other is as the following.

B. Hydrodynamics software calculation

This method is based on the hydrodynamics theory and numerical analysis. After the models of ocean terrain and typical obstacles are built, they are imported into the hydrodynamics calculation software, such as CFX etc. Once the boundary condition and the data necessary are inputted into the software, the ocean current in any position can be calculated in this way. The value calculated using the method above is very close to real condition, so this method is widely used in the research work of AUV.

VI. CONCLUSIONS AND FURTHER WORK

The ocean environment is so complex that any work concerned it is formidable to researchers in this field, and its implement methods presented this paper benefit the research work of the dynamic model of AUV, design of controller, test for hardware and software etc. The terrain implement method is more accuracy since the discrete depth data and characteristic data are included. And the current implement methods are effective for the research work at present, which need make progress in future. The research on the ocean environment is of importance in the AUV robust controller design, terrain matching navigation, path planning and obstacle avoidance strategy etc. The results have been applied to our research work of our digital AUV platform for designing robust controller. Further work will include building distribute simulation system for the cooperation of multiple AUVs.

REFERENCES


