Electronic Chart Based Ocean Environment Development Method and its Application in Digital AUV Platform

Jian Liu *, Kaizhou Liu * **, Xisheng Feng*
* Shenyang Institute of Automation, CAS, Shenyang, Liaoning 110016
(Tel: 086-24-23970732; fax: 086-24-23970076; e-mail: liukzh@sia.cn).
** Graduate School of the Chinese Academy of Sciences

***Abstract*—For the purpose of building a robust AUV controller, which could be used to handle dangerous ocean environment, a method of obtaining benthonic terrain based on Electronic Chart is presented. Firstly, some terrain conversion algorithms for development of the benthonic terrain, such as nearest neighbor interpolation, linear interpolation, cubic interpolation and v4-interpolation are compared; Later a new terrain conversion algorithm for development of the benthonic terrain DTTCGSFD (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, build benthonic terrain making use of Electronic Chart ESRI shapefile database. The result, which is of importance in the AUV research of terrain matching navigation, path planning and obstacle avoidance strategy, has been applied in the research work of our digital AUV platform.**

Keyword: 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 is 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 is being 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 are 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 is 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 etc. at University of Hawaii presented a Distributed Virtual Environment Collaborative Simulator for Underwater Vehicles ODIN etc [2]. The ocean environments above system more or less is considered, But it is so simple that it is difficult to build 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 benthonic terrain, temperature, current, salinity, obstacle and so on [3].

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 benthonic terrain are compared. Later, a DTTCGSFD (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

0-7803-8541-1/04/$20.00 ©2004 IEEE.

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 in the step three; (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 confirmed, (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 1). Because the interface of virtual node just the same as real AUV CR02, this system can be work in virtual mode and real mode [4].

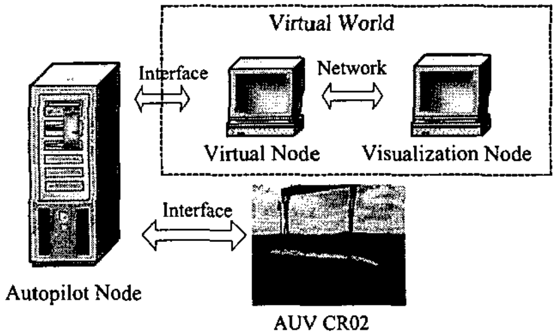

Fig. 1 the overall System

Main Features	Data
Depth	6000 m
Endurance	40 h
Speed	2 Knot
Length	4.5m
Diameter	0.8m
Intelligent Behavior	Obstacle Avoidance, In Mission Re-planning, etc.
Simulator	Based on VR

Table 1 Main features of the AUV CR02

The functions of the autopilot node include: (1) mission planning and task planning according to demand; (2) controlling the AUV and its navigation; (3) planning the optimal path according to Electronic Chart. (4) obstacle avoidance as occasion require.

The functions of the virtual node include: (1) calculate the dynamic model of AUV CR02, and 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) making 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) According to Electronic Chart create the ocean environment such as ocean terrain, current, temperature field, salinity field etc.

The system software flowchart is as the following figure 2.

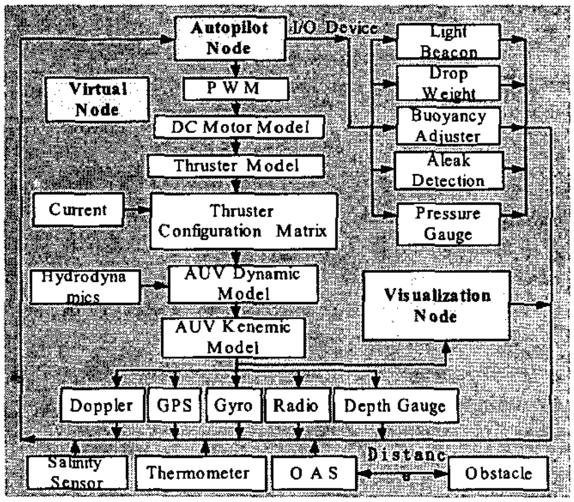

Fig. 2 Flow chart of the software system

III. METHODS COMPARING FOR GENERATING BENTHONIC TERRAIN

A. Nearest neighbor interpolation

If the interpolation method is the nearest neighbor, we take the value of the nearest point:

$$near \equiv \text{round}(s) \quad (1)$$

$$y(s) \approx y_{near} \quad (2)$$

The result can be seen from the following figure 3.

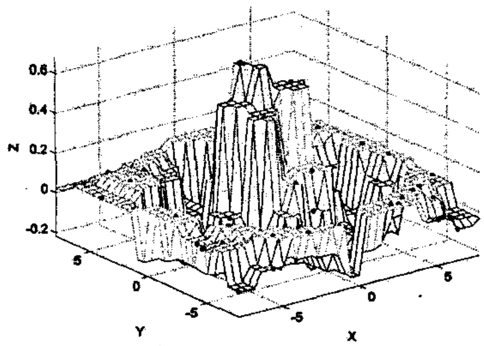

Fig. 3 nearest neighbor interpolation

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:

$$s_l \equiv \text{floor}(s) ; s_r \equiv s_l + 1 \qquad (3)$$

$$y(s) \approx y_l + (s - s_l) \cdot (y_r - y_l) \qquad (4)$$

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

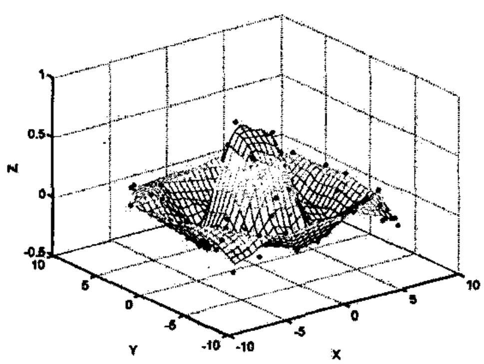

Fig. 4 linear interpolation

C. Cubic interpolation

If we assume that the function that underlies your 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), therefore, is differentiable at sample points. To enforce this, we define the derivatives y'_l and y'_r 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 extremer will be computed correctly if the underlying function can be approximated by a parabola near its extremes (See the following figure 5).

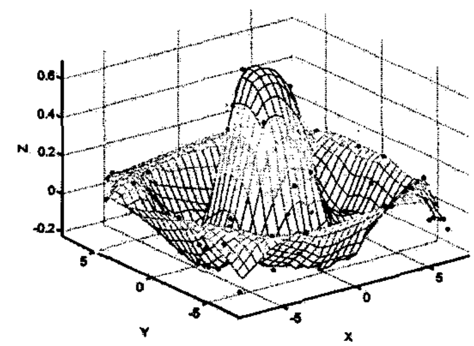

Fig. 5 cubic interpolation

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:

$$\nabla^4 w(x) = \sum_{j=1}^{N} \alpha_j \delta(x - x_j) \qquad (5)$$

where ∇^4 is the bi-harmonic operator, *x* represents a location in a space of *m* dimensions, δ 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,

$$w(x_i) = \sum_{k=1}^{K} \alpha_k \phi_m(x_i - x_k) \qquad (6)$$

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

$$\phi_2(x) = |x|^2(\ln|x| - 1) \qquad (7)$$

and

$$\phi_3(x) = |x| \qquad (8)$$

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

The uniform data levels are then transferred from the discrete geographic data-collection-locations onto the uniform grid mentioned above. This transformation is performed in MATLAB using a method is based on biharmonic spline interpolation by David T. Sandwell [7]. This method was chosen because it handled the non-smooth nature of the wind data better than the other interpolation options such as nearest neighbor interpolation, linear interpolation, or cubic interpolation, which they were all based on a Delaunay triangulation of the data.

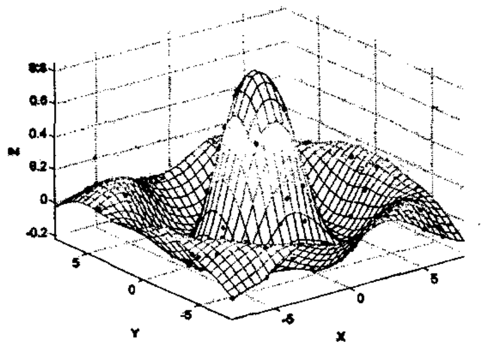

Fig. 6 v4- interpolation

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. DTTCGSFD 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 figure 7:

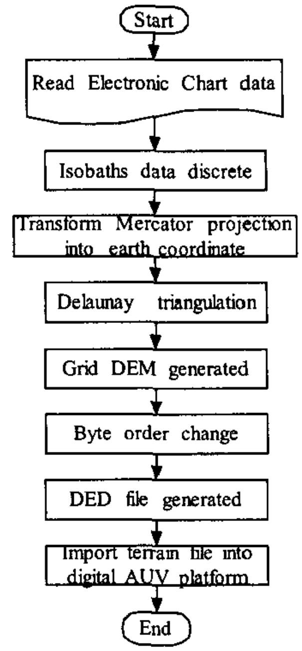

Fig. 7 steps of generating ocean terrain

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. 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. DEM data have different meaning according to difference projection. Mercator projection is a projection with parallel spacing calculated to maintain conformability.

It is not equal-area, equidistant, or perspective. 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, and scale becomes infinite at the poles. So the sparse data source need transform Electronic Chart data into AUV platform data needed.

Given a set of data points, the Delaunay trigonometry 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 is exist one and the only one kind of triangle decompose method, which make the sum of all the minimum angle the most. The Delaunay trigonometry 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 figure 8.

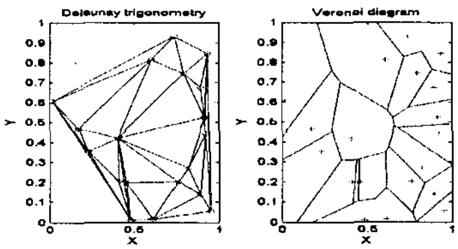

Fig. 8 relation between Delaunay trigonometry and Voronoi diagram

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 speciality data such as isobaths. 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 trigonometry together.

C. Grid DEM Generating

Generally speaking, the method of generating Grid DEM data can be classified as the following: whole interpolate, local interpolate, and point interpolate. Some methods such as spine interpolate, trend interpolate, 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, bilinear interpolation method, Kriging spatial interpolation is very popular in DEM data processing.

Least square method and bilinear interpolation based on triangulation method [5] 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 $P_{ij}(x_{ij}, y_{ij})$ 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_{ij} of point $P_{ij}(x_{ij}, y_{ij})$ can be obtain by the following equation

$$Z = XA \tag{9}$$

where $Z = [z_1 \quad z_2 \quad z_3]^T$, $A = [a_0 \quad a_1 \quad a_2]^T$,and

$$X = \begin{bmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ 1 & x_3 & y_3 \end{bmatrix} \tag{10}$$

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

$$A = (X^T X)^{-1} X^T Z \tag{11}$$

Equation (11) 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

$$\begin{vmatrix} x_2 - x_1 & y_2 - y_1 \\ x_3 - x_1 & y_3 - y_1 \end{vmatrix} \neq 0 \tag{12}$$

and equation (12) means that the three points are not in the same line. We can prove that the undetermined coefficient matrix A can be direct obtained by the following equation:

$$A = X^{-1} Z \tag{13}$$

equation (13) is the known bilinear interpolation method. Compared the equation (12) and (13), the conclusion can be drawn that ①for large area, linear interpolation method is usually adopted; ②if the points are in the same line, least square method is often used, otherwise bilinear interpolation method is often adopted; ③ for the same depth points, least square method will spend more time on the two matrix multiply operation, which is the reason adopting Delaunay trigonometry method.

In this way, all the altitude z_{ij} can be obtained in the grid point of $P_{ij}(x_{ij}, y_{ij})$. This method proves high convergence speed and high accuracy. The result can be seen in the following figure 9 (3D plot).

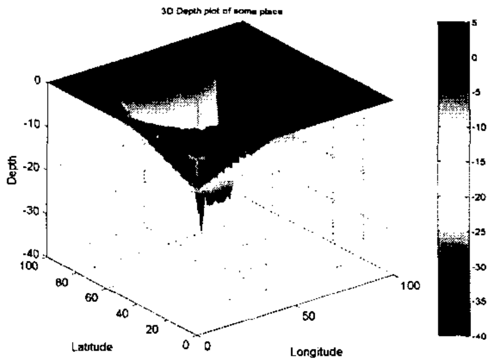

fig.9 ocean terrain of some place

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 [6]. 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 figure 10):

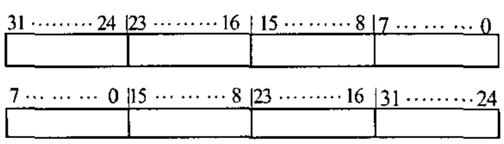

Fig. 10 principle of TransEndian module

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: (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. For other reason, 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 you can control polygon count and maximize terrain accuracy 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 figure 11.

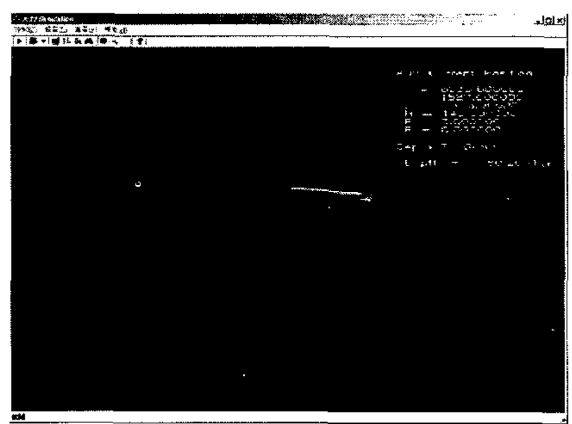

Fig. 11 the experiment of ocean terrain

V. CONCLUSIONS AND FURTHER WORK

This digital AUV platform is keeping ahead in the simulation domain not only in the means of development but also in technology in existence. It accord with the trend of 3D development as well as theory and practical integrate close. A DTTCGSFD approach is introduced which can change the sparse DEM data into DED data format. The result is of importance in the research of obstacle avoidance, path planning and navigation based on terrain. It has been made use of in the digital AUV platform for the research of problems above. Further research work will include the oceans current, which flow in the ocean according to obstacle and terrain.

ACKNOWLEDGMENT

It is a great pleasure to acknowledge the numerous contribution of a team of enthusiastic and dedicated researchers at the AUV group of

underwater vehicle research center, SIA, CAS. discussions with Dr. Tan Dalong and Huang Shabai were useful to our research work.

References

[1] Donald P. Brutzman, A Virtual World for an Autonomous Underwater Vehicles. PhD thesis, Naval Postgraduate School, Monterey, California, December 1994.

[2] S. K. Choi, S. A. Menor and J. Yuh, "Distributed Virtual Environment Collaborative Simulator for Undewater Vehicles", IEEE/RSJ Int. Conf. on Vehicles and Systems IROS'2000, November 2000. pp. 861-866.

[3] Fengju Kang, Huizhen Yang, Lie Gao, Zhigang Hu, Laiyi Du, Juzhong Dong. "The Integrated and Numerical Development of Semi-physical Simulation System for Underwater Vehicle Control Study," journal of system simulation, Vol.11,No.2, pp. 121-125, April 1999.

[4] Kaizhou Liu, Jian Liu, Yu Zhang, Hongli Xu, Xisheng Feng, The Development of Autonomous Underwater Vehicle's Semi-physical

[5] Virtual Reality System, Proceedings of IEEE International Conference on Robotics, Intelligent System and Signal Processing, Changsha, China, October 2003, pp301-306.

[6] Hu peng, You lian, Yang chuan-yong, Wu yan-lan, Map Algebra, Wuhan University publishing company, 2002.2

[7] Li Lirong, Shen Chunlin, Lu Yuping,Wang Chao, 3D ViSual Scene and Spanning Platform of RealTime Simulation Based On SGI Graphical workstation in Low Altitude Penetration System, Journal of Nanjing University of Aeronautics & Astronautics, Vol.34,No.2, 2002.4

[8] Sandwell, D. T. Biharmonic Spline Interpolation of GEOS-3 and SEASAT Altimeter Data. Geophysical Research Letters, (2):139-142, 1987.