Research on data organization and visualization of marine element temporal-spatial process

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Modeling and visualization of marine environment data are important problems to be solved in marine GIS. In this paper, according to the characteristics of marine process data, features are regarded as basic units and object-oriented technology is applied for designing of temporal-spatial attributes, functions and relationships of features. Marine environmental data organization are proposed for marine temporal-spatial process visualization; a software framework of marine processes visualization based on earth model is proposed while a series of visualization methods facing marine data are designed, including time series analysis of point pattern, line pattern, area pattern and volume pattern; visualization methods on marine area process and volume process are mainly studied, ray casting algorithm based sphere model is proposed and process visualization of marine volume data is realized.

[Keywords: marine environment, temporal-spatial process, visualization]

Introduction

Temporal-spatial data model is the core of expression of temporal-spatial process. In temporal-spatial data modeling, ArcMarine defined five universal models: point, line, surface, raster / grid / volume, and multimedia data, with the purpose to establish a unified data framework that enables users to make appropriate modifications based on this framework, so as to suit specific data and applications1. Through process-oriented data organization and storage to achieve a continuous gradient expression of process object, process temporal-spatial data model has become a hot issue in temporal-spatial expression and modeling theory. Reitsma designed process-based temporal-spatial data model from the perspective of process simulation2; Su Fenzhen analyzed the temporal-spatial scope where the process of marine geographic information systems belongs, and discussed the theoretical basis of framework, systems architectures and processes warehouses of marine process geographic information system3; Xue Cunjin took the expression, organization and storage of continuous gradual geographical entities as research objects4. He proposed a process-oriented temporal-spatial data model and took the ocean vortex as an example, to achieve process organization, dynamic analysis and visualization of continuous gradual geographical entities. In this paper, data model based on object characteristics is proposed, whose strength are: (1) it is created based on the characteristics of objects. According to the characteristics of multi-dimensional marine data, features are regarded as basic units and object-oriented technology is applied for designing of this model, temporal-spatial attributes, functions and relationships of features can be easily described; (2) it is based on a unified framework. In this framework, subclasses interacting and having similar conducts with real world objects can be easily created, and to simulate more complex ocean phenomena by combining objects.

By adding time dimension to three-dimensional space, the four-dimensional temporal-spatial data model of the research objects is built, and based on this, dynamic visualization of sea surface elevation, tides, temperature fields, storm surges, CO2 flux literature5-9. In large data rendering, through octree-based data retrieval and LOD strategy the rendering frame rate can be improved10,11; according to display detail-level required for visualization, non-overlapping adaptive grid is adopted to improve rendering efficiency, and this method is actually based on LOD12.

In this paper, Marine environmental data
organization is proposed for marine temporal-spatial process visualization, and the problem of integration, process storage of multi-source, heterogeneous marine environmental data is resolved; a software framework of marine processes visualization based on earth model is proposed; based on the data model and software framework, a series of visualization methods facing marine data are designed, including time series analysis of point pattern, line pattern, area pattern and volume pattern; visualization methods on marine area process and volume process are mainly studied.

Materials and Methods

Marine multi-dimensional monitoring technology provides necessary base and guarantee for obtaining marine data. In this paper, the sources of marine environment data are mainly from field observation survey, remote sensing and numerical simulation.

Spatial object of marine environment

Temporal-spatial data organization of marine environment elements is basis of its visual expression. In this study, features are regarded as basic units, and object-oriented technology is applied for designing of space, time and temporal-spatial attributes, functions and relationships of features. By abstraction of element features, marine environment elements are divided into four categories: marine point, marine line, marine area and marine volume. All spatial objects are inherited from space object class MarineObject. MarineObject class diagram is shown in Fig.1.

Marine points can be divided into three categories: InstantaneousPoint, LocationSeriesPoint, and TimeSeriesPoint. InstantaneousPoint provides a common feature class that requires a location (x, y, z) as well as a time (t) description in addition to any measurement (m1… mn) attributes collected at that location in space and time. Each observation in this generic data type is independent, e.g. data of CTD (Conductance, Temperature, Depth). LocationSeriesPoint subclass represents a series of point locations for an identified feature, e.g. a vessel moving along a track, an autonomous vehicle conducting a dive. TimeSeriesPoint subclass represents features that stay in a fixed location but
record attribute data over time, e.g. weather buoy recording wave heights and wide speeds at a fixed location, a gauging station in an estuary that records changes in salinity.

Elements of marine line include FeatureLine and TimeSeriesLine. FeatureLine subclass provides a common class for the representation of attributes along a linear feature, which require a unique identifier; a vector of x, y, z coordinate pairs; as well as free-form measurement attributes unique to the particular application. TimeSeriesLine provide a common feature class that requires additional starting time, ending time, and duration, e.g. a segment of an autonomous vehicle track.

Elements of marine area include RasterArea and MeshArea. RasterArea is used for describing marine satellite observing data, e.g. sea surface temperature (SST); sea surface height (SSH). MeshArea is used to describe marine grid data of numerical model calculation, such as various types of forecasting and re-analyzing data. MeshArea includes ScalarMeshArea and VectorMeshArea. TimeSeriesRasterArea, TimeSeriesScalarArea and TimeSeriesVectorArea are used to describe area features lasting for a certain period of time.

MarineVolume class has two subclasses which are MeshVolume and TimeSeriesMeshVolume. MeshVolume is an extension of MeshArea on three-dimension, which is used to describe three-dimensional numerical model data, such as three-dimensional temperature, salinity and flow field data. Marine volume allows for the representation of data as a multilayer stack of column and row mesh data. The structure of this feature allows for a flexible definition of regularly spaced mesh features, with discrete mesh grid locations defined in x, y, and z dimensions.

Object temporal relationship refers the relationship of two objects on the timeline. In this study, each spatial object has a ValidTime and a TransactionTime, and the object of time series has a StartTime, an EndTime and a TimeInterval. Topology consistencies are maintained by defining topology rules and constrain expressions, and by means of version control, temporal-spatial topology consistency of marine objects can be maintained.

**Process data organization**

Storm surge is one of the major natural disasters in marine coastal areas. Among the northwest Pacific coast countries, China suffered storm surge disaster most frequently and severely, with affected area almost throughout China coast area. Storm surge hazard processes are interaction results of multidimensional hazard factors. Study of multidimensional elements comprehensive expression throughout the process of storm surge is in the stage of exploratory. Traditional expression of increased water level field is presentation for the result of process changes, and there is difficulty in understanding of the mechanism of process changes. In this section, a typhoon storm surge process is taken as an example, to verify the practicality of data organization methods in marine environmental multi-factor collaborative expression, and to provide data support for storm surge disaster simulation.

Storm surge comes from severe atmospheric disturbances, for example, strong wind and sudden changes in air pressure (usually refers to typhoons, extra tropical cyclones and other severe weather systems) lead to abnormal sea lift. The marine environment factors corresponded with their class objects are used to introduce marine process data organization methods. A storm surge process simulation involves several marine environment elements like sea surface wind field, pressure field, sea surface height, ocean flow field and so on. Data organization of tide storm is shown in figure 2.

Storm surge process table records the start time, end time, typhoon data, satellite data and grid field data associated. Products of numerical model such as sea surface height, atmospheric pressure etc. are expressed with mesh class. MeshObject class defines the size, shape and dimensions of mesh. MeshID as the primary key identifies a unique mesh. Relationship class MeshHasPoint connects MeshObject and MeshPoint. MeshHasPoints class is one-to-many relationship, allowing a mesh with many points.

MeshPoint class is used to describe two or three dimensional numerical model products. MeshPoint class is a subclass of MarineObject, which inherits the attributes of FeatureID and FeatureCode. MeshPoint class adds attributes of IPosition, JPosition, and KPosition, which were used to describe row, column and depth of the point in a MeshObject. MeshID attribute as a foreign key confirms this point were part of the Mesh.

Generally, numerical models produce time-varying scalar or vector data. VectorQuantity and
ScalarQuantity table further define MeshPoints, allowing data to be stored based on its own vector or scalar attribute. Table entities also come with timestamps so that specific number of a single location can verify with time. Points have values in both tables through the relationship class of MeshPointHasVectors and MeshPointHasScalars. These relationships are one-to-many relationships, so that one point can have one or many VectorQuantities and ScalarQuantities.

### StormProcess

<table>
<thead>
<tr>
<th>StormID</th>
<th>MeshID</th>
<th>RasterID</th>
<th>TyphoonID</th>
<th>StartTime</th>
<th>EndTime</th>
<th>TimeInterval</th>
</tr>
</thead>
<tbody>
<tr>
<td>1211</td>
<td>M001</td>
<td>R01211</td>
<td>1211</td>
<td>2012-08-03 08:00</td>
<td>2012-08-02 20:00</td>
<td>2</td>
</tr>
<tr>
<td>1223</td>
<td>M031</td>
<td>R01211</td>
<td>1223</td>
<td>2012-10-24 02:00</td>
<td>2012-10-29 16:00</td>
<td>2</td>
</tr>
</tbody>
</table>

### Software framework of marine environmental data visualization based on earth model

In this paper, an extensible framework for marine environmental data visualization is created, as shown in the figure 3. OSGEarth which is open source 3D GIS software is chosen as basic software platform, so as to provide an integrated data temporal-spatial dynamics visualization environment for data base on 3D earth model. From the bottom to top of the framework are data access layer, business logic layer and presentation layer.

Responsible for data access, Data acquisition layer applies SELECT, INSERT and UPDATE operations to data table, and it is mainly SELECT operation which acquires data used for business logic layer.

Implemented between data access layer and presentation layer, business logic layer plays a role of connecting link in data exchange and process. Following interface-oriented design approach in hierarchical design, the dependency relationship between layers is so weak that changing the design of upper layer has no effect on the underlying layer. When data is acquired, data acquisition layer transmitted it to different spatial objects of business logic layer, to achieve visualization and other operations of the object.
Visualization for one-dimensional data is mainly through graphics and symbols by identifying the value of the location on earth model; cloud map is used for two-dimensional scalar field data; visualization methods for two-dimensional vector field data include expression methods of symbols based and texture-
based; visualization methods for three-dimensional scalar field include three-dimensional profile reconstruction method and ray casting method; symbols based and streaming line based visualization methods are provided for three-dimensional vector field.

Presentation layer is the layer for displaying data and receiving user input data, providing users with an interactive operator interface. Basic functions like interactive roaming, layer management, data query and locate, snapshot and animation are provided in the presentation layer. Thorough interactive operation, user will get the visualization of marine environment element and visual analysis of marine temporal-spatial process in this integrated interface.

**Process visualization of marine elements**

Visualization of marine environment data of different spatial dimensions may use different methods: for one-dimensional data, it mainly identify the numerical information of the location in the space scene with graphics and symbols; visualization methods of two-dimensional scalar data include contour map, imagery, etc., and visualization methods of two-dimensional vector field data include the expression methods based on geometric shapes and texture, etc.. Three-dimensional data visualization is the core of scientific visualization research. Commonly used expression forms of three-dimensional scalar field data include direct volume rendering method, three-dimensional isosurface method and section reconstruction method; for dimensional vector field data, there are section reconstruction method and flow-line method based on geometry.

This section presents visualization methods for point, line, surface and volume process and gives examples of specific applications. Key technologies of marine area process, volume process visualization are described in detail. Through the pyramid slice, efficiency of scalar surface data rendering is improved; through dynamic correction of base state distance and amendments region, rendering efficiency of vector data is improved; Ray casting algorithm based sphere model is proposed and process visualization of 3D marine field data based on earth model is realized.

(1). Visualization of marine point process

Point process visualization method is for spatial point objects, revealing the change process of the physical value of spatial points on time dimension. A time series data obtained by each observation station can be inversed into a point process of the station. The spatial location of the point data keeps relatively unchanged, however, the attribute information changes over time, such as seasonal variations in water temperature, ocean tide changes with time. These changes can be demonstrated with a continuous curve in a two-dimensional geometric coordinates in which the horizontal axis indicates time and the vertical axis indicates the property values.

There is another type of point data, whose spatial position and properties change with time, such as a typhoon process. For simulation of typhoon process, through mapping of spatial location and time, the position and associated attribute information of the point can be dynamically marked in two or three-dimensional coordinate system, as shown in Figure 4.

![Fig.4–Visualization of typhoon process on earth model](image)

(2). Visualization of marine line process

Line process visualization methods mainly focus on linear targets, which may be a fixed horizontal or vertical survey line, or line whose position changes with time. Expression of line process is the process of physical quantities of each point on line changes with time. Visualization methods of line process can be divided into two types: static chart expression and spatial dynamic visualization.

![Fig.5–Visualization of ocean front on earth model](image)
Static chart is suitable to express survey line values change with time, for instance, vertical axis represents the attribute value and the abscissa represents the position of points on line. By using lines of different colors to indicate different time, the change of physical quantity with time can be got.

Spatial dynamic visualization means marking line in two or three-dimensional space, to express physical quantity of each point on the line through symbolic forms (colors, symbols, labels, etc.). As shown in Figure 5, when a time interval is set, dynamic process of the curve can be present by drawing continuously the curve on which time corresponding to physical quantity.

(3). Visualization of marine area process

Area process visualization methods focus on area target, which can be flat or vertical section. Area process visualization is rather intuitive that one can easily reproduce the variation of physical values on the planar through presentation of area process, and to discover laws.

In this paper, an area process is transformed into a time point snapshot on time series, to show the temporal-spatial process of ScalarMeshArea object. First, the data is preprocessed, and the cloud map texture is generated; then area texture is pyramid-sliced to generate TMS (Tiled Map Service) as the successive frames of temporal-spatial process dynamic visualization. By pyramid-slicing the texture, efficiency of data switching and display can be improved. Figure 6 shows seawater temperature variation with depth based on the earth sphere model.

In this paper, vector symbol is used to express VectorMeshArea object. In order to improve the speed of real-time rendering, the idea of base state with amendments temporal-spatial data model is introduced for data rendering. In base state with amendments temporal-spatial data model, base state generally refers to the last updated data state by system, while in this case it refers to complete rendering (all grid points are rendered) data of a single moment. Number of data frames between two adjacent base states is named distance of ground state; marine data differs from other temporal-spatial data on the land, since the continental shelf is determined, there is no need to add or remove object. To judging two adjacent data frames on the same grid points, the value determining whether property value changes is called variation domain (vector data has two properties: magnitude and direction, and any one property changes is considered that the state of the object changes). Figure 7 shows of base state with amendments data models with multi base state and single amendments region.

Determination of base state distance is mainly affected by the time interval, area size and grid density of data products, i.e. it is co-affected by the data amount of a single time and total data amount of time series. Difference of data grid density (i.e. grid interval) directly results of geometrical increase of data amount. The ocean is always changing, and determination of variation domain values is mainly affected by the situations of the sea area reflected by data. When the variation of selected physical quantity is significant the domain value is relatively small, otherwise it is relatively large. When startup
rendering, the base state and amendments region are determined according to the selected time period length and data quantity. By skipping grid points in which both the data value and its previous time value are in amendments region, rendering time can be saved in a certain extent.

Fig.8–Dynamic visualization of sea surface wind on earth model
1st February, 2013 (a: 15:00; b: 16:00; c: 17:00)

Fig.9–Ray casting volume rendering algorithm based on earth model

Step 2, using the ray-casting algorithm to render proxy geometry. After two times of rendering, the forward and back depth map of proxy geometry is obtained. The world coordinates of current fragment is got in fragment shader, and according to its screen coordinates the corresponding back world coordinates is got in back depth map. At this time, the world coordinate of both incident and exit points for light on the geometry have been obtained, and according to the step-length a series sampling locations can be obtained.

Step 3, coordinate transformation and texture sampling. In Step 2, the sample points obtained on a light are all world coordinates, while the input data are all latitude and longitude coordinates. Therefore, when sampling in volume texture, the world coordinates should be converted into latitude and longitude coordinates according to ellipsoidal coordinate conversion formula, and the latitude and longitude and depth data should be normalized between 0-1 to sample in volume texture. In sampling, accumulating ceases when the accumulated opacity exceeds 1.
Step 4, temporal-spatial process visualization. To get volume process, three-dimensional field data of a time-series is needed, however big data volume becomes constraining bottleneck for volume process visualization. In this study, the method of pre-loading by multiple threads is used that when the main thread is rendering the data of a time point, the sub-thread read the data of next time point from disk into memory. Meanwhile, in order to further improve the frame rate, rough drawing is done by increase the sampling step-length when the viewpoint moving, fine rendering is done when the viewpoint stops until the next viewpoint moves.

Results and Discussion

Modeling and visualization of marine environment data are important problems to be solved in marine GIS. This paper explored the temporal-spatial data modeling methods which oriented at the features of the marine environment object, combined with the need of marine process visual analysis, proposed visualization software framework for marine environmental information and implementation methods. The main results in this paper are as follows:

(1) Object feature-based marine temporal-spatial process data storage. In this paper, we analyzed the characteristics of multi-dimensional and multi-source marine data, proposed a data storage model for marine temporal-spatial process visualization, and collaborative analysis of multi-dimensional marine elements. Volume process storage method was emphatically introduced and multi-dimensional storm surge data are took as an example to explain the application procedures. The result shows that the object feature-based marine temporal-spatial process data storage approach not only supports single element storage, but also supports integration organization and storage of multi-dimensional elements.

(2) Marine process visualization software framework. For visual analysis, we have designed marine environmental data visualization software framework based on earth sphere model, that supports objects visualization of different dimensions, such as zero-dimensional points, one dimensional lines, two-dimensional surfaces, three-dimensional volume, and thereby achieve visual analysis of point process, line process, surface process and volume process.

(3) Key technologies of marine area process, volume process visualization are described in detail. Through the pyramid slice, efficiency of scalar surface data rendering is improved; through dynamic correction of base state distance and amendments region, rendering efficiency of vector data is improved; Ray casting algorithm based sphere model is proposed and process visualization of 3D marine field data based on earth model is realized.

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