3D Geo-database Implementation using Craniofacial Geometric Morphometrics Database System

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ABSTRACT

Craniofacial Database System has been developed for storing, manipulation and analysis with Geometric Morphometrics concept. The main objective of the system is to store the normal craniofacial (face and/or skull) of Malaysian people. The 'normal' is used for reference in many areas such as surgical planning, forensic, gear protective design, and anthropology researches. The data with which we are working are surface scans. Typically these are triangular meshes, and may or may not have a texture image associated with them. The data can be obtained from photogrammetry system, laser scanning system, or iso-surfaces from volume images (CT or MRI images).

Our geometrical model is based on existing standards of the Open GIS Consortium. There are new data types have been added to OpenGIS SQL Specification. They are Solid, Voxel, Tetrahedron, Pixel, Triangle, 3DRaster, TetrahedronMesh, 2DRaster, TriangularMesh, Node and Vertices. Implementation in PostGIS, extension module for PostgreSQL ORDBMS, was done. PostGIS follows the OpenGIS "Simple Features Specification for SQL". Some functions to enable spatial queries were added by C language. The modification is called PostGISPlus (PostGIS+). Because of characteristic of the geometrical data model is similar with geospatial data then we try to implement 3D geo-database in our developed database system. This paper reports the problems and their solutions in the implementation.

KEY WORDS: Craniofacial, Geometric Morphometrics, OpenGIS, 3D-GeoDatabase

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INTRODUCTION

Background

The word craniofacial is derived from the word cranium, referring to the skull, and facial, referring to the face. Data of craniofacial is needed in many fields (Chong, *et.al.*, 2004). Measurement or anthropometric of the surface of the human head and face is necessary to design personal protective items (respirators, eyeglasses, and other head/face gear), identify missing persons in forensic, and help predict growth patterns and evaluate patients in craniomaxillofacial surgery.

Anthropometric data of the ‘normal range’ group (Farkas, 1994) of the population are needed to plan craniofacial reconstruction of malformation patients because the normal data are often used as the correct dimension for surgery. The step to achieve this goal is to build a database containing sets of “normal” craniofacial data which allows for a comparison of the current shape of a patient with a typical "normal" shape which taking such factors as age and sex of the patient into consideration. In addition, the normal data are required for the forensic applications.

One important technical problem that we were facing in craniofacial database is that of managing surface data from laser scanner (and volumetric data from CT-scanner), processing them, storing the results of the statistical shape analyses, and making them available to all the institutions participating in the project. To solve that problem, we have developed spatial database system based on geo-database approach. We enhanced the OpenGIS simple feature specification by adding new 3-D primitive graphic classes and implemented the enhancement into PostGIS spatial database system.

Objective

As we started with OpenGIS simple feature as a reference, therefore we want to try implementing 3-D geo-database into our craniofacial geometric morphometrics database management system. This paper reports design and implementation of geo-database using craniofacial geometric morphometrics database.

In this paper we first describe geometric morphometrics concept and craniofacial geometric database development, and followed by the difference between the spatial database in medical and GIS environment (Section 2). In Section 3, the relevant literature on spatial data model and structure is highlighted, followed by OpenGIS specification and the presentation of our proposed data structure for integration into an Object Relational DBMS. The implementation process is described in Section 4. It describes a database application to store, manage, retrieve and analyze craniofacial data as a complex object in PostgreSQL DBMS and followed by 3D visualization software. Finally, Section 5 concludes the paper and indicates research directions for future work.

GEOMETRIC MORPHOMETRICS (GM)

Morphometric is the literally the measurement of appearance. Practically it is the measurement of biological shape. Bookstein (1982) defined morphometric as the fusion of geometry and biology, and deals with the study of form in two- or three-dimensional space. Geometric morphometrics began in the early 1980's and continues as the application of superimposition algorithms to coordinate data collected at anatomical landmarks. These techniques go beyond traditional multivariate statistics of linear or angle measurements by allocating size and shape differences between biological forms. These tools are relevant to applications in craniofacial surgical planning, forensic, anthropology and personal protective items design.

Data and method

Landmarks

For analysis purpose, shape is described by a finite number of points, which are called landmarks on object's surface. So a landmark is a point of correspondence on each object that matches between and within populations. Three basic landmarks are generally used (Dryden and Mardia, 1998):

1. Anatomical landmarks.
2. Mathematical landmarks.
3. Pseudo landmarks.

Traditional Methods

To perform a shape analysis, a biologist traditionally measures ratios of distances between landmarks or angles, and then submits these to a multivariate analysis. This approach has been called 'multivariate mophometrics' in biology (Dryden and Mardia, 1998). A considerable amount of work has been carried out in multivariate mophometrics using distance, ratios, angles, etc. and it is still very commonly used in the biological literature.

Geometrical Methods

Like traditional morphometrics, geometric morphometric methods allow statistical conclusion, but importantly, they present several advantages. They allow the geometry of the objects studied to be better retained. They often enable the quantification of features that are difficult to measure with traditional measurements, and are therefore usually described qualitatively. Finally, they allow morphological differences to be visualized in specimen space using interactive computer graphics. This ability to visualize morphological differences is invaluable, particularly when dealing with complex 3-D anatomical structures.

Dense Correspondence Surfaces

In addition to applying existing geometric morphometric methods to answer the questions in craniofacial studies, we are working on the further development of geometric morphometric methods using pseudo-landmarks (vertices on outlines, surfaces and volumes) on surfaces data.

In our working, we adapt and enhance the algorithms from Subsol, *et.al*. (1998) and Hutton, *et.al*. (2001) for automatically building three-dimensional anatomical line features and dense correspondence mesh surfaces respectively. Once our algorithm computes dense correspondence surfaces, all models can be re-meshed using identical connectivity. This enables a whole series of applications ranging from averaging to the transfer of geometric or attributes properties, such as anatomical landmarks, or textures, from one model to a whole set of models. This method means that new scans can be manipulated and analyzed in a fully automatic, without needing to be manually annotated with landmarks before analysis.

Craniofacial GM Database Management System

The research is attempting to build a database system in which forensic investigations, personal protective items designer, medical researches, anthropologist and especially, surgical planner will post, query, and analyze data, processed data, and the results of the analysis.

The requirements for a database of practical use in the craniofacial information system are quite challenging:

1. The database should store not only clinical data and numerical results of the analysis, but also more complex data like volumes, images, and surfaces.
2. Model from database must be ready for surgical planning and simulation software which usually uses two methods, finite element and mass spring elastic analysis.
3. Using of dense correspondence forms, primary keys and fast indexing mechanisms that speed up the database searches to optimize the database at the time of design.

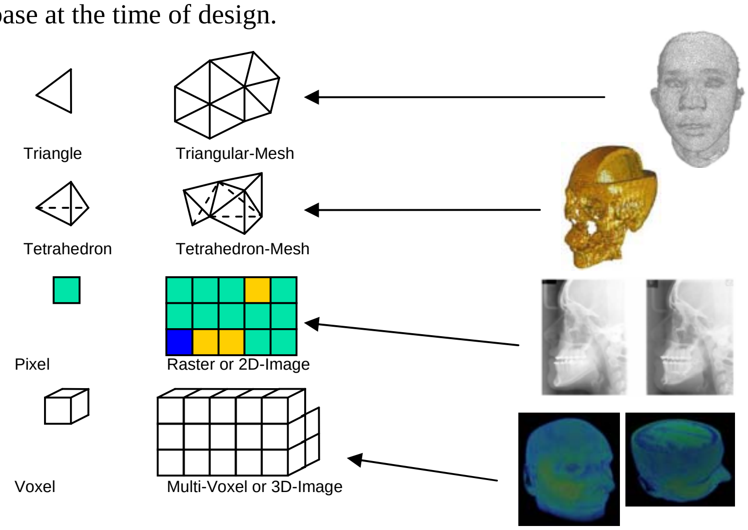

Fig. 1. Geometric Primitive for Craniofacial Data

Table 1. Geometry object in Craniofacial Database

No		Class Name	Geometry Type
1		Exam	
	a	Image	2D Grid
	b	CT Image	3D Grid
	c	X-Ray Image	2D Grid
	d	Laser Image (Surface)	Triangular Meshes
	e	Laser Image (Texture)	2D Grid
2		Model	
	a	Landmark	3D Point
	b	Mass-Spring Model	Triangular Meshes
	c	Finite Element Model	Tetrahedron Meshes
	d	3D Chainmail	3D Grid

There are two important spatial classes in Craniofacial Database, Exam and Model classes. The Exam class has data types including the whole raw data. The important sources of raw data are laser-scan and Computer Tomography images (CT) images, which provide dense surface and volumetric information of the head and face. Sometimes X-Ray images are used too for 2-D mophometrics analysis. Figure 1 visualizes primitive graphics for representation of craniofacial data and table 1 is a list of spatial object in Craniofacial Database. Each object has spatial type correlated with geometry type.

The Differences between CGM and GIS database

The Database Management System (DBMS) technology in GIS environment could be applied into medical or biology environment with some improvements. The improvements or new developments could be introduced back into GIS application. The improvements are needed because there are some differences between the technology and the environment. Belussi *et al*. (1996) give an example of differences between spatial database in GIS and medical field. The spatial database in GIS consists of sets of objects embedded in some spaces. This condition implies that spatial links between objects and space, and also between objects themselves, are to be represented in the model. The spatial database in medical consists of sets of objects that describe different instances of the same object type; these instances could belong, for example, to temporal series or they describe a set of distinct physical objects. Considering that difference, Belussi *et al*. (1996) categorize two most important predicates in object retrieval. They are:

1. Spatial predicates
2. Similarity predicates

Notice that, for the definition of both these types of predicates an important role is played by the spatial relationships. These relationships are based on topological and metric properties. In GIS, such relationships are derived from the embedding of all objects in the same reference space and spatial predicates are used for object query based on the relationships. In medical field, similarity predicates can be based on spatial relationships between objects. Thus two objects are similar, if the same spatial relationships exist among their objects.

3-D SPATIAL DATA MODEL AND STRUCTURE

In literature many conceptual model for 3-D spatial object have been proposed. This chapter reviews the spatial model and how to implement the model into readable and efficient computer format.

Spatial Models

The 3-D spatial models are classified into surface and solid-based and that classification could be differentiated by two different views of space:

1. Space in surface-based model is empty and just littered with objects. Each object is represented individually.
2. Space in solid-based is continuous. Used heavily in the geosciences to study the variability of a phenomenon (called a field), e.g. terrain elevation, water salinity or %gold in rock.

View 1 of space is what is used in vector-based GIS, and in 3-D is often used for the modeling a city with separate, unattached buildings.

View 2 is what geology, for example, is about. We need to discretize a field to model it into a computer. A continuous field can be decomposed:

1. Regularly: elements having same shape
2. Irregularly: with simplices (e.g a Delaunay triangulation or tetrahedralization), or with arbitrary polyhedral.

Each has its strong points, weakness and fields of appropriate application. One of the problems with surfaces is that it is very easy to make mistakes e.g. creating internal representations that are physically not possible or complete. Solid modeling is good for a variety of purposes beyond guaranteeing physically realizable objects. It is easy to derive properties such as length and volume from solids. One problem with solid models is the rendering algorithms are often difficult or produce results of less quality than surface models. This is often resolved by transforming the solid model into a boundary model prior to rendering.

Spatial Data Structures

We must differentiate between spatial data models and spatial data structures – spatial data models are useful as the foundation for spatial data structures and a spatial data model is implemented using a selected spatial data structure. Grid, shape model, facet model, and B-rep are examples of surface-based representation. 3-D array, octree, Constructive Solid Geometry (CSG) and 3-D TIN (Tetrahedral network, TEN) are examples of volume-based representation.

Based on reviewing from Gold and Ledoux (2005) proposal, the main 3-D data structures would be classified as follows:

1. 2-D (surface) decomposition (b-rep, for a single solid object).
   - half-edge, winged-edge, quad-edge, doubly connected edge list (DCEL)
   - Triangulation (TIN)
   - GIS topological models (Zlatanova *et.al*., 2004)
2. Regular 3-D (volume) decomposition
   - voxel, octree
3. Irregular 3-D (volume) decomposition
   - facet-edge, G-maps, generalisation of half-edge to 3-D, and simple tetrahedralization
4. CSG (Constructive Solid Geometry – Boolean combinations of simple solids).
5. Non-manifold 3-D structures.

OGC Specifications

Open GeoSpatial Consortium (OGC) is a non-profit organization dedicated to open systems geoprocessing. OGC gives standards in the GIS field and recommends the directions for GIS researchers. One of the main tasks of OGC is to develop specifications, which follows strict procedures and policies. The OGC creates two kinds of specifications: Abstract specifications and Implementation specifications.

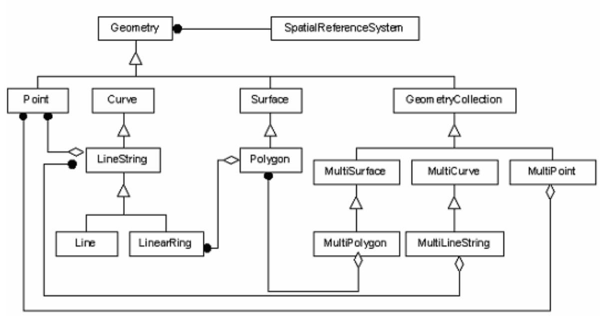

Fig. 2. OpenGIS simple feature geometry class hierarchy

A spatial DBMS supported OGC implementation specification should support the following spatial types (Figure 2): Geometry, Point, Curve, LineString, Line, LinearRing, Polygon, Surface, GeometryCollection, MultiPoint, MultiCurve, MultiLineString, MultiPolygon, and MultiSurface.

DATABASE DEVELOPMENT

One of the most important aspects of the craniofacial database development that is the integration of volumes (solid), 2-D images, 3-D images and surfaces into the database as data types. Volumes and surfaces (images are a sub-type of surface and volumes) are defined as data types that can be included as columns in an object-relational database, and a suitable algebra is defined in order to manipulate them. Therefore, we propose a model that is based on OpenGIS simple feature specification, thus the manipulation is more compact and easier to handle.

Geometric Data Model and Structure

We would like to generate a “complete” 3-D data structure that could integrate at least categories 1, 2 and 3 brief reviews in section 3.2. Boundary modeling (b-rep) is a starting point for our model design. Boundary modeling (b-rep) involves representing the solid object as a set of bounding faces. This requires information about the connectivity of the faces.

Tetrahedron consists of 4 triangle faces that form a closed object in 3-D coordinate space (Fig. 3.a.). The object is well defined, because the three points of every triangle always lie in the same plane. It is relatively easy to create functions that work on this primitive. The disadvantage is that it could take many tetrahedrons to construct one factual object (Aren, *et.al.*, 2005). To solve the disadvantage, we created tetrahedron-collection or tetrahedron-mesh. This is suitable with the concept of Geometry-Collection class which is defined in OpenGIS Simples Features Specification. Figure 3.a shows a tetrahedron object and figure 3.b. shows tetrahedron-meshes that represents 3-D geology layers.

In 3-D GIS application, most of the work done for modeling cities uses vector-based models. Each building or object is represented with a b-rep (boundary representation). Most of the efforts of this community is to develop models to store individual objects and to detect 'topological relationships' between 3D objects, i.e. to know where and if objects touch/intersect each other. Doing these assumes, in our model, that only individual objects are stored in a database as polyhedron and topological relationships are restored 'on-the-fly'.

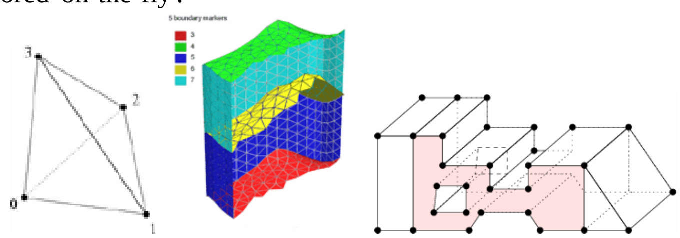

Fig. 3. (a) tetrahedron, (b) tetrahedron mesh for 3D geology model, (c) polyhedron (Tetgen, 2006)

Polyhedron is made up of several flat faces that enclose a volume (see Figure 3.c). An advantage is that one polyhedron equals one factual object. Because a polyhedron can have holes in the exterior and interior boundary (shell), it can model many types of objects.

Triangle, tetrahedron, and polyhedron are composed of vertices, edges, faces and an incidence relationship on them. The arrangement of the vertices of faces in the outer boundaries is counter-clockwise, as seen from the outside of an object, and arrangement of the vertices of faces in the inner boundaries is clockwise (and all inner rings in reverse order). In other words, the normal vector of the face points to the outside of the object.

Definition of Abstract Data Types for New Geometric classes

To achieve that integration, there are some data types must be added to OpenGIS SQL Specification. They are Solid, Voxel, Tetrahedron, Pixel, Triangle, 3DRaster, TetrahedronMesh, 2DRaster, TriangularMesh, Polydedron, Node and Vertices, and the relationships between them are shown in Figure 4 using UML (unified modeling language).

The relationship between the new classes are that Triangle and Pixel as new subclasses from Surface, Solid as a new subclass from Geometry, Tetrahedron and Voxel as new subclasses from Solid, TriangularMesh and 2DRaster as new subclasses from MultiSurface, MultiSolid as a new subclass from GeometryCollection, and TetrahedronMesh and 3DRaster as new subclasses from MultiSolid. To support Triangle and Tetrahedron geometry construction, Vertices and Node classes was created. Vertices class is identical with MultiPoint class but different meaning in representation of real features. Node is a 'symbolic pointer' to point in vertices.

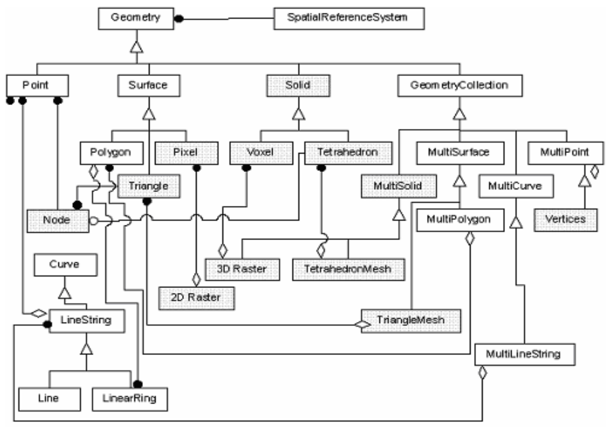

Fig. 4. Enhanced OpenGIS geometry class hierarchy

Data Definition Language

In PostgreSQL, creating a new base type requires implementing functions to operate on the type in a low-level language, usually C. A user-defined type must always have input and output functions. These functions determine how the type appears in strings (for input by the user and output to the user) and how the type is organized in memory.

An accepted way to represent new geometry classes in memory would be the following C structures. The C structures were compiled and held in libpostplus.dll file.

Schema of Data Table

Once the geometric data type is created in PostgresSQL environment then we can create tables for implementing our database design. Creating a table with spatial data is done in two stages: create a normal non-spatial table and add a spatial column to the table using the OpenGIS "AddGeometryColumn" function. In order to create a table named “models” containing geometric data, we can use the SQL statement as:

```
CREATE TABLE models (id int4, type varchar
(128), patient_id varchar (11) );
SELECT AddGeometryColumn( ’models’, ’the_geom’,
-1, ’GEOMETRY3D’, 3 );
```

In OpenGIS specification, data can be organized using WKT or WKB representation. For the purpose of supporting new geometry data, the corresponding WKT and WKB structure should be given. Table 2. lists the WKT representation

Table 2. WKT Representations

Geometry Type	SQL Text Literal Representation	Comment
Tetrahedron	`‘TETRAHEDRON (VERTICES (10 10 10, 20 20 20, 30 30 30, 40 40 40), CONNECTIVITY (1 2 3 4))’`	A Tetrahedron
TetrahedronMesh	`‘TETRAHEDRONMESH (VERTICES (10 10 10, 20 20 20, 30 30 30), CONNECTIVITY (1 2 3 4, 2 3 4 5))’`	Tetrahedron Mesh Consisting of 2 tetrahedron
Polyhedral	`‘POLYHEDRON (VERTICES (10 10 10, 20 20 20, 30 30 30), CONNECTIVITY (1 2 3 4, 2 3 4 5))’`	

Data Manipulation Language and Examples

Manipulation operations on geometric data types include selections on the values associated, volume and surface creation operations, aggregate operations like averages of certain quantities, distance, volume, area, and join intersection unions.

Considering that the current structure of SQL with the SELECT-FROM-WHERE block is complex enough to use by naive users, some statements with SELECT-FROM-WHERE clauses are taken as case studies. The following two samples are simple and complex query.

1. To export the triangular meshes of a given patient and create an image in VRML format.

```
SELECT aswrl(the_geom) FROM models WHERE type=’FEM’
```

2. To ask for all pairs of patients’ p and q such that p has abnormality while q is normal but such that the “abnormal portion” of p’s mandible is more extended than the q’s mandible.

```
SELECT p.patient_id, q.patient_id, FROM model p,
model q WHERE (p.diagnosis = ’abnormal’ and
q.diagnosis = ’normal’) AND
area(difference(p.the_geom, q.the_geom))
```

Spatial Index

PostgreSQL supports three kinds of indexes by default: B-Tree indexes, R-Tree indexes, and GiST indexes. In this research, GiST is used. GiST stands for "Generalized Search Tree" and is a generic form of indexing. In addition to GIS indexing, GiST is used to speed up searches on all kinds of irregular data structures (integer arrays, spectral data, etc) which are impossible done by normal B-Tree indexing.

To query for similar objects in Craniofacial Geometric Morphometrics Database database, we first transform the correspondence facial models to be invariant with respect to scale, position and rotation by means of a modified Principal Component Analysis (PCA). After this normalization step, feature vectors are extracted to capture certain aspects of the models. Therefore, GiST indexing structures is performed for the typically high-dimensional feature vector data. Figure 5 shows the similarity search idea.

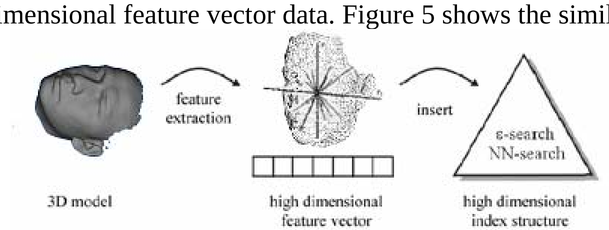

Fig. 5. Main idea behind the similarity search system.

GiST (Generalized Search Trees) indexes break up data into "things to one side", "things which overlap", "things which are inside" and can be used on a wide range of data-types, including GIS data. PostGIS uses an R-Tree index implemented on top of GiST to index GIS data.

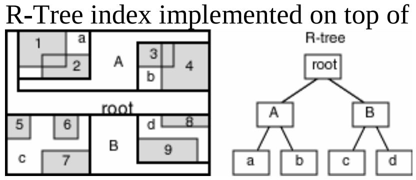

Fig. 6. R-Tree Indexing for 2 Dimension Bounding Box

The 3-D bounding box of geometry object is an object of indexing, so at each geometry objects there is an `xmin`, `ymin`, `zmin`, `xmax`, `ymax`, and `zmax` information. Figure 6 illustrates how the bounding boxes are indexed by R-tree structure.

Validation

It is important that the geometric data be checked when it is inserted or changed in the DBMS. Checking the geometry of the spatial objects is called validation (Arens, *et.al*, 2005). PostGIS uses the GEOS library to provide geometry tests (Touches, Contains, Intersects) and operations (Buffer, GeomUnion, Difference). Because GEOS is not suitable for validation of our new 3-D geometry type then the program TETGEN (Tetgen 2006) developed by Hang Si is used for validation of new 3-D geometry data types.

The inputs of TetGen are called piecewise linear complexes (PLCs). Any polyhedron is a PLC. Furthermore, PLCs are more flexible than polyhedra to represent three-dimensional geometric objects. The definition of PLCs requires that they must be closed under taking intersections, that is two segments only can intersect at a shared point, two facets are either completely disjointed or intersecting only at shared segments or vertices or a union of shared segments and vertices (because facets are non-convex). Another restriction of the facets of PLCs is that the point set which used to define a facet must be coplanar. Figure 7 shows non-closed configurations for examples.

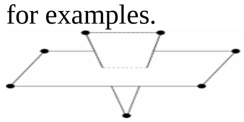

Fig. 7. An invalid PLC example. two vertices and one segment are missing (Tetgen, 2006)

However, geometry objects created by most of the GIS or CAD tools usually do not satisfy this condition. TetGen can check and find out all the intersecting facets of the 3-D geometry record and report in query result.

Visualization

Geometric objects and meshes are best understood by visualization. We used two types of programs: our developed client/server application or VRML viewer. Borland Delphi programming tools enriched with GLScene components (GLScene, 2006) were used in order to simplify the procedures of creating real 3-D scenes client/server application. GLScene is an OpenGL based 3-D library for Delphi.

Zeos component (Zeos, 2006) is used for database connection. Zeos library is a component set for Delphi to access some database engines. The protocol property allow the selection of the database server. It supports Postgresql and other popular DBMSs.

A number of functions enabling to modify the visualized 3-D scene and make it dynamic were introduced into the created application, referred to as "3-D Visualization". The choice of a given option is made in the unrolling menu, using scroll and mouse buttons.

Fig. 8. Client/server application: facial data and skull visualization

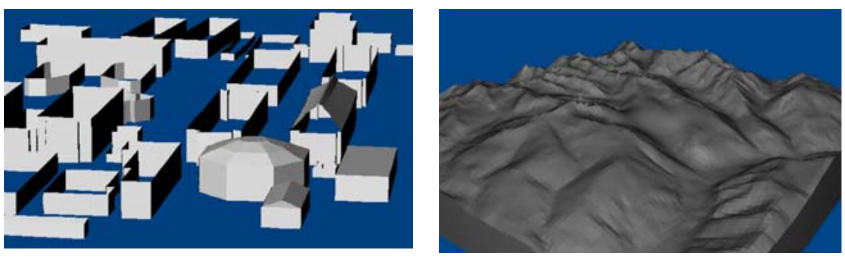

Fig. 9. Visualizations of 3D geodatabase by our client/server application

Figure 9 shows 3D spatial data visualization by our client/server application. Figure 9.a. is visualization of polyhedral of buildings, figure 9.b. is visualization of terrain surface and figure 9.c. is visualization of terrain by tetrahedral mesh.

CONCLUSIONS

New geometric data types implemented in extended PostGIS are suitable for geo-spatial database. The polyhedron structure and tetrahedron-mesh could be used for representing of building object in city modeling and solid terrain, respectively. Tetgen library supports some operations in system, especially for 3-D geometry validation process. In the further work, we will to include The Computational Geometry Algorithm Library (CGAL, 2006) to add 3D spatial operations.

At last, a graphic library in the OpenGL standard was used in our original application designed for dynamic 3-D visualization of objects registered in database. Delphi programming tools enriched with GLScene components were used in order to simplify the procedures of creating real 3D scenes. The program was tested. The application proposed in the study enables dynamic and photorealistic 3D visualization of objects recorded in database.

References

Arens, C., J.E. Stoter, and P.J.M. van Oosterom, 2003. Modelling 3D spatial objects in a GeoDBMS using a 3D primitive. In Proceedings AGILE 2003, Lyon, France, April 2003.

Belussi, A., Bertino, E., Biavasco, A., and Rizzo, S. (1996). Filtering Distance Queries in Image Retrieval. In: Subrahmanian, V.S. and Jajodia, S. ed. Multimedia Database Systems. Berlin, Germany. Springer-Verlag. 185-211.

Bookstein, F.L. 1991. Morphometric Tools for Landmark Data. (Cambridge University Press)

Chong, A.K., Majid, Z.B., Ahmad, A.B., Setan, H.B. and Samsudin, A.B.R. 2004. The users of a national craniofacial database. New Zealand Surveyor. 294: 15-18.

Dryden, I.L., and Mardia, K.V. 1998. Statistical shape analysis. London: John Wiley and Sons.

Farkas, L.G. ed. 1994. Anthropometry of Head and Face. 2nd ed. New York: Raven Press.

Hutton, T.J., Buxton, B.F., and Hammond, P. 2001. Dense surface point distribution models of the human face. In Proc. IEEE Workshop on Mathematical Methods in Biomedical Image Analysis, Kauai, Hawaii. p. 153–160.

Subsol, G., Thirion, J.P. and Ayache, N. (1998). A scheme for automatically building three-dimensional morphometric anatomical atlases: application to a skull atlas. Medical Image Analysis. 2(1): 37-60.

Zlatanova, S., A. A. Rahman, and W. Shi, 2004. Topological models and frameworks objects. Computers, Environment and Urban Systems, 30:419–428.