THREE-DIMENSIONAL GEOGRAPHIC INFORMATION SYSTEMS - STATUS AND PROSPECTS

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ABSTRACT:

From the beginning after the introduction of geographic information systems (GIS) the R&D activities concentrated mainly on the computerized link of two-dimensional geometric and various thematic data. Resulting software packages – also called GIS products – are used for digital mapping, spatial data analyses, or simply for data retrieval. Currently, efficient GIS products are offered by vendors which besides the two-dimensional x, y-geometry integrate a digital terrain model (DTM) $z = z(x, y)$ for the representation of the 3rd dimension. The introductory part of the paper reviews concepts and realizations for the extension of the geometric GIS dimensions. After some metric definitions several approaches are presented in more detail to overcome the lack of single valued 3D geometry. It is shown, that most commercial GIS products use the layer-oriented DTM integration. The second part of the paper deals with 3D modelling of other georelated disciplines such as geology, geophysics, hydrology, etc. It can be seen, that these disciplines apply modelling strategies of solid geometry. The link of the data models applied here with the DTM integration of the surveying disciplines comes to strategies which integrate both: the topographic boundary and solid 3D geometry. The 3D data retrieval differentiated in *measurement functions, spatial predicates*, and *object generating functions* is discussed. The resulting query language should take into acount these classes of data retrieval. The last part of the paper gives an outlook on using object-oriented techniques for solving the 3D modelling problem. Using the example of automated extraction of buildings an object class builder is shown which takes into account the DTM (regular grid, TIN) and the 3D representation of buildings. Also existing object-oriented database management systems will be discussed which are used for 3D data models and its data retrieval.

1 INTRODUCTION

The fast development of the fascinating field of geographic information systems (GIS) was dominated for a long time simply by converting analog map data into large digital databases. For more than two decades the 'map geometry' (i.e. x, y-coordinates, 2D topology) was digitized, linked with attributes of various themes, and then stored in non-standard database systems (H.J. Schek, 1996). Most of the progress in GIS was initiated during the last 10 years – the use of relational database management systems (RDBMS), data standardization procedures, object-oriented modelling techniques, and last but not least height data integration, to name only few.

The problem of integrating some height information is a matter of great concern not only for photogrammetry, but also for other georelated disciplines which make fully use of 3D data. Therefore it is out of question, that GIS R&D can not accept any longer only 2D geometry, particularly if topographic mapping is concerned, and if the actual shape of the Earth' surface is investigated for exploration and environmental purposes.

First proposals, initiated by the domain of utility information systems, assigned $z-$values as attributes for the (x, y) location. This non-geometric height data integration was capable to overcome an urgent need being three-dimensional. But research in the recent past has shown, that regional and local GIS as well as its software (GIS products) that is specifically designed for topographic mapping, should be at least two-and-a-half-dimensional (2.5D). For geoscientific data, where objects at one (x, y) location only have a single z value, a 2D GIS product might be adequate (D. Fritsch/D. Schmidt, 1995, D. Schmidt/D. Fritsch, 1996), because the 2D data model can be extented to 2.5D. Most 2D GIS products have facilities for perspective display of surfaces that are single valued (not more than one z value per location x, y).

Besides that, GIS and belonging products designed specifically for geological work, particularly for mining and oil exploration, need to be fully three-dimensional, so that each data object is characterized by its location in space with three spatial coordinates x, y, z (T. Bode et al., 1994, M. Breunig, 1996, H. Kasper et al., 1995). The same holds true for urban information systems, that can not renounce on three-dimensional modelling and graphical output. Therefore, in the following the state-of-the-art of height data integration is reviewed. Some interests are also directed to the potential of 2.5D and 3D that should be opened for GIS applications in near future.

The starting point for height data integration at least for a 2.5D approach is the geometric-topological data structure for vectorial data that combines nodes, edges, and areas. Using the entity-relationship (ER) model the following 2D data structure is given

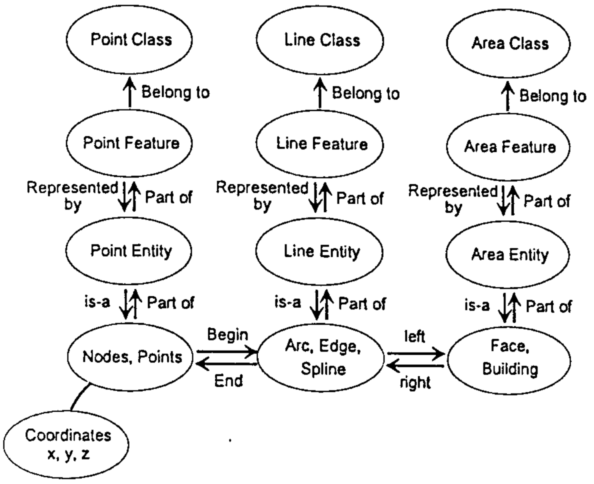

Figure 1: 2D geometric-topological data structure of GIS

The extension of this data structure was first proposed by D. Fritsch (1991) and M. Molenaar (1992). In the meantime, some proposals are made taking into account a real integration of topographic geometry and topology with the counterparts of planimetry (M. Pilouk/O. Kufoniyi, 1994, P. van Osterom et al., 1994, D. Fritsch/D. Schmidt, 1994).

2 DTM INTEGRATION

The integration of digital terrain models in GIS is announced by some vendors of GIS products. But a closer look indicates that the DTM is not at all linked with the x, y geometry and therefore represented only as an additional isolated data layer $z = z(x, y)$. In this case, a weak 2.5D description is reached that might be adequate for medium scale applications but not for large scale mapping.

In country-wide applications a DTM is often modelled by a grid of fixed raster cells or variable raster cells (e.g. quadtree structure). As mentioned before the underlying data structure is differentiated in its topological elements and geomorphological features (see fig. 2)

If there is no link between the two structures (fig 1) and (fig. 2) then undesired results appear, particularly because of superimposed graphical output, for instance, contour lines are derived within the planimetric ring polygon of a building, and are on top of street surfaces etc.

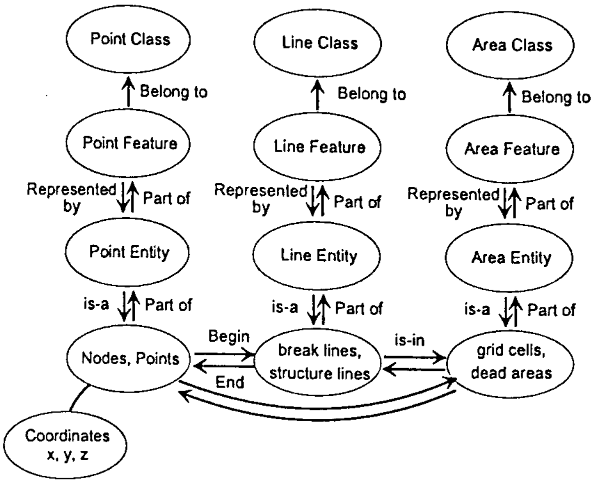

Figure 2: Geometric-topological data structure for a DTM of fixed raster cells

A useful topological data structure for the presentation of irregular distributed points on the Earth' surface is performed by *triangulation* algorithms. Very often, a Delaunay triangulation is carried out that can be derived from the *Voronoi diagram* (see fig. 3). For the points $p_i \quad \forall 1 \leq i \leq n$, the Voronoi diagram consists of n regions $V(i)$ with the characteristics that if $(x, y) \in V(i)$ then p_i is the nearest neighbour of (x, y). If $H(p_i, p_j)$ is the half-plane with the set of points closer to p_i than to p_j, then

$$V(i) = \bigcap\nolimits_{i \neq j} H(p_i, p_j)$$
$$\text{with} \quad d(v, p_i) \leq d(v, p_j) \forall v \in H(p_i, p_j)$$

The Voronoi diagram delivers one method to derive the triangulation after Delaunay. The straight lines dual to this diagram form the edges of the triangles. A defining property of the Delaunay triangulation is that the circumcircle of each triangle does not include any other point in its interior. Fig. 4 demonstrates the dual-graph property of the Voronoi diagram and the Delaunay triangulation.

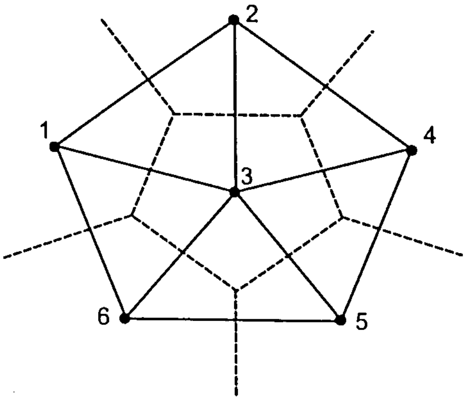

Figure 3: Voronoi diagram

A corresponding geometric-topological data structure of a triangulation in comparison with a gridded DTM delivers a similar pictogram (see fig.4). The advantage of an irregular triangulated network (TIN) compared with a gridded DTM is taken from the fact that triangles of a TIN represent very close geomorphological features. This results simply from the primary data acquisition process that discretizes the continous Earth' surface mainly in those points in which geomorphological characteristics change.

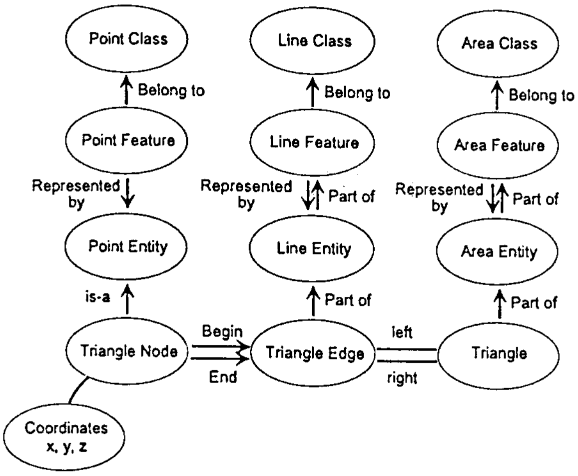

Figure 4: Geometric-topological data structure of a TIN

Fig. 4 is derived from a fully geometric-topological data structure. Further structures that define topological TIN organizations according to triangles and edges, respectively, are given by D. Fritsch (1991).

2.1 Layer-oriented DTM in GIS

The layer approach is the oldest data structure that emerged from the superimposition of various analog maps. The link of the DTM with planimetric features is realized by the coordinate reference system, which has to be identical for the layers superimposed with each other. This superimposition should not be called ' integration ' because no real integration step is carried out.

Contrary to the primary DTM interpretation problem there is no doubt that the layer approach of DTM derivates in vector and raster form, for instance contour lines, slope and aspect information, shaded reliefs etc. delivers an adequate data storage model. In some cases, the superimposition of a few derivates comes out with new information in the sense, that the terrain can better be interpreted than before, and spatial analysis is performed in an excellent manner.

2.2 Fully integrated 2.5D data model

The integration of DTM data structures with their planimetric counterparts is also dealt with in P. van Osterom et al. (1994), M. Pilouk/O. Kutoniyi (1994) and K. Kraus (1995). Above all, the integration consists of a link between planimetry and topography. That means, a geomorphological feature should have a counterpart in planimetry, but must not necessarily. The way of implementation is not to be defined in a strict sense, as also shown in the section of open system architectures.

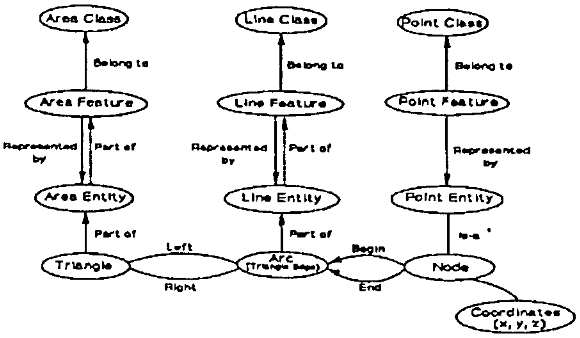

Figure 5: 2.5D data structure of integrated TIN (Copyright/Courtesy: M. Pilouk/O. Kutoniyi, 1994)

The proposal of M. Pilouk/O. Kutoniyi integrates a TIN DTM and multitheme geoinformation as represented by fig. 5 in a most rigorous approach. In their model, terrain features are classified into three geometric types: point (0 simplex), line (1 simplex) and area (2 simplex) in each mapping theme. In addition, features are grouped into mutually exclusive thematic classes in each layer. These classes are simply represented by class labels. The type to which a feature belong will be decided during the implementation step. For the representation of terrain features, point, line and area entities are used. The same data structure is worked out by K. Kraus (1995).

The implementation of the integrated 2.5D data structure can be realized in a purely relational scheme (M. Pilouk/O. Kutoniyi, 1994). Only eight normalised relations are necessary.

```
R1: AREA (a_id, af_id, layer, a_name, a_class)
R2: LINE (l_id, lf_id, layer, l_name, l_class)
R3: POINT (p_id, pf_id, layer, p_name, p_class)
R4: PNODET (p_id, p_node)
R5: ARC (arc_nr, beg, end, l_tri, r_tri)
R6: NODE (node-nr, x_coord, y_coord, z_coord)
R7: ARCLINE (arc_nr, al_id)
R8: TRIANGLE (tri_nr, ta_id)
```

These relations are derived from six dependency statements. The data types and the link types serve as field names in the final relational structure.

3 THREE-DIMENSIONAL DATA MODELS

Three-dimensional data models often refer to spatial data structures used for mapping of nodes, edges, faces (areas), and volumes. Applications can be found in the geosciences in which particularly solid bodies have to be modelled, analyzed and visualized.

Volume modelling technology and its integration with variable prediction provide a range of options for performing more precise volumetrics analyses. This includes determination of the volume of any irregular shape, or the volume of its intersection with another irregular shape, or the volume of an isosurface of a variable value, and the ability to analyze the contents of any volume or intersection in terms of contained variable values. Most progress realizing these tasks have been reached in geology, demonstrated by S.W. Houlding (1994), G. F. Bonham-Carter, (1994), T. Bode et al. (1994), M. Breunig (1996), and H. Kasper et al. (1995).

3.1 Raster data models

To create a solid model for fully three-dimensional geometry hexahedral volume elements, or *voxels* are introduced, particularly to represent geobodies (S.W. Houlding, 1994). In the simplest voxel representation, a cube, each face is a square. In a more complex voxel, each face can have a different size and shape. This flexibility ensures that the output of practically any finite difference modelling application can be readily accepted as model input.

Voxels are therefore defined using any of several grid structures. In fig. 6 four common structures are sketched that are also implemented in available 3D GIS products (for instance the MGE Voxel Analyst, INTERGRAPH, 1993).

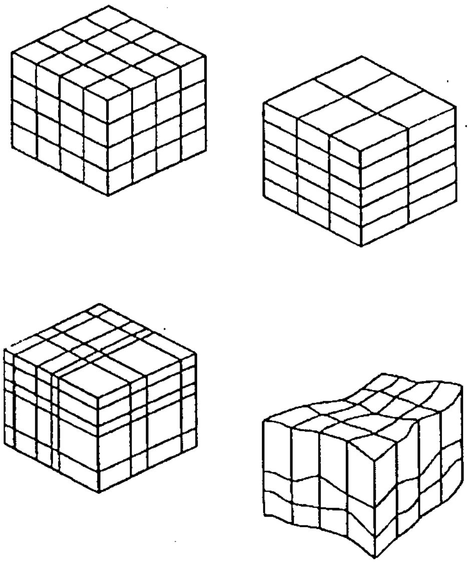

Figure 6: Geobody modelling - (a) uniform, (b) regular, (c) irregular, and (d) structured (Copyright/Courtesy: INTERGRAPH Co., Huntsville).

In the *uniform* approach the grid spacing along all orthogonal axes is constant and identical; all edges are the same length (cubic voxels). The *regular* modelling uses different grid spacing but constant along each orthogonal axis; edges are constant along each axis. In the contrary, if grid spacing varies along each orthogonal axis, and the edges vary in length along each axis, then the *irregular* voxel representation is used. Last, a most deformed voxel representation that is often referred to in geological modelling is the *structured* one, in which grid spacing varies along each orthogonal axis; each edge of each voxel can be of different length. The data results from modelling techniques to conform to geophysical or geological formations and shapes.

3.2 Tetrahedral tessellations

A generalization of the planar Delaunay tringulation leads to Delaunay tetrahedral tessellation (DTT). This is one kind of a simple data structure for spatial solid modelling, particularly if irregular distributed 3D data are captured. Due to its many advantages there are some proposals to use the DTT for 3D GIS (X. Chen et al., 1994). The DTT is derived by the 3D Voroni diagram that is quite similar to the definition of section 2.

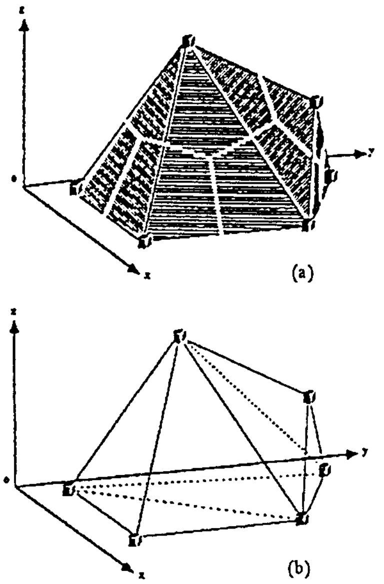

Figure 7: The 3D-Voronoi diagram (a) and the Delaunay tetrahedral tesselation (b) (Copyright/Courtesy: X.Chen/K.Ikeda, 1994)

The Delaunay tetrahedral tessellation is the straight-line dual of the 3D Voroni daigram and is constructed by connecting the points whose associated Voroni influence volumes share a common boundary. The Delaunay tetrahedral tessellation is thus formed from four adjacent points whose Voroni influence volumes meet a vertex, which is the center of the circumsphered sphere of the Delaunay tetrahedral.

The integration of the Delaunay tetrahedral tessellation (DTT) in 2D GIS data structures is proposed in a further contribution given by X. Chen et al. (1994). It is shown, that not only DTT representations but also voxel definitions can be linked with geometric-topological data structures.

4 STRUCTURED QUERY LANGUAGE

The integration of height information extends the query space for spatial queries considerably. New spatial operators can be defined and the existing structured query language, the standard of relational databases, has to be redefined. In general, three different classes of queries can be defined

- Numeric (e.g. the altitude of a mountain), also called *measurement functions*

- Boolean (e.g. is point B visible from point A?), also called spatial predicates or boolean operators
- Operators to create new spatial objects, also called object-generating functions

These three groups of spatial operators will be examined in more detail. It is interesting to see that already the 2.5D approach delivers an considerable improvement of the query space.

1. Measurement functions (for vectorial data)

   HEIGHT interpolates within the GRID, TIN or HYBRID DTM for the height of an arbitrary position (x, y).

   SLOPE derives and interpolates the maximum slope (gradient) for an arbitrary position (x, y).

   EXPOSITION derives and interpolates the direction of the gradient for an arbitrary point (x, y).

   DISTANCE$_{2.5}$ computes the Euclidean distance on top of the DTM. (The equivalent for 2D is DISTANCE$_2$).

   PERIMETER$_{2.5}$ computes the length of a spatial polygon positioned with coordinates (x, y, z). The distance function is a sub-function of PERIMETER. (There is also an equivalent for 2D).

   AREA$_{2.5}$ computes the area of a polygon defined by (x, y, z) coordinates. (The equivalent for 2D is AREA$_2$.)

   VOLUME computes the volume of two different DTMs.

2. Spatial predicates (ordered for points, lines and faces)

   - point/point

     POINT_EQUALS: point is identical with another point

     DISJOINT: point is separated from another one

     VISIBLE: points are mutually visible

   - point/line

     INSIDE/CONTAINS: point is located on an edge, arc, spline etc., an edge (arc, spline) contains a point

     BORDERED_BY/BORDERS: point borders an edge, point is start (end) node of an edge

   - point/face

     INSIDE/CONTAINS: point is located inside a face (area), area contains point

     BORDERED_BY/BORDERS: point borders is located onto the bordering polygon of the face

     DISJOINT: point is not located within a closed polygon representing the face

   - line/line

     TANGENT_TO: the line is a tangent to a polygon (polyline)

     CROSS: the line crosses another line (polygon)

     LINE_EQUALS: the line coincides with another line (polyline)

     DISJOINT: the line is not crossing and bordering another line (polyline)

   - line/face and face/face: equivalent predicates as cited before can be defined (D. Fritsch/D. Schmidt, 1994)

3. Object-generating functions

   INTERSECTION computes new areas (faces) by the intersection of DTM faces with planimetric areas.

   FLOW MODELLING computes for instance the water flow in terrain

SQL3 is the new draft proposal presented by ISO/ANSI. It adresses new features for object-orientation like encapsulation, subtypes, inheritance and polymorphism. It is planned to integrate also the spatial queries that are given before.

5 PROBLEMS AND PROSPECTS

5.1 Open system architectures

Most recently, the problem of data integration is a matter of great interest not only in the field of GIS. The uniform database scheme for one (logical) central database is no longer an absolute necessity. Also the idea, that all data that are needed for an application, should be stored in one database system, is no more obligatory. Very radical and open system solutions are under discussion that allow various modelling concepts and also data levels. These discussions will also have some impact onto 2.5D and 3D GIS and associated products.

In this vision it is generally open, onto which platforms the spatial datasets are stored. A planimetric geometric-topological dataset can be stored on a server on location A, and the topographic dataset on a server or client located in B. The main point is here the link of the two datasets that virtually defines one closed database. This idea of decentral data distribution is researched in computer science since the 1980s under the headline of *distributed databases*.

5.2 Object oriented modelling techniques

Since the 1960s a new technique of software coding is under development that has led to paradigm of object-oriented programming. An important advantage of object-oriented software development is the better correspondence between objects of the real world and objects defined in software development. Every physical object can be transformed to an object in the programming language.

Object-oriented analysis methods provide a tool for designing object-oriented systems. There is a general use of objects from analysis through design to implementation. The object-oriented paradigm provides several advantages, as cited in the following: the reuse of software and design, increased quality of software, easier maintenance, and the most adaptive interface for human cognition.

The object-oriented paradigm has also led to a new generation of databases called object-oriented (OO). Some commercial OODBS are offered by the vendors of DB software, for instance ObjectStore, Ontos, Versant, ODE, O_2, Itasca, Objectivity/DB etc. that are realized as extensions of C++ and Lisp.

In D. Schmidt/D. Fritsch (1994), D. Fritsch/D. Schmidt (1995) two object-oriented DTM integrations have been proposed: the first was implemented in the language E using the Exodus Storage Manager (SM) of the University of Wisconsin, and the second uses the programming language Python. Both implementations presuppose the existence of persistent objects. The following classes were implemented:

DTM This is the highest level of hierarchy. Every access on DTM data is handled by defined or virtual (i.e. only declared) functions of this data type.

GRID Only height values are stored in a grid structure. There is no topological information necessary.

TIN The data is organized by vertices, edges and faces. A grid can easily be converted to a TIN structure.

HYBRID Data is organized as a grid with some meshes containing TIN data structures.

GMF Geomorphological features that are subdivided in subtypes
- **Heightpoint** Point with x, y, z-value (i.e. peaks)
- **Borderline** The border of a DTM, border of areas of equal height or undefined height
- **Breakline** Interuption in surface continuity
- **Structure line** Height value increases or decreases monotonically along the line.

The implementation of these four classes is demonstrated by the data structure of fig. 8, for instance if the DTM class `TRIANGLE` is used. The class `LINKS` needs some pointers backwards, and `NODES` must be notified to store three-dimensional coordinates and two-dimensional ones. The low-level classes `NODE` and `LINK` have counters to store the number of references from each class in the mid-level hierarchy. Every class can be accessed by a spatial index tree (R-Tree).

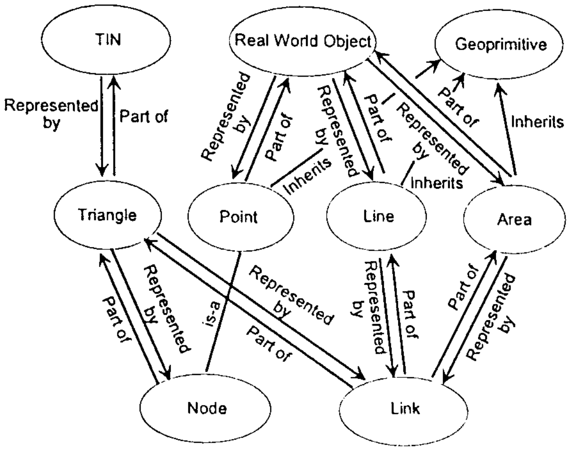

Figure 8: 2.5D data structure of an object-oriented integrated TIN

6 CONCLUSIONS

The integration of height information into GIS databases is an important topic for present and future R&D in this field. Although some progress could be reached in the recent past, the solutions offered so far are not yet fully satisfying.

With the evolution of object-oriented techniques new but probably simpler techniques of height data integration are feasible. New standards will evolve and hopefully merge soon to make the programming effort more valuable by using a common interface.

It seems reasonable to have first a 2.5D data integration. This boundary description is especially desired in topographic mapping. The link of 3D objects with a 2.5D description comes out with a complete modelling of real world objects that is restricted on being *stationary*. The data display can be solved by public domain software products, for instance *Geomview*. This is an interactive program for viewing and manipulating geometric objects. It allows interactive control over the point of view, speed of movement, appearance of surfaces and lines (see fig. 9)

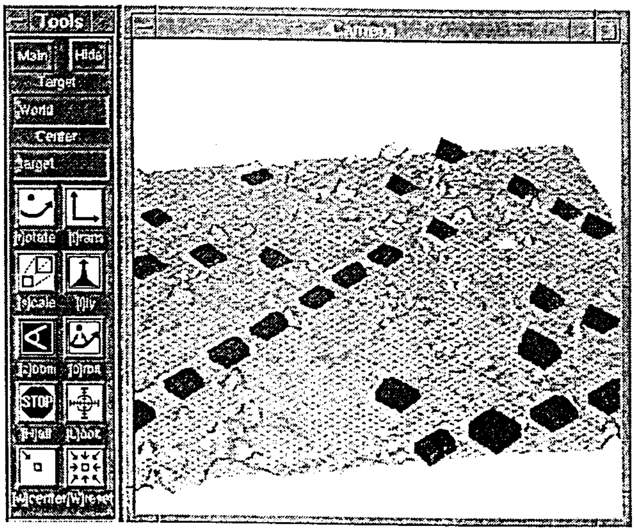

Figure 9: Geomview control panel with grid DTM and attached buildings in camera view

In figure 9 Geomview is used as display engine for 3D spatial data. Geometric descriptions will be sent object by object with an internal name used to reference the geometry. The coordinates will then be send back to the main program together with the name of the selected object. In this way, points or objects can be selected for processing in more complex queries. It is also possible, to dynamically change the geometry, color etc. of the object or adding other objects.

This last visualization gives a concluding impression on the possibilities of efficient height data integration. The real world is three-dimensional – it does not matter how this 3D world is mapped into spatial databases. The main point is the availability of 2.5D and 3D capability in GIS what should be realized in an efficient and robust manner.

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