A Digital Urban Space Model

---- A Three Dimensional modelling technique of Urban Space in a GIS Environment

Commission 4

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ABSTRACT

Conventional two dimensional(2D) maps and DTMs are insufficient to represent geographic information in urban space comprising high-rise buildings and underground structures. There is a pressing need for a model of three dimensional(3D) representation of urban space, that is, a Digital Urban Space Model(DUSM). However, existing solid modelling techniques cannot be directly applied to the 3D representation due to several problems such as the inefficiency in building and updating 3D spatial database. Based on the boundary representation(BR) model, the authors proposed a Surface Represetntation(SR) model which can greatly improve the efficiency in building and updating 3D spatial database. Through an example of the 3D representation of urban space, it is demonstrated that the SR model incorporated with an elevation interpolation method can be succussfully applied.

Keywords; three dimensional(3D) representation, Solid modelling method, Urban space, Boundary Representation(BR) model, Surface Representation, Elevation interpolation

1. INTRODUCTION

In the process of many urban activities such as urban planning, infrastucture construction and facility management , conventional maps and map-derived data such as digital terrain models(DTMs) are used. Although geographic objects represented in these maps are given elevation data, they are not three dimensional(3D) objects because they are represented based on a 2D coordinate system and cannot have multiple elevation values. They should be called 2.5D objects.

However, geographic objects in urban space, such as high-rise buildings and underground structures, have multiple elevation values. The conventional maps and DTMs cannot be successfully applied to the representation of urban space, while they can be sound basis for handling 2.5D spatial data in rural areas.

In several fields such as the planning of urban redevelopment and infrastructure construction, there is a pressing need for a 3D representation model of urban space which can be a basis in integrating geographic data in an urban area. The authors call the 3D representation model a Digital Urban Space Model (DUSM, figure 1).

To handle 3D geometric data , solid modelling methods have been developed for computer aided design(CAD)/ computer graphics(CG) systems. In geological information management, solid modelling methods and related surface interpolation techniques such as NURBS [Fisher and Wales, 1991] are applied for the 3D representation of geological objects [Raper et.al, 1988], [Jones, 1989], [Raper and Kelk,1991].

However, these solid modelling methods could not be directly applied to the 3D representation of urban space because urban space contains a much wider variety and larger amount of geographical objects. It is essential to review the requirements for a Digital Urban Space Model and to discuss the applicability of the solid modelling methods.

The objectives of the study are;
1) to review the basic requirements for a Digital Urban Space Model and to discuss the limitations of existing solid modelling methods,
2) to propose a Digital Urban Space Model and an associated technique of elevation interpolation and,
3) to show the applicability of the proposed model through an example of the 3D representation of urban space.

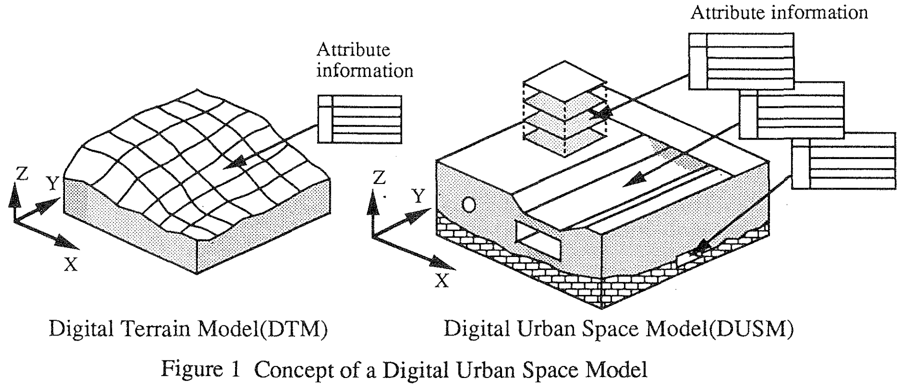


Figure 1 Concept of a Digital Urban Space Model

2. BASIC REQUIREMENTS FOR A DIGITAL URBAN SPACE MODEL(DUSM)

The basic requirements for a Digital Urban Space Model (DUSM) can be summarized as follows [Shibasaki et.al.1990].

1)Ease of representation of a variety of geographic objects in urban space.

In CAD systems for machinery production, almost all spatial objects such as mechanical parts can be represented only by solids. However a much wider variety of geographical objects are to be represented in urban space representation. To represent them with enough fidelity with less data requirement, the combination of geometric features such as points, edges and polygons as well as solids are very useful .

2)Efficiency in building and updating 3D spatial database

Even in building spatial databases based on 2D or 2.5D map data, the cost of the input and update of the data is one of the major inhibiting factors for the wider utilization .The dimensional extension from 2.5D to 3D inevitably increases not only the size of the data but also the complexity of their topological relations, leading to an explosive increase in the cost and care. It is very desirable that 3D spatial database based on a Digital Urban Space Model can be efficiently built and updated.

3)Ease of spatial query and analysis

The variety of potential applications depends on the variety of easily-accessible methods of spatial query and analysis. A spatial modelling method such as a Digital Urban Space Model and the associated data structure should support the easy and efficient query and analysis of 3D spatial data [Smith, 1987].

4)Compatibility with existing map data and CAD/CG systems

Since a large amount of 2D or 2.5D map data have already been prepared to date in many cities, it would be very labor-efficient and time-saving if the existing map data could be directly used in building 3D spatial databases. More importantly, in managing geographic information of a whole urban area, it would be necessary that 3D spatial data should be used together with the existing map data because an intensively utilized area which requires 3D representation is relatively small and surrounded by less intensively used areas where the conventional map representation is sufficient. And also it would be very beneficial if 3D spatial data could be easily transferred to CAD/CG systems for their handling and visualization.

3. PROBLEMS WITH EXISTING SOLID MODELLING METHODS

By reviewing major solid modelling methods from the viewpoint of the requirements for a Digital Urban Space Model, [Shibasaki, et.al.1990] shows that they could not be directly applied to urban space modelling. Among them, although the Boundary Representation(BR) model

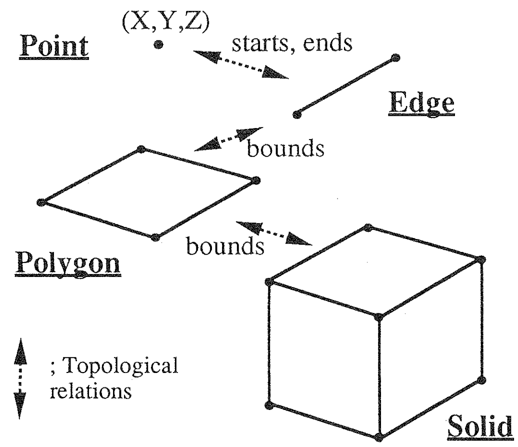


Figure 2 The Boundary Representation(BR) model

(figure 2) fulfills both the compatibility with 2D map data and the ease of the representation of urban space, the input and update of 3D spatial data with the BR model is severely labor-demanding. The inefficiency of the BR model comes from the complicated topological relations to be established in building and/or updating spatial databases.

In building and updating 2D or 2.5D spatial database based on vector data, the automatic identification of polygons by examining the connectivity of edges greatly improves efficiency in the input and the update of a large amount of map data. The polygon identification can be easily automated because the topological structure of 2D vector data based on a planar graph is very simple.

In building 3D spatial databases with the BR model, it is very necessary to efficiently establish far more complicated topological relations, that is, efficiently identify polygons in edges and solids in polygons. An algorithm was proposed for uncovering both planar polygons in edges(wire frame data) and solids in polygons [Markowsky,1980]. However, the identification of non-planar polygons in edges still remains very difficult.

Thus in the input and update with the BR model, users are required to generate enormous number of bounding edges to represent the surfaces with planar polygons. To successfully apply the BR model to urban space modelling, it is very necessary to improve the efficiency in identifying polygons and interpolating their surfaces. Once polygons are identified, topological relations from points to solids can be easily established.

4. A DIGITAL URBAN SPACE MODEL

The authors propose a "Surface" based BR model which can improve the efficiency in the polygon identification in edge data and their surface interpolation.

4.1 "Surface" based Boundary Representation model ---- Surface Representation(SR) model

4.1.1 Introducing a "surface" to the BR model

Many geographic objects in urban space might be located in a relatively smaller number of surfaces. For example, in a terrain surface, many urban objects such as buildings, roads are located and represented by polygons. Edges in such a surface as a terrain surface might be able to be handled as if they belonged to a conventional 2D map data based on a planar graph. If so, polygons could be efficiently and reliably uncovered and the surfaces could also be interpolated very easily.

The authors introduce a "2.5D surface" into the conventional BR model and later examine the possibility of the extension to a 3D surface. A "2.5D surface" is a surface which is represented by a single-valued and continuous function of C_0 class defined on a 2D coordinate system, i.e. v=f(s,t) (figure 3). The v-axis is called a normal direction of a 2.5D surface.

A planar graph in a 2.5D surface can be projected to a planar graph in the s-t plane along v-axis without changing the topological relations. Thus the polygons in the 2.5D surface, whether planar or non-planar, can be uncovered by applying a conventional algorithm to the planar graph in the s-t plane. Surface interpolation algorithms(e.g. TIN) for 2D data can be directly applied to the interpolation of their surfaces. After the identification of polygons and the interpolation of their surfaces, solids can be easily identified by combining 2.5D surfaces.

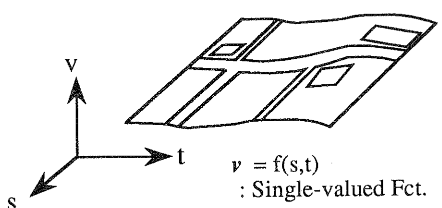


Figure 3 A 2.5D surface

4.1.2 The data structure of the Surface Representation (SR) model

In the update of a 3D spatial database, it would be very convenient to update topological relations by 2.5D surfaces respectively. To support this process, it is necessary to give each edge an attribute of which 2.5D surface contains it so that existing edge data can be retrieved by 2.5D surfaces.

In figure 4, the basic data structure of the Surface Representation(SR) model is described based on the formal data structure of 3D vector maps [Molenaar,1990]. The data structure is the same as that of the conventional BR model except that each edge belongs to 2.5D surfaces respectively. In figure 4, arcs are introduced to avoid n to m (many to many) links between edges and polygons. A class denotes the class of an attribute of geometric features. It should be noted that polygons and edges can be connected with each other through edges even though they belong to different surfaces.

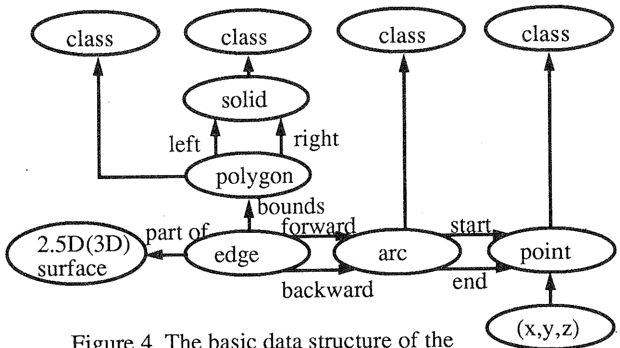


Figure 4 The basic data structure of the Surface Representation(SR) model

4.1.3 Input and update of 3D spatial data with the Surface Representation (SR) model based on 2.5D surfaces

With the SR model, the input and update of 3D spatial data can be done as follows (figure 5);

(1) point data with x-y-z coordinate values and edge data which bound objects such as roads and buildings are allocated to 2.5D surfaces (figure 5, b),c)).

(2) polygons, whether they are planar or non-planar, are identified automatically in each 2.5D surface, and, if necessary, attribute data can be given to them (figure 5,d)),

(3) the surfaces of the polygons can be interpolated using the point data with (x,y,z) with a conventional algorithm such as a triangular tessellation (figure 5,d)),

(4) after the 2.5D surfaces are automatically connected with each other, solids can be uncovered automatically in the same manner as with the conventional BR model (figure 5,e))

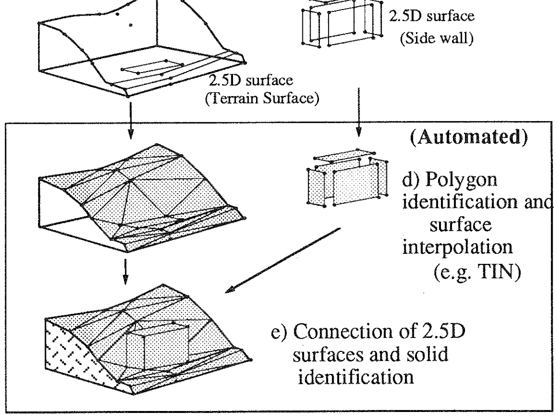


Fig.5 Building 3D spatial database with the SR Model based on 2.5D surfaces

In step (2) ,the polygons can be identified more reliably than by the conventional algorithm [Markowsky,1980], because the reliability of this method cannot be affected by the coordinate errors of points, which often cause the failure of the identification of planar polygons by the conventional algorithm.

Thus the complete topological relations between 3D geometric features can be automatically established with bounding edge and point data obtained by digitization and/or surveying, except that the edge and the point data have to be manually allocated to 2.5D surfaces.

4.1.4 The advantages and limitations of the SR model based on 2.5D surfaces.

The advantages of the SR Model are summarized as follows.

(1)Higher efficiency of the input and update of 3D spatial data .

A 3D spatial database can be built and updated very efficiently only by providing edge data and point data with x-y-z coordinate values as 2.5D surfaces.

(2)Ease of representation of urban space

With the SR model, urban space can be represented easily by geometric features such as edges, polygons and solids in the same manner as with the BR model.

(3)Integrated use of 2.5D map data in a 3D spatial database.

2.5D map data can be stored and simultaneously utilized in a 3D spatial database with the SR model because the 2.5D map data can be stored as a single 2.5D surface.

The limitation of the SR model based on 2.5D surfaces comes from both the manual allocation of edges and points into each 2.5D surfaces and the influence of coordinate errors on the connection of 2.5D surfaces. For example, a building and a terrain surface with a step must be divided to 2.5D surfaces unnaturally (figure 6). Although an example of urban space modelling shows that both are not severe, the authors examine the possibility of extending 2.5D surfaces to 3D surfaces in the next section.

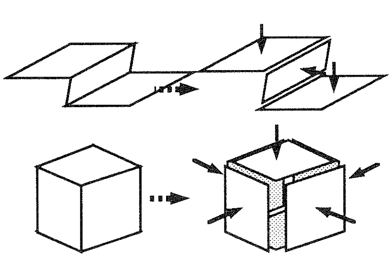
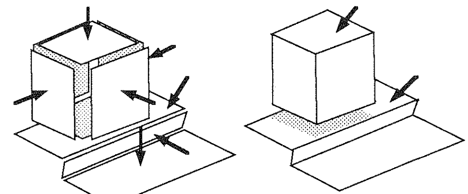


Figure 6 Decomposition to 2.5D surfaces

4.2 A possibility of extension of 2.5D surfaces to 3D surfaces

1) Constraint conditions on 3D surfaces to ensure semi-automatic polygon identification



Representation by 2.5D surfaces Representation by 3D surfaces

Figure 7 An advantage of 3D surfaces in represeting 3D spatial objects

A 3D surface is a surface which can be embeded into a plane or a sphere with holes. It does not intersect with itself and so an edge in a 3D surface bounds with no more than three polygons. By 3D surfaces, 3D spatial objects can be represented more naturally and easily (figure 7). However, several limitations must be given to 3D surfaces to ensure that the polygon identification and the surface interpolation can be done semi-automatically. The limitations can be summarized as follows.

(1)Constraint conditions on the number of edges at one point:

i)The number of edges which start or end at one point should be less than three or,

ii)if the number of edges is more than three, the "order of edges over a surface " must coincides with the "order through the projection".

The "order over a surface" is obtained by tracing the edges over a surface formed by them (figure 8). The "order through the projection" is obtained by ordering projected edges on a projection plane which is a rough approximation of a surface formed by the edges, in a counterclockwise or clockwise manner as shown in figure 9. Figure 10 is also an example where both orders of edges agree with each other, while figure 11 shows an example of the disagreement.

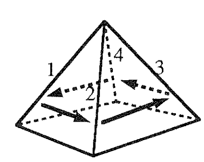


Figure 8 Ordering edges over a surface

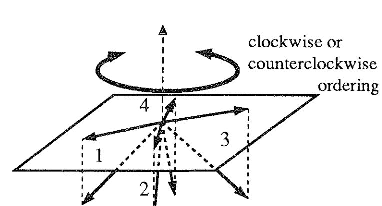


Figure 9 Ordering edges through the projection to a plane

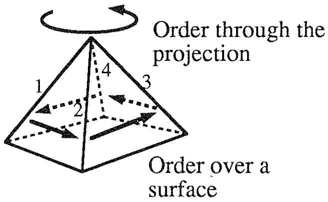


Figure 10 An example of the agreement of the two kinds of edge orders

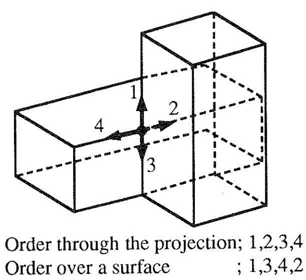


Figure 11 An example of the disagreement of the order through the projection with the order over a surface

(2)A constraint condition on torsion angles of polygons

A torsion angle of a polygon along a bounding edge is defined as an angle between two normal vectors neighboring along the bounding edge (figure 12). The torsion angle must be as small as possible. As shown in figure 13, the large torsion angle causes ambiguity in tracing edges to identify polygons.

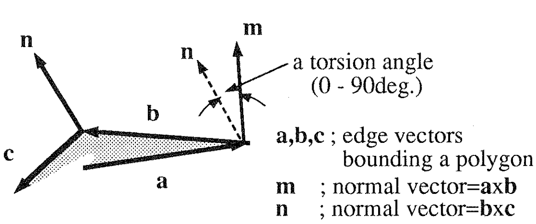


Figure 12 Definition of a torsion angle of a poygon

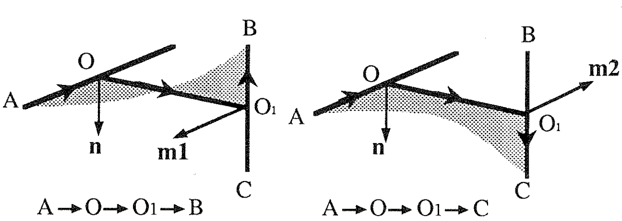


Figure 13 An example of an ambiguity in identifying polygons by tracing an edge when a torsion angle is large (~90deg)

2) A procedure to identify and interpolate polygons in 3D surfaces

Under these constraint conditions, polygons whether planar or non-planar, can be identified in a 3D surface and their surfaces can be interpolated. The procedure is summarized as follows.

(i)Preprocessing:

Isolated points, and edges connected with less than two edge are all removed. Only points where more than two edges meet are recognized as points in the following process.

(ii)Generation of the alternatives of the edge order at each point:

Two alternatives of the edge order over a surface are generated at every point. In the case of three edges, there exist only two(=(3-1)!) alternatives of the edge order. In the case of more than three edges, two kinds of orders through projection, clockwise or counterclockwise, are generated as alternatives of the order over a surface.

(iii)Determination of the edge order at each point:

The order of edges at at least one point must be determined by a user as an initial condition. The order of edges at other points are determined by tracing edges from the points where the orders are already determined.

Suppose the edges at the point O are already ordered in figure 14. The order of edges at O_1 must be determined. There are two alternatives of the edge order at O_1. One is a clockwise order. With this order, a pair of edges, A,O,O_1,C and B,O,O_1,D will bound two polygons respectively. Another is a counterclockwise order. With this order, a pair of edges, A,O,O_1,D and B,O,O_1,C will bound two polygons respectively.

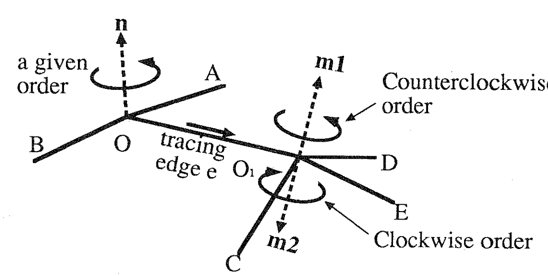


Figure 14 Determination of the order of edges at O_1 by tracing edge e

Since the torsion angles(0-90 deg.) of a pair of polygons bounded by A,O,O_1,C and B,O,O_1,D respectively is larger that those by A,O,O_1,D and B,O,O_1,C in this example, it can be concluded that the counterclockwise order is more likely.

If the torsion angles are almost the same (it is very likely when the edges are contained in a single plane), normal vectors **m1** and **m2** at O_1, which correspond with a counterclockwise order and a clockwise order respectively, are compared to normal vector **n** at O in terms of intersection angle (0-180 deg.). In this case, since the intersection angle of **m1** and **n** is smaller, we can conclude that the counterclockwise order is more likely.

If the order do not coincide with the other determined from other neighboring points, a user is required to check the ordering result.

(iv)Polygon identification in each 3D surface:

By tracing edges according to the order of edges at each point, polygons can be identified in a 3D surface.

(v)The surface interpolation of polygons in each 3D surface:

If a polygon is convex, the surface is interpolated by iterating the generation of triangular planes by connecting neighboring edges. When a polygon is not convex, i.e. a polygon is concave and/or other polygons and points are contained in the surface of an object polygon, the polygon is divided into concave polygons by adding edges to connect points where the intersecting angle of edges is over 180 deg.

Since there are possibilities that some data may violate the constraint conditions, the normal vectors at points must be displayed to ease the user's check of the result of edge ordering. With this procedure of uncovering polygons in a 3D surface, the SR model based on a 3D surface can be implemented.

5 INTERPOLATION OF ELEVATIONS IN A DIGITAL URBAN SPACE MODEL

5.1 Introduction

A large amount of elevation points are necessary to represent 3D spatial object with a DUSM. Especially the representation of terrain surfaces requires many reliable elevation points. This is not only because terrain surfaces have complicated shapes but also because the elevation of other spatial objects such as underground structures have to be determined based on the elvations of terrain surfaces.

However it is no easy task to assign elevation data to many points manually. For example, it is very labor-demanding to obtain elevation data from conventional maps in urban areas because contour lines are usually cut in pieces due to buildings and other man-made features. With aerial surveying techniques, it is not so easy to obtain enough number of elevation points due to occlusions. Only roads and the roofs of buildings are exceptionally easy place for 3D measurement. A method of elevation interpolation in urban areas is indispensable to reduce the requirement of elevation data and to give a sound basis of elevation to a DUSM.

5.2 A method of elevation interpolation

Existing surface interpolation methods usually assume that terrain surfaces are smooth although the discontinuities of slopes and elevations are often the case in urban areas. To make larger-scale representations of terrain surfaces and related spatial objects in urban areas, the following geometric conditions must be considered, which characterize terrain surfaces in urban areas (figure 15).

Break lines: The steepness of slopes shows discontinuities on a break line. Break lines are often to be seen in the boundaries of man-made objects such as roads and levees.

Step lines: Elevation shows a abrupt change (like steps) on a step lines. Retaining walls and the side walls of buildings are generated by step lines.

Horizontal planes: Every points in a horizontal plane has the same elevation value. Floors of buildings are the examples.

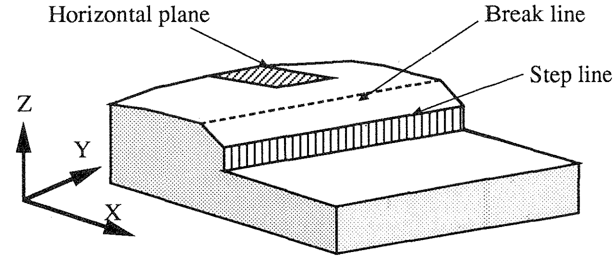


Figure 15 Examples of geometric constraint conditions in elevation interpolation

Under these geometric conditions, surfaces are represented by TIN to easily integrate the interpolated surfaces with a DUSM. At places where these geometric conditions do not hold, elevations are interpolated under the assumption that a terrain surface is smooth. Smooth terrain surfaces are obtained to maximize the sum of the square of inner-products of unit normal vectors of neighboring triangular planes. Moreover, some lines such as road boundaries sometimes have to be interpolated smoothly. The "smoothness" of lines is evaluated in terms of the sum of the squares of vertical changes of unit vectors along the lines. Thus elevations are interpolated so as to maximize the smoothness of terrain surfaces and lines under the above geometric constraint conditions.

6 AN EXAMPLE OF URBAN SPACE MODELLING

An example model based on a 2.5D surface has been made of Nishi-Shinjuku, which is one of the busiest business and commercial districts in the Tokyo Metropolitan Area (figure 16). The size of the example area is about 1.5km by 2.0km.

Figure 17 is a 2.5D surface representing the terrain surface and the ground floors of buildings. Polygons are uncovered in the edges and given attribute data of categories of floor-uses . Figure 18 shows the result of the surface interpolation. The total number of triangular polygons representing the terrain surface is more than two thousand even though the example area is not large. With the conventional BR model, a human operator would be required to generate edges bounding many triangular polygons by connecting an enormous number of elevation points.

In this example, several important 2.5D surfaces such as those of the terrain surface, the first and the second basement floor and the second floor etc. were input by the digitization of existing maps. But many of the other surfaces such as those for the other floors of buildings could be generated with a "copy" command using some additional data such as elevation data of the floors.

Each floors are connected with stairs, where present, so that a path could be found between a given pair of points with a search for a minimum path.

Figure 19 is a perspective view of the Nishi-shinjuku area with the translucent terrain surface, and Figure 20 shows a cross sectional view.

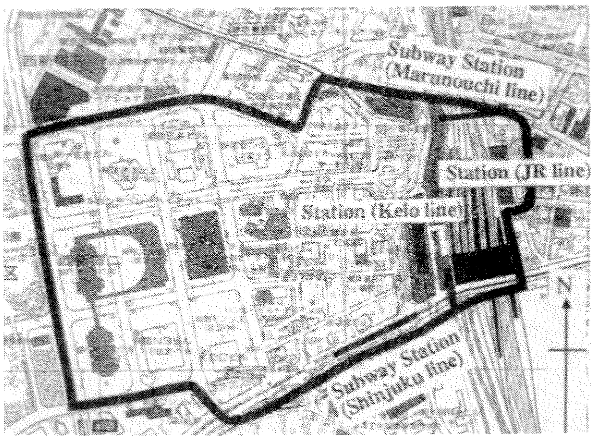


Figure 16 An example area (Nishi-Shinjuku Area)

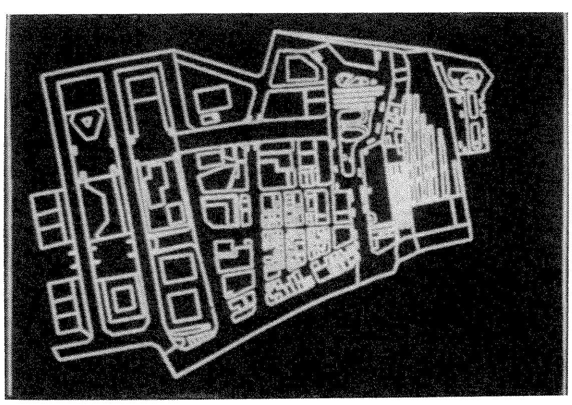


Figure 17 An example of a 2.5D surface (terrain surface)

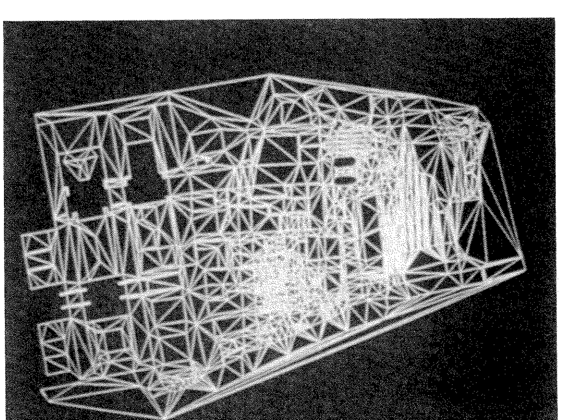


Figure 18 A result of terrain surface interpolation

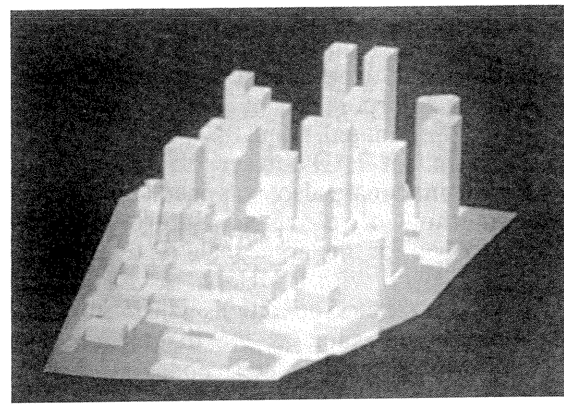


Figure 19 a) A perspective view from ablove the east side of Shinjuku station

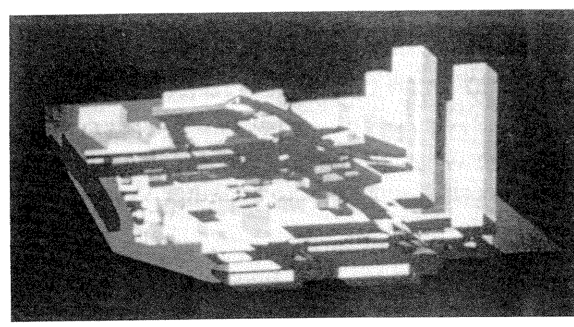


Figure 19 b) A pespective view from under the ground

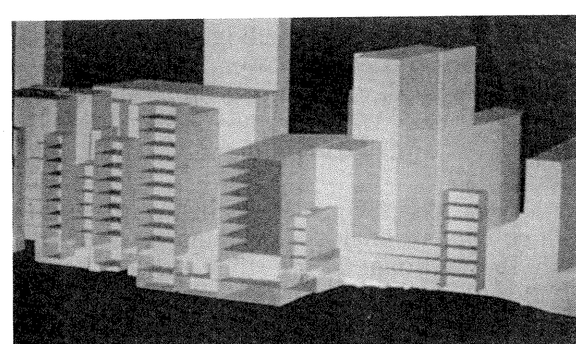


Figure 20 A cross sectional view of buildings and underground structures

7 CONCLUSIONS

The conclusions of this study are summarized as follows.

1) Basic requirements for a Digital Urban Space Model(DUSM) are reviewed. The discussion concludes that among the existing solid modelling methods, the BR model is promising but that the input and update of 3D spatial data with the BR model are prohibitively labor-demanding.
2) A model (Surface Representation(SR) model) for 3D urban spatial modelling is proposed which introduces a "surface" into the conventional BR model. With a SR model based on 2.5D surfaces, the efficiency in

building and updating 3D spatial database can be greatly improved because both the identification of polygons in edge data and the surface interpolation of the polygons can be easily automated. And the possibility of the extension of 2.5D surfaces to 3D surfaces in the SR model are also examined.

3)A method of elevation interpolation are developed for the larger scale representation of urban space with a DUSM. It can represent several geometric conditions which characterize urban space such as the discontinuities of elevations as well as the steepness of slope.

4)Through an example of the modelling, it is demonstrated that a SR model based on 2.5D surface is very effective in building a 3D spatial database.

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