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CAD Data Conversion to a Node-Relation Structure for 3D Sub-Unit Topological Representation

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3차원 위상구조 생성을 위한 노드 - 관계구조로의 CAD 자료 변환

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Abstract : Three-dimensional topological data is essential for 3D modeling and application such as emergency management and 3D network analysis. This paper reviewed current 3D topological data model and developed a method to construct 3D topological node-relation data structure from 2D computer aided design (CAD) data. The method needed two steps with medial axis-transformation and topological node-relation algorithms. Using a medial-axis transformation algorithm, the first step is to extract skeleton from wall data that was drawn polygon or double line in a CAD data. The second step is to build a topological node-relation structure by converting rooms to nodes and the relations between rooms to links. So, links represent adjacency and connectivity between nodes (rooms). As a result, with the conversion method 3D topological data for micro-level sub-unit of each building can be easily constructed from CAD data that are commonly used to design a building as a blueprint.
Key Words : Topological Node-Relation, Medial-Axis Transformation, 3D Modeling, Adjacency, Connectivity

요약 : 3차원 위상 자료는 응급상황 처리와 3차원 네트워크 분석 등의 3차원 공간분석에 필수적으로 요구된다. 이 연구에서는 현제까지의 3차원 위상 데이터 모델에 대해 살펴보고, 건물을 설계하기 위해사용되는 2차원 CAD 도면 데이터로 부터 3차원 위상적 노드-관계 데이터를 추출하는 방법을 개발하였다. 이 방법은 중심축 변환과 위상적 노드-관계 알고리듬들을 이용한 두 단계로 이루어진다. 첫번째 단계는 중심축 변환 알고리듬을 이용하여 CAD 데이터에서 폴리곤이나 이중 선으로 표현되는 벽으로부터 그 중심선을 생성하여 벽의 골격을 추출하는 것이다. 두번째 단계는 추출된 벽의 골격 자료를 이용하여 방을 3차원 노드로하고 방들간의 연결을 관계로하는 위상적 노드-관계 구조를 생성하는 것이다. 따라서, 그러한 연결들은 노드들간의 이웃성 또는 연결성을 표현하게 된다. 결론적으로, 이러한 변환방법으로 미시적 수준의 개별 건물들의 내부구조를 표현하는 3차원 위상구조 데이터는 건물의 도면 작성에 자주 사용되는 CAD 데이터로 부터 쉽게 생성될 수 있을 것이다.
주요어 : 위상적 노드-관계, 중심축 변환, 3차원 모델링, 인접성, 연결성

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1. Introduction

As geographic information system (GIS) continues to mature, there is increasing demand for three-dimensional modeling (Zlatanova, et. al., 2002; Coors, 2003; Zhou and Zhang, 2003).

Cadastre is one discipline in which the necessity of more intricate 3D modeling is becoming increasingly evident (Benhamu and Doytsher, 2003). Emergency services are also relying ever more heavily on GIS (Kevany, 2003). The ultimate GIS would function on macro scales with low levels of detail, but also be able to "zoom in" and provide detailed information about the world on a micro scale. For example, an emergency response GIS in a large city might route responders to a building on the quickest path, then route them to the room of the emergency on the quickest path once they arrive to the building entrance (Kwan and Lee, 2005). Also, if there is a fire on a room in a building, 3D GIS can provide the quickest path for evacuation to outside.

3D modeling has become a tool for GIS analysis with varying levels of success (Zlatanova, 2002). However, most current commercial GIS typically do not provide tools to model 3D sub unit structures. They only include surface-based 3D representation methods.

Buildings, for instance, are generally represented as convolutions of the surface of the earth (shells), not as objects. This is known as a boundary representation; the outer boundary of the object is modeled, but not any inner structure (Tse and Gold, 2003). Modeling for architecture, engineering, and construction (AEC), on the other hand, is focused on representing individual objects in their entirety. However, AEC systems do not function well in macro scales; and, GIS are not designed to represent the details of complex structures (Zlatanova and Prosperi, 2005).

While the technology to model and analyze 2D networks of roads and streets is well developed, it is immature for the 3D networks of the internal structure of buildings. The Topological Node-Relation (TNR) structure is an example of a system that has been developed to represent the internal structure of buildings (Lee, 2001). This model represents rooms as destinations not volumes, much like a geometric network may represent cities as destinations, not areas. Halls are represented as edges the way geometric networks symbolize roads as edges.

Whichever model is chosen to represent the internal structure of buildings, a key issue is how we generate the data needed to power this model. In the previous 3D model research studies, rooms that are the nodes in the models have been identified manually from the blueprint of a building. The manual approach to extract 3D nodes for creating a 3D model for a large building, let alone a city, would be an arduous task (Zlatanova, 2000). Previous However, 3-D models of many buildings are already available. Computer-aided design (CAD) has been used to represent three-dimensional figures since the 1980s (Marion, 2004). Today, CAD data for buildings is available on a widespread scale in the form of construction blueprints.

Therefore, the objective of this paper is to develop a method to convert CAD data of a building to a TNR structure. This method should provide the TNR structure with a virtually infinite supply of source data.

The rest of this paper is organized as follows: section 2 discusses 3D topological structures for representing buildings; section 3 explains the algorithms to convert CAD data to medial-axis and TNR structure; section 4 presents the implementation of the algorithms to perform the conversion; and finally key points are summarized in section 5.

2. 3D Topological Models

One major issue that 3D GIS intend to address is the routing of pedestrian traffic through the internal structure of a building. The advantages of a system that could perform such analysis are apparent in industries such as emergency response services. In order to perform relevant analysis on the sub-units of buildings such applications must be, above all else, quick and responsive. And because of the number of sub-units of modern buildings, especially when considered in the scope of an entire city, the data representing the sub-unit should be as concise as possible.

Most commercial GIS systems are primarily concerned with 3D visualization. ESRI provides the 3D Analyst (3DA), which deals with 2.5D data and allows users to generate surfaces, compute volume, and perform viewshade analysis. ArcScene is another product from ESRI, which emphasizes visualization through texture mapping and fly-through. ERDAS Imagine VirtualGIS also provides visualization tools such as fly-through. Intergaph GeoMedia Terrain can perform terrain analysis, terrain model generation, and fly-through. PAMAP GIS Topograph from PCIGeomatics provides much of the same functionality found in the other commercial systems. These systems do not provide the level of 3D analysis or structuring required for modeling the internal sub-units of buildings (Zlatanova, et. al., 2002).

Boundary-based representations (B-Rep) are the most popular way to represent 3D structures with the detail needed for 3D analysis. B-Rep models describe objects in terms of their boundaries: faces, edges, and nodes. A variety of B-Rep models have been proposed to represent urban structures. Coors (2003) has proposed the Urban Data Model (UDM). This model builds on the 3D formal data structure (3D-FDS), but eliminates the explicit storage of edges. This model has not been tested for representing the internal sub-units of buildings, but could theoretically be applied for this purpose. This model is query-oriented and, therefore, the relationships between rooms could be queried. However, these relationships are implicit and processing power is needed to interpret them.

Billen and Zlatanova (2003) have proposed the Dimensional Model (DM). This model considers objects to be composed of "dimensional elements". Relationships between objects are defined by the type of dimensional element that the objects share. This system allows for topographical associations between any combination of one, two, and three-dimensional objects to be analyzed. This system is intended to handle complex 3D relationships; however, it would also be resource intensive when applied to an entire building.

While B-Rep models provide the level of detail needed for 3D analysis, most require a large volume of data and considerable power to process. To address these issues, Lee (2001) has proposed 3D TNR structure. The TNR structure is much simpler than many other models. It does not represent the volume or shape of objects directly. In a 3D structure, a 3D space is represented as a node and horizontally or vertically adjacent spaces of the space are linked by relation, which is the modification of 2D dual graph to 3D space (Figure 1). The focus then becomes the relationships between the objects: adjacency and connectivity. While the TNR structure may not be as useful for cadastral purpose, it does allow for concise representation of the internal sub-units of a building. This method is simple and requires minimal storage space and processing power. Therefore, this paper focused on the construction of the TNR structure data from CAD design files, which are often used as blueprints to design buildings. The construction process needs two methods: medial-axis transformation and TNR construction

3. Conversion Algorithms from CAD Data to TNR Structur

Converting CAD data to a TNR structure needs two algorithms. The first algorithm of conversion is a medial-axis transformation (MAT) to extract wall structure. A CAD drawing is the "real world" design in which all walls represented closed double lines (polygons). To extract rooms from the combination of walls, the polygon walls are converted into simple lines. This process needs three steps (Figure 2). The first step of MAT is creating bisectors of the inner angles at each vertex of wall polygon. The second step of MAT is extracting terminal and junction nodes. If two inner bisectors meet inside polygon, the point will be a terminal node of wall skeleton. If an inner bisector does not meet another bisector, a point called a junction node will be calculated. A junction node is a half location of a line segment between the origin vertex of the bisector and the nearest vertex of the origin vertex. Finally, all terminal nodes will be connected through junction nodes.

The second algorithm is a 3D TNR construction. In the node-relation structure, rooms (volumes) are represented as 3D nodes. Relationships (adjacency and connectivity) are 3D links. The TNR structure contains only these two elements. Both identifier and coordinates of each node are important. Its coordinates are the simplification of the location of the room for further geometric identification. Its IDs are linked to a room number and other attributes, which will be more meaningful to end-users. Links' important characteristics now include type (either adjacency or connectivity), in addition to its end-nodes. In the node-relation structure, nodes are the basic unit and links only exist to define the relationships between them.

The algorithm needs four steps (Figure 3). The first step of the TNR construction algorithm is to remove vertices in order to establish a topology between the walls. The CAD files have no topology. Lines that cross are not necessarily connected. More importantly vertices that lie on a line do not divide it. So, all vertices should be converted into nodes in order to properly define rooms. A wall should be a boundary of no more than two rooms. The second step is to remove doors. Doors are represented by openings within walls. Rooms are polygons, therefore a door opening need to be filled to close the polygon. Any wall from which a door is removed is designated as "has door" for later use to build connectivity relation. The third step is to identify rooms. A room is considered to be a closed polygon that is not divided into any sub-polygons.

The 3D node representing a room is the gravity center of its polygon. The final step is to define relationships between rooms. The TNR structure uses two types of relationships: adjacency and connectivity. Two rooms are said to be adjacent if they share a wall. More generally, they are polygons that share a common boundary. Two rooms are considered connected if they share a wall that contains a door.

4. Implementation of 3D CAD Data Conversion Algorithms

The system designed to accomplish the above algorithms includes two modules: MAT and TNR (Figure 4). The system is built around three types of objects: nodes, lines, and polygons (Table 1). The system designed to accomplish the MAT algorithm consists of three sub-modules: Bisector, Inner-Nodes, and Skeleton modules. The Bisector module draws the bisectors of all inner angles of the wall polygon (Figure 5.a). The Inner-Nodes module extracts inner nodes from the intersection of the bisectors (Figure 5.b). The Skeleton module extracts a medial axis of the wall polygon by connecting inner nodes extracted in the previous step (Figure 5.c).

TNR module includes four sub-modules: Remove-Vertices, Remove-Doorways, Identify-Rooms, and Build-Topology. The Remove-Vertices module converts all vertices to nodes. When the user selects "Remove vertices", the program checks each node to determine if it lies between the end-nodes of any other line. If so, that line is broken into two lines that meet at the node. One line (Id: 10007) in Figure 6.a is separated into two lines (10014 and 10015) in Figure 6.b. This process is complete once each node has been checked. The Remove-Doorway module finds the two walls on either side of a doorway, combines them into one wall (Figure 6.c). When the user selects "Remove doorways", the program checks for nodes that participate in only one line, designated as "lonely" nodes. For each lonely node (node A), the system finds: 1) all lonely nodes that fall on the graph of the node A's wall, 2) those nodes that fall in the direction of the node A's wall, 3) the node closest to node A (node B), and 3) the line containing node B (Figure 7). Once the two walls have been found, the nodes (A and B) are removed and a new wall added with end points at the far nodes of the original lines.

The Identify-Room module starts by choosing a node to begin with, the first "from-node". Then a wall that the node participates in is selected. This wall is the first baseline. The node at the other end of the baseline becomes the first "to-node". If there are more than two possible walls making left turns from the baseline, the one that intersects the baseline at the smallest angle in clockwise direction is chosen. Once the next wall has been chosen, that wall becomes the baseline, the to-node becomes the from-node, and the node at the opposite end of the baseline is the new to-node. This process is repeated until all polygons are identified. Once a room has been identified, rooms are represented by a node at their centroid (Figure 6.d).

The Build-Topology module constructs relationships using identified nodes. Building the adjacency between the rooms in the building is a simple task at this point. If a room shares a wall with any other room, a link is drawn between the center points of the two rooms. If the wall they share contains a door, the link is designated as connectivity. At this point the complete TNR structure has been built (see Figure 6.e). The completed TNR structure can now be written to text files which can be interpreted by a TNR analysis tool.

CAD drawings of buildings are generally organized by floor. Each floor in the building should be passed through the algorithm to obtain a layer for each floor. The extracted TNR data represent the sub-unit structure of each floor of a building, which has elevation value of the floor. So, the sub-unit structures in each floor are represented by 3D (x, y, z) coordinates. Then, TNR structure of each floor can be linked using vertical adjacency and connectivity (Figure 8). Vertical topology structure is easily constructed using the TNR algorithm. If a sub-unit is a room, the room is vertically adjacent with above and below rooms. Connectivity is a higher-order relationship; it is a special case of adjacency. If a sub-unit is an elevator or a stairway, the sub-unit is vertically connected with above and below elevators or stairways.

5. Conclusion and Further Study

This paper discussed data conversion method from 2D CAD to 3D topological node-relation structure. The conversion of CAD data is accomplished in two algorithms: medial axis transformation (MAT) and topological node-relation (TNR) structure. MAT needs three steps.

First, inner angle bisectors of wall polygon should be created. Second, both terminal and junction nodes should be extracted from the bisectors. Finally, all nodes should be connected to complete a medial axis of the wall polygon.

TNR structure algorithm needs four steps. First, the walls are segmented at their connections. Second, doors are removed. Third, rooms are identified. Finally, relationships are defined. These logical steps implemented in several modules: Load, Remove vertices, Remove doors, Identify rooms, and Define relationships. The result data of the implemented system is a TNR structure. The TNR structure allows for simple compact storage of rooms within a building and the adjacencies between them. This structure can be very useful for applications such as emergency response services.

Currently the MAT algorithm is limited primarily by the complexity of the input data. Certain constraints are required of the input CAD for the algorithm to properly interpret the sub-units of the building. Lines must represent only walls. Often in blueprints, lines are used to represent other entities other than walls. Therefore, some manual process should be performed before using the introduced MAT algorithm. In TNR structure algorithm, doors must be represented by gaps in walls. Some blueprints may contain explicit door objects. The current algorithm only recognizes doors as openings in walls. In the future, the algorithm could recognize a standard door object in a continuous wall and designate that wall "has door".

Even with these limitations, the algorithms suggested in this paper are efficient tools for extracting medial axis and generating 3D TNR data from CAD design files. Then, TNR structure of each floor can be linked using vertical adjacency and connectivity using TNR algorithm. The complete 3D TNR structure can be used to analyze 3D networks.

This paper introduced the possibilities of using CAD design file to build 3D TNR data. For further studies, the proposed algorithm should be applied for real CAD files for a complex building to extract 3D TNR data. Also, 3D network analysis algorithms such as 3D routing methods should be developed and applied for real applications.

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