INTEGRATING MODELING FOR PROFILE ANALYSIS OF URBAN UNDERGROUND PIPELINES BASED ON 3D GIS

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ABSTRACT:

Profile analysis of urban underground pipelines solely from 2D GIS data is very difficult because the two-dimensional geographic information system technologies do not quite meet all the utility's needs. The present study aims at developing a quick and practical method to automatically produce the utility's profile using 3D GIS techniques. A 3D Urban Pipe Network Model (3DUPNM) about underground pipelines was proposed on the basis of analyzing the basic characteristics of urban underground pipelines in detail. Also, the approach to dynamically analyze the spatial relations between pipelines was presented by integrating the 3DUPNM with the knowledge related to planning of urban pipelines. Finally, the algorithms of automatically producing the cross-sectional profile and vertical-sectional profile were given particularly. Study shows that these algorithms are more efficient than those using 2D GIS techniques.

1. INTRODUCTION

With the wide acceptance of the concept of "Digital Earth", the construction of "Digital Cities "is in its full swing. The coming of bit city brings new methods of planning cities, managing cities and resolving urban problems. The theory supporting point of Digital City is searching for scientific and rational data models to describe real cities. It is well known that the urban underground pipelines are important infrastructure on which the city development and existence rely. In addition, they usually lie in underground and are invisible. Therefore, it is very important to research on profile analysis of urban underground pipelines in order that urban planner, designer and custodian make decision more scientifically and efficiently. Profile analysis of urban underground pipeline only based upon 2D GIS data is very difficult, because the two-dimensional geographic information system technologies do not fully manage and deal with real 3D data but consider height as attribute.

Previous studies for profile analysis of urban underground pipelines were mainly by using computer-aided design (CAD) or automated mapping/facilities management (AM/FM) systems. However, these methods only map a profile graphics, do not take the knowledge of utility planning into account. Therefore it is impossible for decision-maker to know the dynamic processes of urban development. Some studies show that two-dimensional geographic information system technologies can model the underground pipelines efficiently. However, the 2D GIS technologies do not solve some problems as representing vertical pipelines. At the moment, there is no real 3D GIS software available in the GIS market (Li, 2000; Raman, 2001). Therefore, in this paper, we will develop a novel method to model the underground pipelines in three-dimensional geographic information systems by means of integration techniques.

2. THE CHARACTERISTICS OF URBAN UNDERGROUND PIPELINES

Generally, underground pipelines are divided into two categories: underground piping and underground cable (Qu, 1998). Underground piping consists of water piping, drainage piping (stormwater, sewage), gas piping (coal gas, natural gas, liquefied petroleum gas), heating power piping and industrial piping. Underground cable includes electric power and telecom cable. Underground piping, underground cable, civic public pipeline and special piping used exclusively by enterprise, railway, civil aviation, army and so on, laid in the underground in urban region, are called urban underground pipelines. It is the physical bases on which urban development and existence depend, so it is called the " lifeline" of city. Urban underground pipelines serve the life of inhabitant and industrial manufacture. Hence, it should be laid out according to the spatial distribution of urban population and enterprise, and is influenced and restricted by urban terrain and other infrastructure. At the same time, the varieties of urban pipelines coexist each other in space, and form huge complicated networks. So we think that "pipe networks" called by us is more suitable than "pipelines". System science regards that a system is an organism, which comprises many elements associating, restricting and coordinating each other, and possess certain functions. As optimizing and planning urban pipelines in space, we should consider other factors besides urban pipelines itself. They are physical conditions, which include urban topography and its features, and social economic factors, which consist of urban infrastructure, the spatial distribution of urban population and enterprise. Thus, urban pipe networks should be composed of bridge, culvert, ditch, road, railway, subway, and river, in addition to pipelines (overground, ground, and underground).

The data of urban pipe networks is spatial data, essentially geographical networks as well. The following will be

Network elements	Meaning
Network Links	Representing the interconnected linear entities that are the conduits for transportation and communication, such as the highways, water transmission lines
Network Nodes	Endpoints and connecting point of network links, for instance well for examining and repairing in utility network
Stops	Locations visited in a path or tour, such as bus stop
Centers	Discrete locations that have a supply of a resource or commodity
Turns	A transition from one network link to another at a network node
Barriers	Network nodes which resources can not pass

Table 1. Main network elements of geographical networks

respectively analyzing their characteristics in geometry, attribute, time, particularity and so on.

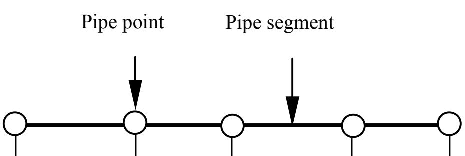
2.1 Geometric Characteristics

Urban pipe networks are artificial construction except the rivers. It mostly includes pipeline, ditch and its attachment. In GIS, the network data model can be used to model the pipe networks. Network elements consist of network links, network nodes, stops, centers, turns, barriers in terms of network data model (table 1).It can be deduced from table 1 that network data model is composed of network links and network nodes. In urban pipe networks, the former is called pipe segments; the latter is called the pipe points. For the sake of convenient, we mainly analyse the geometric characteristics of piping (actually, urban pipe networks mostly is composed of piping). In 3D Euclid space, the geometric feature of pipe networks may be determined by way of its pipe point locations (*X, Y, Z*), its diameter (generally inner diameter), its wall thickness and the distance to ground. Its diameter and wall thickness must meet engineering specification in industrial fields; for instance, piping wall thickness is 10% of its diameter. Thus, as far as a certain pipe segment is concerned, its location in space (*G*) is confirmed in terms of its end coordinate (*X, Y, Z*), its diameter (*D*), the distance to ground (*H*). Its expression is shown in (1).

$$G = F(X, Y, Z, D, H) \tag{1}$$

2.2 Attribute Characteristics

It is discovered that the attribute of urban pipe networks such as material, diameter varies frequently (see figure 1). Apparently, it is very difficult to manage the attribute data by means of the conventional arc-node topological model. Therefore, the dynamic segmentation technique should be employed in urban pipe network domain (Peng, 2002).



Material	Steel	Brick	Stone	RC
Diameter	800mm		1000mm	500mm
Groundsill	180^0 concrete	135^0 reinforced concrete		
Gradient	5‰		3‰	2‰
Time	1985 year			

Figure 1. Variational attribute data for underground pipelines

2.3 Time Feature

Urban pipe networks are always being modified according to city development and alteration, widening of urban road. Hence, urban pipe networks take on the peculiarity of dynamic change. Matter, power, information stream flowing in urban pipe networks is provided with this dynamic peculiarity yet. In order to make certain rationally maxim sewage capacity which the pumping station and sewage disposing factory should meet, it must be considered that for sewage flux to vary with time in certain pipe networks. According to the demand of Digital City, urban pipe network information system should manage current data and past data as well. Actually, it may supply rational data of decision-making for city planing, constructing and managing by analyzing current data and past data pertinent to urban pipe networks. For example, we may find the sewage flooding reasons of certain area by analyzing past data. Time characteristics of urban pipe networks include the change of their spatial location, shape, and attribute.

2.4 Complicated Spatial Relation

Urban pipe networks interlace vertically and horizontally and are fine as a cobweb. A pipe network is composed of piping segments, constructing or buildings and its attachment. It mostly unfold like tree, circularity or radial shape, and forms an artificial system in which changing elements interact & interface, any their change must make other relevant change of that, and change of anyone may lead to entire system paralysis finally. Because of the concealment of pipe networks, accident location and its incidence are not made certain easily, it will lead to the blindness of repair. If some kinds of pipe networks is out of order in operating brings out the failure of other pipe networks' running. Therefore, urban pipe network information system should deal with relations among the elements within a pipe network and with other networks.

2.5 Meeting Engineering Specification

Layout of urban pipe networks should meet the engineering specification. There is horizontal distance and vertical distance limit between varied pipelines. The distance of pipe networks to buildings (constructing) or to the ground should accords with the engineering standard.

2.6 Height Data

The calculating vertical distance between pipelines not only needs height data, but also optimizing designs do. Thus, urban pipe network information system should be capable of managing and analyzing 3D data.

3. 3D URBAN PIPE NETWORK MODEL CONCERNING TERRAIN

We should set up the spatial data model of urban pipe network considering the characteristics of pipe network elements and urban terrain together, from systems engineering view. The problem, which mostly should be studied further in the literature (Bai, 1997), is how to explore an approach to integrating the analysis of geographical network with analysis of terrain. It is proved that the urban terrain factor is very important in the rational layout and design of the urban pipe network. According to expression (1), it can be deduced that five parameters are needed to make certain 3D spatial location of urban pipe networks and the relationship relative to the ground. The most of urban pipe network are buried in underground; it is difficult to attain the distance *H* from pipeline to the ground. We may make the height *E* of a ground point corresponding to the random point in pipelines to take the place of the distance *H* from pipeline to the ground. Thus, the expression (1) is modified as (2).

$$G = F(X, Y, Z, E, D) \tag{2}$$

Where E= the height of ground point corresponding to the random point in pipelines.

Form above analysis, it can be deduced that we may represent spatial characteristics of pipe network, spatial relations between pipelines, and relationship between pipelines and the ground using five parameters including *X, Y, Z, E* and *D* in pipeline domain *P*. So it is expressed as formula (3).

$$P = F(X, Y, Z, E, D) \tag{3}$$

In order to set up uniform data model, we use the elevation of random point in a pipeline z_{bi} to take the place of *Z* and z_{ti} to take the place of *E*. Therefore, the three-dimensional pipeline domain (*P*) is shown in expression (4).

$$P^{SD} = \{P^{(S+D)} \mid \exists i, 1 \le i \le \infty \wedge \exists x_i, y_i, z_{bi}, z_{ti} \in P^S, \exists d_i \in P^D\} \tag{4}$$

Where P = three-dimensional pipeline domain
S = extended spatial domain
z_{bi} = altitude of pipelines
z_{ti} = the ground altitude related to point (x_i, y_i, z_{bi})
D = pipeline diameter domain

The data model integrates the element characteristics of pipe network with the terrain factor, and formularizes in 3D space. Thus, we call it 3D urban pipe network model (3DUPNM).

It is well known that we may apply the field model and object model to express geographic model. The field model is fit for the continuous space, and object model is fit for the discrete space. In terms of object-oriented thought, the chief spatial object corresponding to the urban pipe networks is the pipe points and pipe segments. The former is called nodes; the latter called arc. Any arc is only relating to first node and last node in it. Thus, data structure on the pipe points and pipe segment is

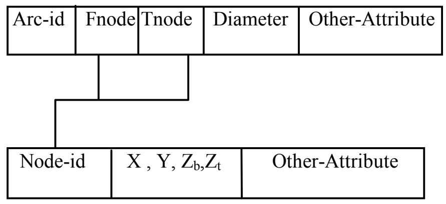


Figure 2. Logical model of 3DUPNM

shown in figure 2. X, Y, Z_b , Z_t are regarded as spatial data in our model, but height Z is regarded as attribute data in 2.5D GIS model. It is out of question that we may describe vertical pipelines using the model. From this model, it is very convenient to know the spatial relation between pipelines, and relations between ground and pipeline exactly. For instance, we know the pipeline was located at underground if z_{ti}-z_{bi}>0; If z_{ti}-z_{bi}<0, the pipeline is above the earth's surface. Therefore, it is very easy to manage the spatial relation among pipelines, and the relation between pipeline and ground.

In order to provide it directly to decision-making supporting for urban planning, designing, constructing and managing, it is necessary that the above model is combined with the specialty knowledge. For examples, minimum horizontal distance and minimum vertical distance between pipelines, minimum deepness under the ground and horizontal distance relative to the building must meet the specification. Setting up spatial database, we should turn above specification into constraint rules. If the urban pipeline planning and designing meet it, the planning and designing are rational, otherwise, the location and elevation of pipelines will be adjusted automatically. For example, if we build a sewage pipeline (*P*) which intersects gas pipeline (*R*) below it in space, and border upon electric power pipeline (*L*) and telecom cable (*D*) in horizontal direction. According to the specification: minimum vertical distance c>0.1m, minimum horizontal distance relative to electric power pipeline s_1>1.0, minimum horizontal distance relative to telecom cable s_2>0.5m, minimum deepness under the ground *H*>0.7m. Thus, the constraint rule is shown in expression (5).

$$\forall P(c(P,R) > 0.1) \wedge (s_1(P,L) > 1.0) \wedge s_2(P,D) > 0.5 \wedge (H > 0.7) \tag{5}$$

By the same reasoning, all specification may be expressed restricting condition in order to plan pipeline networks in 3D space. If the value of expression (5) is true, it indicates that the pipeline planning and designing is rational, otherwise, dynamically adjust the location (X, Y, Z) of pipelines.

4. PROFILE ANALYSIS OF URBAN UNDERGROUND PIPELINES

The organization of pipeline information and its specific form have a close relationship with the relative management. The previous pipeline information is represented by the way of two-dimension on the map, which characterize the tendency direction of pipeline. It is difficult to present clearly and correctly the there-dimensional information of the deepness and the diameter of pipeline. The profile graphics and diagrams, however, can preferably represent both the spatial relationship among types of pipelines and the deepness from the pipelines to the ground. According to the 3D data model of urban pipe network considering city terrain factor, we dynamically can not only figure the location relative to other infrastructure, but automatically produce the profile graphics of random location in pipelines. The profile graphics consist of cross section, which intersects the underground pipelines, and vertical section, which is along the pipelines. The algorithms above producing cross-sectional profile are as follows.

Step 1: Encoding of pipeline and road data.
Step 2: Automatically building of topological relations of pipelines.
Step 3: Drawing random profile line AB.
Step 4: Calculating the coordinate of intersection point between AB line and pipelines.
Step 5: Checking the pipeline data, if the data is entire, then next step, or step 10.
Step 6: Calculating the height of intersection points and ground point corresponding to pipelines by interpolating.
Step 7: Drawing profile according to pipeline type.
Step 8: Drawing ground elevation line according to the distance to A point.
Step 9: Labeling and ornamenting graphics.
Step 10: End.

The steps of drawing the vertical-sectional graphics are as follows.

Step 1: Encoding of pipeline and road data.
Step 2: Automatically building of topological relations of pipelines.
Step 3: Selecting pipeline segment.
Step 4: Checking the pipeline data, if the data is entire, then next step, or step 14.
Step 5: Searching for opening segment (suppose first node is A).
Step 6: Searching for next segment by using topological relation.
Step 7: Drawing ground height line according to Z_{ti} value.
Step 8: Drawing pipeline bottom height line according to Z_{bi} value.
Step 9: Drawing pipeline top height line according to Z_{bi} and pipe diameter value.
Step 10: Drawing well line at the ends.
Step 11: Calculating the coordinate of intersection point between selection pipe segment and other pipeline, its Z_{bi} and horizontal distance relative to A point by means of interpolating.
Step 12: Drawing pipeline section according to pipeline type.
Step 13: Labeling and ornamenting graphics.
Step 14: End.

Because the above algorithms integrate the characteristics of terrain with those of the underground pipelines from 3D GIS, the methods of profile analysis are more efficient than those using 2D GIS techniques. From the profile map we can query the altitude at any location and intersection pipeline information such as material, diameter. So this is not only a map, but also an information system, which can produce profiles and manage the pipeline's relations each other. Not only does meet the practical needs, but also dynamically manage the information of the profile map.

5. DISCUSSIONS AND CONCLUSIONS

An approach to dynamically analyze the spatial relationships between pipelines was presented by integrating the 3DUPNM with knowledge related to planning of urban pipelines. Also, a method to automatically produce cross-sectional profile and vertical-sectional profile was presented by means of integrating 3D GIS with the knowledge related to planning of underground pipelines in order to overcome the shortcomings which the conventional 2D GIS faces in modeling the 3D linear features. In the further research, we'll take linear referencing or dynamic segmentation techniques and temporal dimension into account in our 3DUPNM. As a result, the model has been placed in "Urban Pipeline Decision Support System" produced by the project entitled: "Three-Dimensional Urban Pipeline Information System", funded by Xi'an municipality, P.R. China. The practice shows that the model not only displays the pipelines' relationships efficiently, but also meets the local decision maker's needs.

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