t-GIS AND ENVIRONMENTAL DYNAMIC MODELS

WU Hong

KEY WORDS  temporal geographic information system; environment; dynamic model

ABSTRACT  Temporal geographic information system (t-GIS) is a kind of computer information system that can display, process and analyze the micro-format distribution of temporal-spatial information of real world. It includes both spatial geographic information and temporal information, and can analyze both the static geographic information and the dynamic geographic information.

Three models based on t-GIS for environment dynamics, namely, the mechanism method, the experience method and the mixed method are given.

t-GIS based on the environment dynamic model has more new functions than traditional GIS, such as fast I/O, inquiry, static/dynamic display and visible analysis of spatial and temporal sequence information, especially it can display the image of the evolution in the past, current and future environment through the extrapolation method within its defining region. The velocity for analogue display can be accelerated by setting up time-varying-area-function for position and attribute.

Dynamic environmental information analysis systems based on t-GIS are applicable to almost all the fields related to management, display and analysis of local environmental dynamic information. For this reason, some considerations to construct distinct information systems have been enumerated in this paper, such as, the analysis information system for terrain evolution, the analysis information system for the condition of water and fertilizer of farmland, analysis and the evaluation information system for ecological environment, and the analysis information system for distribution changes of population of China, etc.

1 Introduction

Today it seems that people's interest and attention to GIS mainly focus on the aspect of spatial attributes of geographic information, not sufficiently on time factor. This is an erroneous tendency, and it will be disadvantageous to the balanced development of GIS when explaining GIS as either geographic information system or geographical information science and finally will limit their development. The functions of geographical information system should agree with their aim. For this reason, it is necessary to bring the coordinate of time into the coordinate system of GIS.

Temporal geographic information system (t-GIS) is a kind of computer information system as a micro-format that can display, process and analyze the distribution of temporal-spatial information of the real world. It includes both spatial geographic information and temporal geographic information, and can analyze both the static geographic information and dynamic geographic information. The environmental dynamic model is the summation of the regularity of environmental evolution or its quantitative expression. Since the real environment is a variable geographic substance, the combination of t-GIS with the dynamic model can more truly realize its format. The key to realize quantitative descrip-
tion of time-varying characters of geographical information in GIS is to build up the relationship between space vs. time and attribute vs. time.

Three modeling methods based on t-GIS for environment dynamics, namely, the mechanism method, the experience method and the mixed method are given on the basis mentioned above.

t-GIS based on the environment dynamic model has more new functions than traditional GIS, such as fast I/O, inquiry, static/dynamic display and visible analysis of spatial and temporal sequence information, especially can display the image of evolution of the past, current and future environment through the extrapolation method within its defining region. The velocity of analogue display can be accelerated by setting up time-varying-area-function for position and attribute. For those GIS softwares that possess the second-development function, they can be reformed directly into the dynamic environmental information analysis system.

2 Temporal attribute of geographic information and micro-projection of GIS

2.1 Temporal attribute of geographic information

The temporal attribute of geographical information is determined by materiality of the real world. Any geographic information is time variable, such as natural environment evolution and changes in man-made environment, without any exception. Strictly speaking, there is not time-space-unchangeable geographic information in the world. Key to realize quantitative description of time-varying characters of geographical information is to build up the relationship between space and time as well as attribute and time. So above all, it is necessary to give a definition for the description of geographic information on time.

Theoretically, for the given coordinate system of time-space, the geographic substance in any positions, shapes and states can be written as follows

\[ G = g(x, y, z, t, a, \beta, \gamma, \delta, \cdots) \] (1)

where \( x, y, z, t \) are the coordinates of space; \( t \) is time and \( a, \beta, \gamma, \delta, \cdots \) are the factors that control and affect the geographical substance.

Because the effects (or actions) of \( t \) on variables: \( x, y, z, t, a, \beta, \gamma, \delta, \cdots \) are independent of each other, so Eq. (1) can be rewritten as a parameter equation, namely

\[ G = \xi(x(t), y(t), z(t), \alpha(t), \beta(t), \gamma(t), \delta(t), \cdots) \] (2)

For the specific environmental problems, the parameter equations on time \( t, x = x(t), y = y(t), z = z(t), \alpha = \alpha(t), \beta = \beta(t), \gamma = \gamma(t), \delta = \delta(t), \cdots \) take different forms. The quantitative description of real geographical world can be realized through Eq. (2).

2.2 Reduced-mapping of GIS

A digital image displayed on CRT of computer may be written as follows

\[ I(x, y, z, t) = \int C(x, y, z, t, \lambda) V_s(\lambda) d\lambda \] (3)

where \( C(x, y, z, t, \lambda) \) represents the distribution of the emitting energy of image in space. It is the function of \( G = F(G) \). \( V_s(\lambda) \) is the relative light effect function, i.e., the spectral response of human visual sense. \( \lambda \) is the wavelength of the emitting energy of image source. In the same way, the color response of standard observer is measured by a group of values that cover three stimulus, it is in linear proportion to quantity of red, green and blue lights for matching some color lights. For any coordinate system from red, green and blue, three instantaneous stimulus are respectively as follows

\[ I_R(x, y, z, t) = \int C(x, y, z, t, \lambda) R_s(\lambda) d\lambda \] (4)

\[ I_G(x, y, z, t) = \int C(x, y, z, t, \lambda) G_s(\lambda) d\lambda \] (5)

\[ I_B(x, y, z, t) = \int C(x, y, z, t, \lambda) B_s(\lambda) d\lambda \] (6)

where, \( R_s(\lambda), G_s(\lambda), B_s(\lambda) \) are three stimulus values that are composed of spectrum of red, green and blue cardinal color, respectively.

Therefore, display of the picture of real scenery through GIS can look upon as some reduced-mapping of \( G \) on CRT.

\[ \xi_{GIS}: G \rightarrow C \rightarrow I, \text{for black and white image} \] (7)
or
\[ \xi_{tGIS}: G \rightarrow C \rightarrow |aI_R \oplus bI_G \oplus cI_B|, \]
for color image (8)

\[ |aI_R \oplus bI_G \oplus cI_B| \] is pseudo-color composition transform, \(a, b, c\) are weight coefficients for pseudo-color composition, their values are positive and real numbers between 1 and 0. Because \(G\) varies with \(t\), and so does micro-projection \(I\). Thus, reduced-mapping and micro-display of \(G\) have been realized.

In a sense, a successful \(t\)-GIS should be a projector \(\xi_{tGIS}\) that has perfect reflective functions through the micro-display of the picture of real world scenery (see Fig 1).

3 From temporal database to \(t\)-GIS

The pure spatial dimension GIS with practicability came out in the early 1960’s. And \(t\)-GIS emerged in the middle-later period of the 1980’s. The emergence of \(t\)-GIS is closely related with the time database. It is necessary to the modern science and technology[20-48].

In fact the temporal database entering our daily life was earlier and wider than GIS, for instance, the system auto-counting interest for the deposit in the bank is a typical system of temporal database.

Similar technologies of temporal database are also applied in other fields, for example, auto-counting cost and automatic control. The study on the temporal database has reached the climax in the early and middle periods of 1980s, there was a good deal of works related to this study, such as to hand the time dimension in a database (Jones and Mason, 1980)[21]; Time Relational Model (Ben-Zvi, 1982)[10]; A Temporal Framework for Database Specifications (Castillo, 1982)[13]; Formal Semantics for Time in Databases (Clifford, 1983)[15]; Model of Dynamic Cartography (Cebrian, 1983)[14]; Space-time Data Display Techniques (Calkins, 1984)[12]; Integration of Time Versions into a Relational Database System (Dadum, 1984)[16]; Verification of Database Temporal Constraints (Kung, 1985)[22]; Taxonomy of Time in Databases (Snodgrass and Ahn, 1985)[41]; Modeling Time Aspects of Information Systems (Studer, 1986)[44]; Analysis of the Structural, Dynamic and Temporal Aspects of Semantic Data Models (Urban, 1986)[45]; Performance Evaluation of a Temporal Database Management System (Ahn and Snodgrass, 1986)[4]; Temporally Oriented Data Model (Ariav, 1986)[5]; Multihomogeneous Model for a Temporal Database (Gadia, 1986)[19]; Temporal Databases (Bibliography, 1986)[31]; Time in Databases (Snodgrass, 1986)[39]; Physical Organization of Temporal Data (Rotem and Segev, 1987)[36]; Logical Modeling of Temporal Data (Segev and Shoshani, 1987)[37]; Temporal Query Language Tquel (Snodgrass, 1987)[40]; Towards the Minimum Set of Primitive Relations in Temporal Logic (Zhu, Loh, and Siy, 1987)[49]; Temporality in Spatial Databases (Armstrong, 1988)[61], etc.

Among them Snogdrass’s systematic study is the most noticeable. It is worth to say that Calkins has already touched the essence of \(t\)-GIS in the study about the spatial-temporal display technology in 1984, but it is a pity that he did not go further ahead, if not, \(t\)-GIS had come out about five years ago probably. Anyhow, just thanks to active study on the temporal database in that period a foundation for \(t\)-GIS emerged afterwards was laid.

As the ratio of computer performance to price is
greatly being raised, development of GIS and the importance of environmental problems rising at high speed in later 1980s, request for visible analysis of dynamic geographical information is more and more being highlighted. Bringing $t$ into the coordinate system of GIS has already become an aim beyond controversy. On this background it became the historical necessity that temporal database mixes GIS together, thus t-GIS came out. Langran Gail at first introduced time into GIS and made a great deal of creative and systematic researches on the design of t-GIS\cite{23}, system frame\cite{27}, accessing and fetching temporal information\cite{24}, the relation of temporal database to t-GIS\cite{25} as well as the application of t-GIS\cite{26} etc., these results extremely propelled t-GIS forward, van Deursen related the GIS with time from the angle of dynamic models and has studied specially combination of t-GIS with practical problems, and thus made the t-GIS widely practicable\cite{48}. The main difference between their work is that Langran’s study laid particular emphasis on the motion of object-oriented, and Deursen’s on the object of motion-oriented.

It can be seen that the process went for eight years from Jones & Mason’s tentative study for temporal database\cite{21}(1980) to the time that Langran’s t-GIS came out\cite{23}. The conclusion is clear, that is, temporal database developing promoted the evolution from pure spatial dimensions GIS to t-GIS. The monograph, “Time in geographic information system” by Langran\cite{18} was published in 1993, which can be looked upon as the sum of that stage of t-GIS studying. In 1995, Deursen published her work, “Geographical information system and dynamic models”\cite{18} and discussed the technologies and theories related to an integration of t-GIS with the dynamic models in it, but there still remains a great deal of questions have to be solved, for example, analytic description of t-GIS, the mathematical and physical functions of an integration of t-GIS with the dynamic models, temporal data structure as well as visual analysis for the procedure of dynamics, etc.

4 Environment Dynamic Models based on t-GIS

4.1 Integration of environmental model with GIS

The dynamic model in a narrow sense belongs to the concept of physics, but it has already spread out to events related to the all matter movement. In this paper, the dynamic model for environment discussed is meant for the mathematical model that can quantitatively describe the position, state and procedure of evolution of the geographical substance. This model is a function of time. Its form may be a formula, a set of algorithms, a group of rules or their combination. The pure dynamic model is not directly related with GIS. The different dynamic models belong only to their own special fields. The reason to compact the dynamic model with GIS as a unit is mainly the ability of visual reflection and analysis. Since visual description of any spatial dynamic procedures depending on the reflection to the time and spatial information that makes the use of Eq. (2) possible.

Some people suggest that the integration of dynamic models for environment with GIS should be divided into different link levels (Raper et al., 1993; Fedra, 1993a; Nyerges, 1993; van Deurson, et al., 1990, 1993). Perfect level of integration demands support of database either to the spatial distribution of geographical data, or to the memory, the control parameters and distributive input for time (and space). van Deursen (1995) has discussed three link levels for the integration of GIS with dynamic models, but did not give their internal relation.

Three considerations to build up the dynamic models for environment turning in the direction of t-GIS, namely, the mechanism method, the experience method and the mixed method are given as follows.

4.2 The mechanism-modeling method

To completely start with the principle and mechanism of evolution of the natural environment, and according to known relations and laws, the equations have been derived and calculated that may quantitatively describe the changes of environment.
For example, supposing the movements of substance of environmental evolution obey some dynamical laws $V$, the potential function of environmental evolution and relevant fixed solution question exist, therefore, $V$ can be obtained by solving the mathematical and physical Eq. (9), that is

$$F\left[\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2}, \alpha, \beta, \gamma, \delta, \cdots\right] = 0 \quad (9)$$

Because $G$ is the function of $V$, from which the Eq. (1) can be obtained. This method is very ideal but extremely difficult to realize. Using it is practicable only under the conditions of specified homogeneous environment and relatively unitary and measurable influential factors for environmental changes.

### 4.3 The experience-simulating method

To construct the experience formulas for describing the changes of environment in term of the data of practical observer through long-term quantitative observation on the specific environmental objects and/or measurement in the laboratory, the dynamic procedures of the evolution of environment have been simulated. This method is simple and easy to operate, but the main problem is the need of long period of time for acquiring serial time data of the whole natural process. For example, the duration that evolution of landforms can reflect clearly detectable changes is ten years at least. But there is nothing the matter with changes of short period of human and social environment.

### 4.4 The mixed method

The mixed method is the combination of above two methods. The application of the theoretical model or the experience model depends on concrete conditions.

van Deursen (1995) classified the dynamic models into two patterns dependent on number of dimension and complexity. The former is divided into 1-, 2- and 3-dimension model. To keep generality, here only the 3-dimension model is given,

$$S_{x,y,z,t} = f(I_{x,y,z,t}, P_{x,y,z,t}) \quad (11)$$

Relative static model of 3-dimension is

$$S_{x,y,z,t} = f(I_{x,y,z}, P_{x,y,z}) \quad (12)$$

where $S$ is state of system; $I$ is forced function input; $P$ is parameter; $I_{x,y,z,t}$ and $P_{x,y,z,t}$, are all the functions of time.

The latter is the mathematical equation that determines the number of subsystem, the amount of state variables and the procedures in the models are in accordance with their level of complexity. For this reason, there are three main types of model for environment: (1) Response function models based on the concept; (2) Procedure model based on the concept; (3) Model based on the complex nature.

The environmental models divided on the level of complexity can include variable of time, and the environmental models divided on dimension can belong to different levels of complexity, so, practically there is a certain connection in common use between the two dividing mode of models.

### 5 System function and its design

Analysis system based on t-GIS for the environment has the functions of fast I/O, inquiry static / dynamic display of temporal picture files, and visible analysis for the spatial and in series of temporal information. Theoretically, so long as the coordinate of time and its range are given, the environmental pictures in any time, i.e. in the present time, in the past time and in the future time, should be displayed and the process of evolution for environment will be lively described. Of course, the display for looking back upon the past pictures and prognosticating the future pictures can not be extrapolated without limitation. It should be subjected to limit the domain of the dynamic models.

#### 5.1 Structure of temporal data

The Eq. (2) is the base of the structure of data from the environmental information system of t-GIS. However time of display of an environmental picture should be very long if the time variation for each spatial coordinate and the attribute is calculated by Eq. (2). For the practicality of system it is the decisive point whether the calculating time for model can be controlled in an acceptable range or not. For this reason, it is necessary to build the structure of temporal data suitable for this condition.

One of the considerations is to build varying range function of the location and attribute time, that is, in terms of some conditions an area of picture is di-
vided into several sub-areas. The division principle is that there should be same parametric equations of \( t, x = x(t), y = y(t), z = z(t) \) and \( a = a(t), \beta = \beta(t), \gamma = \gamma(t), \delta = \delta(t) \) in the same area. In this way, when carrying out the time analysis of environment image temporal changes of positions and attributes there is no need to be calculated point by point, but only in order of sub-areas. Thus, calculating speed can be increased greatly.

5.2 Remaking GIS into t-GIS

The ultimate goal of researching t-GIS and dynamic models for environment is to build a tool-type system of dynamic analysis and assessment of environment information for the suitability of different environment problems. It is unnecessary to abandon the original GIS for environment and develop t-GIS from the start if the platform of GIS has opening data structure and secondary developing ability. The GIS can be remade into t-GIS only by means of Eq. (2), and by setting the special dynamic models for environment into the previous GIS and complementing some operations on the design. Of course, the systematic programming is unavoidable if it is necessary to build a tool-type t-GIS facing the analysis of environment.

6 Conclusions

All the departments and the professions dealing with administration, display and analysis of local dynamic geographical information can build the information system based on t-GIS and dynamic models for environment to meet their needs. Its application is concerned with many fields.

6.1 Information analysis system for landform evolution

The dynamic models include the model of landform deformation under exogenous force (caused by weathering and denudation of rock, soil erosion, human effects, etc.) and the model of internal landform deformation under internal force (caused by fold, fault, fault depression and magmatic intrusion etc.), etc. The spatial-temporal variables include the altitude, range, form, width and length of line, position of point and buffer zone, etc. The attribute-temporal variables include the level, geological type and rate of its variation etc.

6.2 Information analysis system for condition of water and fertilizer of farmland

The dynamic models include the model of condition of inorganic composition of soil, model of soil humidity, model of soil structure, model of soil temperature, etc. The spatial-temporal variables contain the range, form, depth, width and length of line and position of point, etc. The attribute-temporal variables contain the degree, types of water and fertilizer, rate of its variation, etc.

6.3 Analysis and assessment system for ecological environment

Auto-assessment of ecological environment involves in a wide range. The dynamic models include the model of soil erosion, model of vegetation cover, model of rock desertification, model of soil pollution, model of air pollution, model of human-earth mutual effect, etc. The spatial-temporal variables cover the range, form, boundary line, position of point, buffer zone, etc. The attribute-temporal variables cover the degree, rate of variety, type of region, etc.

6.4 Analysis system for distribution and condition of population change in China

The dynamic models include the national model, the model of sex, model of age, model of education condition, model of state of health, model of birthrate, model of death rate, etc. The spatial-temporal variables include the range, boundary, position of point, etc. The attribute-temporal variables include the degree, types, etc.

To sum up, transition from GIS to t-GIS is an inevitable trend. It is a technological revolution that makes simulated display-express of the real world close to the true. Because the problem of environment is human’s theme in the 21st century, the role, benefit and significance produced by combining t-GIS with dynamic models for environment will be inestimable.

In China the contact between GIS and time has been discussed from the point of view of 4D GIS, and 4D GIS has been listed as an advanced development direction, but up to now, its practical achievement has not been made. Therefore, it is clear that 4D GIS can not involve in all the content of t-GIS
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