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GIS-based Simulation of Soft Geo-objects

Dayong Shen[1], Kaoru Takara[1], Yasuto Tachikawa[1]
[1]*Disaster Prevention Research Institute, Kyoto University, Uji, Kyoto 611-0011, Japan*

ABSTRACT: To simulate dynamic soft geo-objects and reflect geoscientific laws, the authors discuss the characteristics, mathematical expression, parameter representation and rendering of GIS Flow Element (FE) and GIS Soft Voxel (SV). The simulation and rendering algorithms of GIS FE and GIS SV are based on particle system and metaball technology in computer graphics. The main differences are that GIS FE and GIS SV have definite geoscientific meaning and they are simulated based on geoscientific models so they can well represent geoscientific characteristics of simulated objects. Compared to traditional GIS modeling approaches such as TIN, grid, tetrahedron, octree and others, this approach is more convenient, realistic and efficient in simulating dynamic soft geo-objects. This paper selects the simulation of soil erosion process on hillslopes as a case study, and proves that the approaches of GIS FE and GIS SV can enrich the capability of GIS. Therefore, they have the potential for widely practical use.

1 INTRODUCTION

Objectively geo-objects are divided into rigid geo-objects and soft geo-objects. The critical characteristic of a soft geo-object is that the object will change shape when influenced by forces or collisions. There are many kinds of soft geo-objects such as flood, landslides, mudflow, lava flow, wind, cloud, smoke, fire and others in the real world. However, how to appropriately represent soft geo-objects in GIS is still a challenge even though traditional GIS modeling approaches (Wu and Shi 2003) such as TIN, grid, tetrahedron and octree can well represent rigid geo-objects.

In this paper, we mainly test GIS-based simulation of soft geo-objects using the approach of GIS FE and GIS SV.

2 GIS FE AND GIS SV

A GIS FE is an object with position, velocity and direction and other parameters that change over time. But it neglects volume. A GIS SV is an object with position, velocity, direction and volume and covered by an isosurface. When several GIS SVs meet together, one smooth surface will be formed. Both GIS FE and GIS SV are basic simulation units to simulate dynamic soft geo-objects and built based on pixels from remotely sensed imagery and scientific computation of geoscientific models (as shown in Table 1).

2.1 Structure

● A GIS FE has coordinates of starting point and end point, velocity, direction and geoscientific models for computing V and D as shown in Figure 1.
● A GIS SV has two basic components: a critical point (or point skeleton) and an implicit surface (sometimes include constraints). The critical point is a point-shaped GIS FE and parameters of the implicit surface are shown in Figure 2, where strength and threshold have the same meaning as that in computer graphics (Geiss 2000). As we draw GIS SVs using marching cube algorithm, the depth of division will affect both rendering speed and

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accuracy. Considering faults simulation is very important in geology, and it may cut many imagery pixels into pieces, we use constraint functions to control the shape and volume of a GIS SV. Index identity number is used in template-based rendering algorithms, which will be discussed in the following context.

Table 1. GIS FE and GIS SV

Description	GIS FE	GIS SV
Key geometric components	Starting point and end point	A critical point and an isosurface
Aims	Computing, simulating and analyzing the velocity and direction of soft geo-objects based on geoscientific models	Computing, simulating and analyzing the volume and deformation of soft geo-objects based on geoscientific models
Scale	Considering existing accuracy of data acquisition, it is simulated based on pixels of remotely sensed imagery	Considering existing accuracy of data acquisition, it is simulated based on pixels of remotely sensed imagery
Geoscientific meaning	Reflecting dynamic change of velocity and direction of soft objects in a pixel	Reflecting the dynamic change of volume and shape of soft geo-objects in a pixel
Critical characteristic	Reflecting dynamics and stochastics of soft geo-objects realistically	Simulating the deformation of soft geo-objects naturally

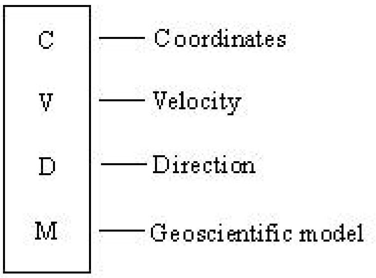

Figure 1. Structure of a GIS FE

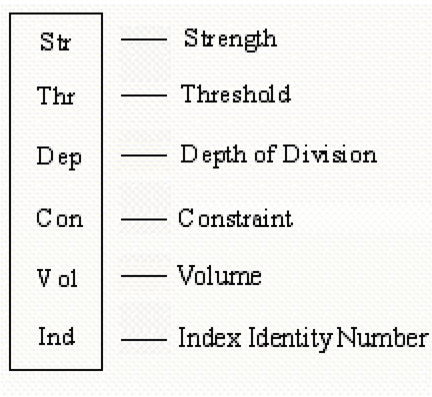

Figure 2. Structure of the implicit surface

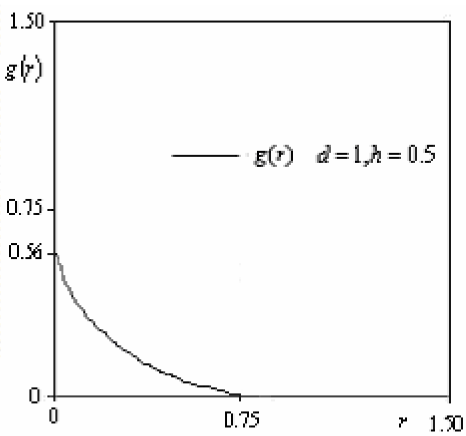

Figure 3. Field function graph of a GIS SV

2.2 Mathematical expression

● Velocity of a GIS FE is computed using geoscientific models as seen in Eq. (1), where M_1 is geoscientific model, $p_1, p_2, \ldots, p_j$ are affecting factors of V.

$$V = M_1(p_1, p_2, \ldots, p_j) \tag{1}$$

Considering that V is in direct proportion to L, which is the length of a GIS FE, we get:

$$V = \lambda L \tag{2}$$

where λ is a proportional coefficient and $\lambda > 0$.

● Implicit surface of a GIS SV is created by a field function as seen in Eq. (3):

$$g(r) = \left(r - \sqrt{2d^2 + h^2} \Big/ 2 \right)^2 \tag{3}$$

where *d* is the length of a pixel, *h* is the average thickness of soft objects, (x, y, z) are 3-D coordinates of the critical point of a GIS SV, $r^2 = x^2 + y^2 + z^2$. Note that $g(0) = \left(2d^2 + h^2\right) \Big/ 4$ and $g\left(\sqrt{2d^2 + h^2} \Big/ 2\right) = 0$. Between $r = 0$ and $r = \sqrt{2d^2 + h^2} \Big/ 2$, values of $g(r)$ decrease smoothly from $\left(2d^2 + h^2\right) \Big/ 4$ to 0 (as seen in Figure 3).

Note that volume of a GIS SV Vol is computed based on its inscribed cuboid, as seen in Eq. (4):

$$Vol = d^2 h \tag{4}$$

2.3 Parameter representation (as shown in Table 2 and Table 3)

Table 2. Representation of a GIS FE

Parameters	**Representation**
Shape	A point, line, surface, or volume
Color	Depends on the color of the geo-object
Opaqueness	Depends on the opaqueness of the geo-object
Initial Position	The center point of current pixel
Velocity	Computed using geoscientific models
Direction	8-neibourhood tracing algorithm
Lifetime	When a GIS FE moves out of the simulated control boundary, its life will be ended and not rendered any more

Table 3. Representation of a GIS SV

Parameters	**Representation**
Shape	A voxel covered by an isosurface
Color	Depends on the color of the geo-object
Opaqueness	Depends on the opaqueness of the geo-object
Initial Position	the perpendicular projection of the center point of a GIS SV in a pixel plane is the center of the center point of current pixel
Velocity	Computed using geoscientific models
Direction	8-neibourhood tracing algorithm
Deformation	Computed based on separation and fusion algorithms; constraints will be added if necessary
Volume	Computed based on its inscribed cuboid; volume control will be considered when deformation occurs
Lifetime	When a GIS FE moves out of the simulated control boundary, its life will be ended and not rendered any more

2.4 Rendering

● Basic methods for rendering GIS FEs take each GIS FE as a point (or linear if motion blur is considered) light source. Each GIS FE has a constant color, without difference in luminance and hue, and no obstacles. Then accumulate the contribution made by all GIS FEs and integrate it into normally rendered scenarios. Advanced methods include setting light and shadow and processing GIS FEs in hidden surfaces. Note that theoretically the shape of a GIS FE can be rendered as arbitrary point, line, surface or volume. However, the perpendicular projection of a GIS FE in a pixel plane should be completely within the pixel considering that it is created based on the pixel.

● To render GIS SVs, basic methods include tracing isosurface, controlling shape and setting light, texture and shadow (Geiss 2000); advanced methods contain special algorithms for separation and fusion (Desbrun and Gascuel 1994) and template-based algorithms, which are used to create GIS SV template data and their index identity numbers to raise rendering speed.

3 CASE STUDY

3.1 Simulate water flow based on GIS FEs

● data structure: struct WaterFlow{

```
C3DfPoint bPoint;        //coordinates of the starting point (center of the base circle)
C3DfPoint ePoint;        //coordinates of the end point (center of the top circle)
float radius;            //radius of the base
float velocity;          //velocity of motion
float angle;             //direction of motion
COLORFLT    color;       //r(0.0 – 1.0); g(0.0 – 1.0); b(0.0 – 1.0)
float transparency;      //0.0 – 1.0
};
```

● geoscientific models: velocity model of overland flow is as seen in Eq. (5):

$$V = a_0 (q / h)^{a_1} S^{a_2} \tag{5}$$

where *V* is velocity of overland flow (m s^{-1}); *q* is discharge per unit width ($m^{-3}m^{-1}s^{-1}$); *h* is depth of runoff (m); *S* is slope angle (°) and a_0, a_1, a_2 are coefficients and indices of geography.

●rendering: Figure 4 shows the technical routes for rendering overland flow. Figure 6 shows rendering effects of dynamic overland flow.

read DEM data
⇩
trace flow direction
⇩
compute slope length
⇩
compute unit discharge
⇩
compute the depth of runoff
⇩
compute the velocity of overland flow
⇩
define the structure of a GIS FE
⇩
preset the route of overland flow
⇩
render DEM
⇩
render dynamic overland flow

Figure 4. Flow chart of rendering overland flow

read DEM data
⇩
read the template data for GIS SVs
⇩
read the index data of the template data for GIS SVs
⇩
read graded data of the intensity of water erosion
⇩
color GIS SVs based on graded erosion intensities
⇩
trace the movement direction for GIS SVs
⇩
compute the velocity of GIS VSs
⇩
preset the movement route for GIS SVs
⇩
render DEM
⇩
render the dynamic process of hillslopes soil erosion

Figure 5. Flow chart of rendering the process of soil erosion on hillslopes

3.2 Simulate soil erosion based on GIS SVs

●erosion model:

$$E_{sl} = a_0 (I - I_0 / I)^{a_1} h_{sl} (\phi)^{a_2} (\sin 2\alpha)^{a_3} \exp(-a_4 S_{vc}) \tag{6}$$

where E_{sl} (mm a^{-1}) is the intensity of soil erosion on hillslopes; I is the intensity of rainfall (mm a^{-1}); I_0 is the threshold value of the intensity of rainfall causing erosion; h_{sl} (mm a^{-1}) is the intensity of runoff on hillslopes; ϕ (%) is preponderant percentage of soil particle size; α is the gradient (radian); S_{vc} (%) is vegetation coverage; a_0, a_1, a_2, a_3, a_4 are geographical coefficient and indices (Shen et al 2003).

● rendering: Figure 5 shows the technical routes for rendering soil erosion scenarios. We collect data sources from a sub-watershed in China Loess Plateau region and simulate one rainfall process in that region. In Figure 6, the texture is based on a 1:10,000 color infrared aerial photograph. In Figure 7, DEM is digitized from a 1:5,000 relief map. The deeper color of a GIS SV, the greater erosion intensity of the pixel in which the GIS SV is located.

Figure 6. Simulate overland flow based on GIS FEs

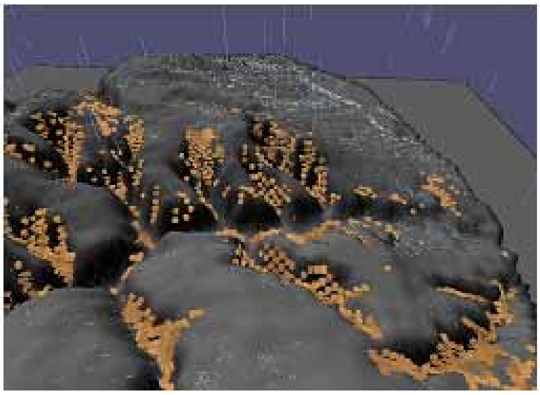

Figure 7. Simulate the process of soil erosion by water on hillslopes based on GIS FEs and GIS SVs

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5 CONCLUSION AND DISCUSSION

This paper discusses theory and methods of GIS FE and GIS SV, and proves that the methods are quite efficient through a case study in China Loess Plateau region. Considering existing accuracy of data acquisition, both GIS FE and GIS are simulated based on remotely sensed imagery pixels. Therefore, they can be used as basic units for simulating soft geo-objects and have the potential for widely practical use such as flood disaster modeling and simulation (Takara et al 1998). As the approaches of GIS FE and GIS SV are in progress, it is necessary to enhance their functions in geoscientific analysis to more conveniently show the strong capability of GIS.

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