High-Fidelity Roadway Modeling and Simulation

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Abstract: Roads are an essential feature in our daily lives. With the advances in computing technologies, 2D and 3D road models are employed in many applications, such as computer games and virtual environments. Traditional road models were generated by professional artists manually using modeling software tools such as Maya and 3ds Max. This approach requires both highly specialized and sophisticated skills and massive manual labor. Automatic road generation based on procedural modeling can create road models using specially designed computer algorithms or procedures, reducing the tedious manual editing needed for road modeling dramatically. But most existing procedural modeling methods for road generation put emphasis on the visual effects of the generated roads, not the geometrical and architectural fidelity. This limitation seriously restricts the applicability of the generated road models. To address this problem, this paper proposes a high-fidelity roadway generation method that takes into account road design principles practiced by civil engineering professionals, and as a result, the generated roads can support not only general applications such as games and simulations in which roads are used as 3D assets, but also demanding civil engineering applications, which requires accurate geometrical models of roads. The inputs to the proposed method include road specifications, civil engineering road design rules, terrain information, and surrounding environment. Then the proposed method generates in real time 3D roads that have both high visual and geometrical fidelities. This paper discusses in details the procedures that convert 2D roads specified in shape files into 3D roads and civil engineering road design principles. The proposed method can be used in many applications that have stringent requirements on high precision 3D models, such as driving simulations and road design prototyping. Preliminary results demonstrate the effectiveness of the proposed method.

1. Introduction

Roads are an essential component of civilization and many different types of roads exist, e.g., highways, freeways, expressways, arterial streets, and rural roads. With the advances in computing technologies, road models are widely used in many applications such as games and virtual environments. In early computer applications involving road models, almost all 2D and 3D road models were generated by professional artists manually using modeling software tools such as Creator, 3ds Max, and Maya. Good results can be achieved through manual road modeling at the expense of extensive labor and time.

Various methods have been proposed to automate the road modeling process. Procedural modeling methods allow automatic generation of objects according to specifically designed procedures and they have been utilized for automatic road generation. Parish and Muller introduced the L-system for natural phenomena modeling in their procedural modeling software CityEngine for road generation, building construction, and building face creation [1]. Sun et al. extracted four kinds of common road patterns (Population-Based, Raster, Radial, and Mixed) from existing road networks and generated road networks for virtual city modeling based on these pattern templates [2, 3]. Watson et al. used an agent-based technique to generate road network as a part of virtual cities generation [4, 5]. Glass et al. attempted to combine various existing procedural techniques including Voronoi diagrams, subdivision, and L-system to replicate the identified features of road patterns in south African informal settlements [6]. Chen et al. put forward a tensor field based procedural method to model the street networks of large urban area interactively [7]. However, all these methods focused on the creation of artificial road networks for virtual environments to achieve visual satisfaction; the detailed road geometric design and structure based on civil engineering principles were not addressed in these methods.

Automatically generating high-fidelity roadways from real terrain and GIS data with special focus on combining procedural modeling and civil engineering principles is a very challenging problem but with many applications, such as, such as driving simulation and road design prototyping. To this end, this paper proposes a method that takes into account road design principles practiced by civil engineering professionals, and as a result, the generated roads can support not only general applications such as games and simulations in which roads are used as 3D assets, but also demanding civil engineering applications, which require accurate geometrical models of roads. The inputs to the proposed method include road specifications, civil engineering road design rules, terrain information, and surrounding environment. Then the proposed method generates in real time 3D roads that have both high visual and geometrical fidelities. This paper discusses in details the procedures that convert 2D roads specified in shape files into 3D roads as well as civil engineering road design principles.

The remainder of the paper is organized as follows. Section 2 describes the system design of the proposed road generation method. Section 3 discusses the implementation of the system design in detail using the generation of a parametric road curve as an example. Section 4 shows some experimental results. Lastly, Section 5 concludes this paper and discusses future research directions.

2. System Design

The major goal of this work is to automatically generate high-fidelity roadways from real geographical information, satisfying civil engineering requirements. The overall structure of the proposed method is illustrated in Figure 1. Inputs to the proposed method include road design rules, road specification, and terrain and GIS data and the outputs are road representations produced by the proposed method.

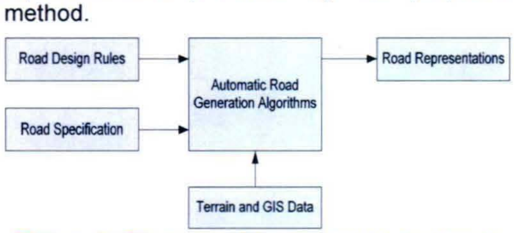


Figure 1: Structure of the proposed automatic road generation system

Road design rules vary with countries and states. Thus, based on the target area for which the roads are to be generated, appropriate design rules should apply. For roads in the US, the US Department of Transportation (DOT) Federal Highway Administration developed Federal Lands Highway Project Development and Design Manual [8]. In addition, state DOT's also provide highway design manuals and guidelines. These road design manuals describe every aspect of road design, such as road cross sections, interchanges, maximum and minimum grades, overbridges, underbridges, abutment, merges and diverges, roundabouts, and turn radius. Clearly it is not necessary and infeasible to use all design rules in our automatic road generation system for modeling and simulation applications. As a result, it is necessary to determine a minimum set of design rules for our automatic road generation system.

The road specification describes the requirements and features of the road to be generated, including items such as road functional class (local, connector, arterial, freeways), number of lanes, speed limit, lane width, road signs, road environment (urban or rural), surface type, interchanges types, curvature, visibility, and superelevation. These parameters of road specification define the requirements for the items included in the minimum set of design rules. For example, Figure 2 illustrates basic elements for describing a superelevation transition [9]. Terrain and GIS data can complement the parameters in the road specification. For example, the GIS data may provide the shape file for road centerlines as well as the number of lanes. Other GIS data such as land use and satellite images can also be useful for road generation.

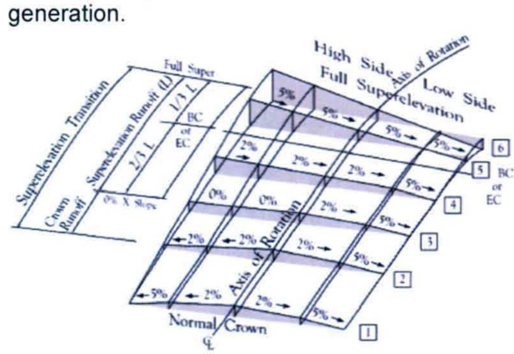


Figure 2: Elements of a superelevation transition [9]

At the core of the proposed method is the automatic road generation component, which consists of two major parts: data structures and algorithms.

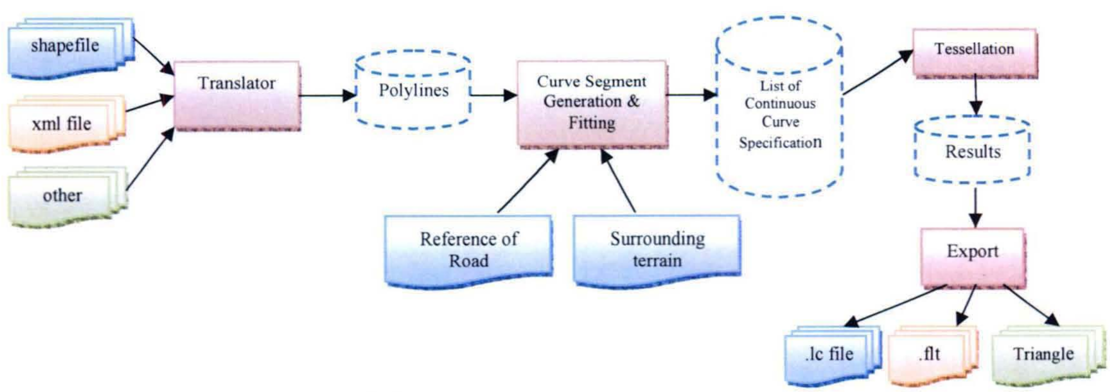


Figure 3: Functional blocks in the proposed method

Data structure will be developed to represent the road design rules, road specifications, terrain, GIS information, as well as the roads to be generated. In addition, different levels of representations can be utilized. For example, two different representations of the generated roads can be utilized: high level representation and low level representation. High level representation stores the road topology (links and nodes), attributes of each link (number of lanes, speed limit, length, etc.), and low level representation can be a triangular mesh of a short road segment for high-fidelity driving simulator applications. The automatic road generation algorithms produce the roads based on the road design rules and road specifications. Different algorithms will be developed to generate different road features, such as road surfaces, interchanges, merges and diverges, and traffic signs. A hierarchy of algorithms will be developed. For example, the top level (class) of the hierarchy will generate the composition of the entire road (route), while the middle and low classes will generate the details of each component. Other classes will produce the final outputs of the generated roads. Procedural methods such as the L-system will be investigated and used if necessary. The proposed algorithms also need to adjust the terrain so that the generated roads fit their surrounding environments well.

3. Implementation

The whole road generation process is shown in Figure 3. First road specifications, in the form of various file formats, e.g., shape file and XML file, are transformed by a translator into polylines, which represent the coarse position of the road centerline and will be used as road prototype. These polylines are then refined and optimized into road segments in Segment Generation & Fitting based on reference of road, namely, road design rules and additional road specifications, and surrounding terrain. All of these road segments are represented by a set of parameters and then tessellated into different levels of discrete road representations and finally can be exported into various file formats. In the following, generation of a road curve will be used as a typical example to illustrate the implementation and some preliminary results will be shown in section 4.

3.1 Segment Generation & Fitting

Among all the functional blocks in the proposed method, the segment generation is one of the focal points. The input, output, and main functions of this functional block are described as follows:

Input: The input of this process is a polyline representation obtained from a translator which reads and translates various file formats, such as shape files and XML files.

Output: The output of this process is parametric representations of road segments. An example of the parametric specification includes entry point(TS), alignment point(PI), exit point(ST), radius(R), length of entry spiral (L1), length of exit spiral(L2), and superelevation (SE), as illustrated in Figure 4.

To design a road, civil engineering professionals make use of a set of parameters to specify the road geometry, such as superelevation, spiral length, and radius. To generate high-fidelity roads that comply with civil engineering principles, such parameters are generated by the proposed method. The polyline road representations in the shape files contain a series of points or vertices for each road segment, which is defined by connecting the consecutive points or vertices. Thus polyline road representations are linear approximations of ideal road curves. To extract the road curve parameters from the polyline representations, the proposed method first divides the polylines into different segments through a segmentation process and then finds parametric representations of each segment using the least square method.

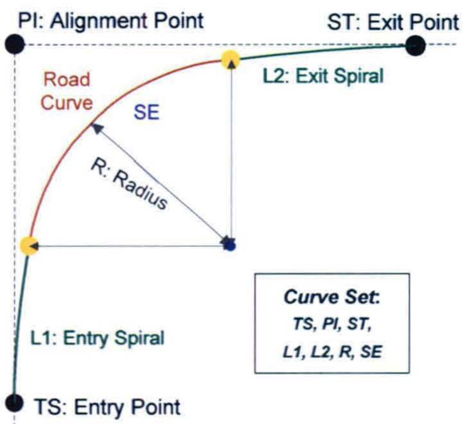


Figure 4: An example of the parametric representation of a curved road segment. A road curve contains three point positions, which are the entry point (TS), alignment point (PI) and exit point (ST), two length values, which are entry spiral (L1) and exit spiral (L2), a radius (R), and the superelevation (SE).

3.1.1 Road Polyline Segmentation

In order to divide the road polylines into different segments, we identify three types of critical points which are used to segment the road polylines. The critical points are defined based on their geometrical features as follows.

- Sharp turn: The angle between the adjacent line sections of this point exceeds a predefined threshold, resulting in a sharp turn when driving or passing through this point.
- S-turn: Curvature can be calculated for each point of the polyline and the curvature of each point has a radius. A tangent circle of each point is a circle with the same radius as that of the curvature. The center of the tangent circle can be on either left or right side of the polyline. S-turn is such a point at which the center of its tangent circle changes from one side of the polyline to the other side.
- Turn start/end: The polyline representations of roads tend to have dense points for road segments with large curvature and sparse points for relatively straight road segments. Thus the lengths of two line segments at a point can be used to indicate a transition from a straight line to a curve, or vice versa. The proposed method calculates the ratio of the lengths of the two adjacent line segments at a point and compares it with a predefined threshold. If the ratio is greater than the threshold, that point is the start or end of curved road segments.

3.1.2 Parametric Representations Using Least Square Fitting

In this section, we present the results for fitting a set of points (x_i, y_i), $i = 1, \ldots, N$ into a line or circle using the least square method. The derivations are omitted due to space limit.

- Line Fitting

A line can be represented by the equation $y = ax + b$. The parameters a and b can be calculated using the least square method as follows.

$$a = \frac{\sum x_i y_i \sum x_i - \sum y_i \sum x_i^2}{(\sum x_i)^2 - N \sum x_i^2},$$

$$b = \frac{\sum x_i \sum y_i - N \sum x_i y_i}{(\sum x_i)^2 - N \sum x_i^2}$$

- Circle Fitting

A circle can be determined by its center (A, B) and radius R. The parameters A, B, and R can be calculated using the least square method as follows.

$$A = \frac{a}{-2},\ B = \frac{b}{-2} \text{ and } R = \frac{1}{2}\sqrt{a^2 + b^2 - 4c}$$

where

$$a = \frac{HD - EG}{CG - D^2},\ b = \frac{HC - ED}{D^2 - GC},$$

$$c = -\frac{\sum(X_i^2 + Y_i^2) + a\sum X_i + b\sum Y_i}{N},$$

and

$$C = (N\sum X_i^2 - \sum X_i \sum Y_i),$$
$$D = (N\sum X_i Y_i - \sum X_i \sum Y_i),$$
$$E = (N\sum X_i^3 + N\sum X_i Y_i^2 - \sum(X_i^2 + Y_i^2)\sum X_i),$$
$$G = (N\sum Y_i^2 - \sum Y_i \sum Y_i),$$
$$H = N\sum X_i^2 Y_i + N\sum Y_i^3 - \sum(X_i^2 + Y_i^2)\sum Y_i.$$

3.2 Tessellation

This section mainly discusses parametric representations of curved road segments. A spiral curve is a curve of constantly changing radius. Spiral curves are generally used to provide a gradual transition in curvature from a straight section of road to a curved section. Figure 5 shows the components of a spiral curve. Spiral curves are necessary on high-speed roads from the standpoint of comfortable operation and gradually bringing about the full superelevation of the curves.

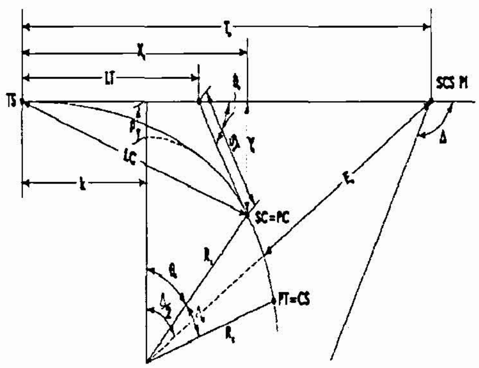


Figure 5: Components of a spiral curve

Definitions

- SCS PI = Point of intersection of main tangents.
- TS = Point of change from tangent to spiral curve; SC = Point of change from spiral curve to circular curve; CS = Point of change from circular curve to spiral curve; ST = Point of change from spiral curve to tangent.
- LC = Long chord; LT = Long tangent; ST = Short tangent.
- PC = Point of curvature for the adjoining circular curve; PT = Point of tangency for the adjoining circular curve.
- T_s = Tangent distance from TS to SCS PI or ST to SCS PI.
- E_s = External distance from the SCS PI to the center of the circular curve.
- R_c = Radius of the adjoining circular curve.
- Θ_s = Central (or spiral) angle of arc l_s.
- Δ = Total central angle of the circular curve from TS to ST.
- Δ_c = Central angle of circular curve of length L extending from SC to CS.
- k = Abscissa of the distance between the shifted PC and TS.
- Y_c = Tangent offset at the SC; X_c = Tangent distance at the SC; x and y = coordinates of any point on the spiral from the TS.

4. Experimental Results

4.1 Segmentation and Fitting Results

Figure 6 shows an example of road segmentation and fitting using part of Interstate I-64 as an example. Figure 6(a) displays the original polylines imported from a shape file. Figure 6(b) shows the results after segmentation. Polylines are divided into several segments separated by critical points: red points for curve segment and black points for straight line segments. Figure 6(c) shows the results line and circle fitting using the least square method. Two circles with radii of 1433.1m and 686.7m are extracted from points on the curved parts and three straight lines are extracted from points on the line segments. It can be seen the proposed segmentation and fitting methods are very effective, producing parametric representations of the road segments that fit very well the original polyline representations.

4.2 Tessellation Results

This part uses horizontal alignment as an example. In order to create the alignment of the road surface, one needs to know the coordinates of centerline at any arbitrary intervals. Usually, these intervals are 25 ft or 50 ft. Design of a spiral curve begins by specifying the following key parameters.

1) R or D (degree of curve) is given by design considerations (limited by design speed).

2) L_c is chosen with respect to design speed and the number of traffic lanes.

In addition to these parameters, Δ, Chainage of PI, and TS, are determined in the field. All other spiral parameters can be determined by computation and/or by use of spiral tables.

Example: A simple curve is to fit a road curve with a radius of 1000 ft for a D.S. of 50 mph. The intersection angle Δ = 30°. Determine the spiral offset (y) from TS to SC in ½ station intervals (50 ft) if station of TS = 150+00.

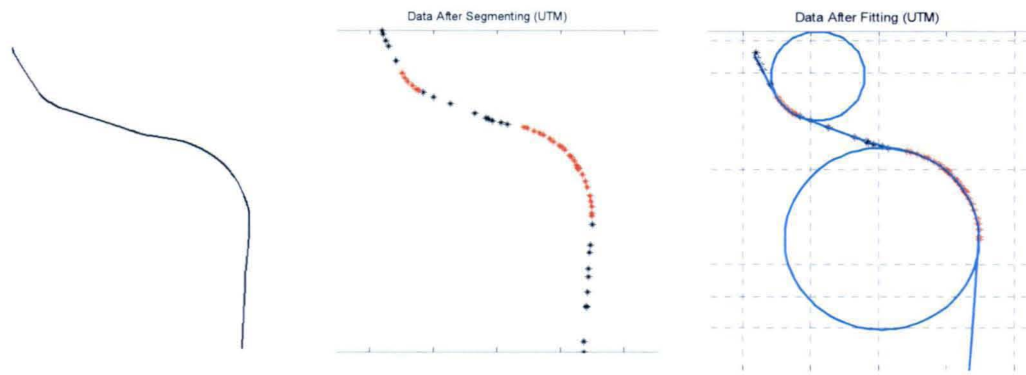
Length of the spiral:

$$l_c = \frac{1.58V^3}{R}, X_c \cong l_c, \quad y_c = \frac{l_c^2}{6R}, \quad D = \frac{5730}{R}, \quad \theta_s = \frac{l_c \times D}{200},$$
$$p = y_s - R_c(1-\cos\theta_s), E_s = (R_c + p) \times \sec\left(\frac{\Delta}{2}\right) - R_c, \quad X_c = \sqrt[3]{y_c \times 6 \times R_c \times l_c}, \quad k = X_c - R_c \sin\theta_s,$$
$$T_s = (R_c + p)\tan\left(\frac{\Delta}{2}\right) - k, \quad y = \frac{x^3}{6R_c l_c},$$

After finding all these values, the coordinates of TS can be computed. Then, the distances found above can be used for calculating the coordinates of the stations. When reaching at point SC, the circular arc begins. Based on the radius and angle of the circular curve, all the elements of the circular arc can be computed.

5. Conclusion

This paper presented a method to automatically generate high-fidelity roadways based on shape files, civil engineering rules, terrain information and surrounding environment. Using curve generation as an example, detailed procedures for polyline segmentation and parametric representations using the least square method was presented. Road curve computations based on civil engineering principles were also included. Preliminary results demonstrated the effectiveness of the proposed method. This work is an ongoing project and we will continue to improve our algorithms and representations, model more road features and apply our work to other applications as well.



(a) (b) (c)

Figure 6: Results from Polyline segmentation and fitting. (a) shows the polylines for a part of I-64 HOV lane based on the input shape file. (b) Segmentation results. Polylines are divided into several segments: red points for curve segment and black points for straight line segment. (c) Data after curve and line fitting. Radiuses for curve parts are extracted from discrete point data.

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