7.5 GIS Data Based Automatic High-Fidelity 3D Road Network Modeling

GIS Data Based Automatic High-Fidelity 3D Road Network Modeling

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Abstract. 3D road models are widely used in many computer applications such as racing games and driving simulations. However, almost all high-fidelity 3D road models were generated manually by professional artists at the expense of intensive labor. There are very few existing methods for automatically generating 3D high-fidelity road networks, especially those existing in the real world. This paper presents a novel approach that can automatically produce 3D high-fidelity road network models from real 2D road GIS data that mainly contain road centerline information. The proposed method first builds parametric representations of the road centerlines through segmentation and fitting. A basic set of civil engineering rules (e.g., cross slope, superelevation, grade) for road design are then selected in order to generate realistic road surfaces in compliance with these rules. While the proposed method applies to any types of roads, this paper mainly addresses automatic generation of complex traffic interchanges and intersections, which are the most sophisticated elements in the road networks.

1.0 INTRODUCTION

Road networks are critical infrastructures of human civilization and probably the most important means of transportation. With advances in computing technologies, 2D and 3D road models have been employed in many applications, such as computer games and virtual environment construction. Roads are complex 3D structures and 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. Procedural modeling based automatic road generation methods [1-6] create road models using specially designed computer algorithms or procedures and they can dramatically reduce or eliminate the amount of manual editing needed for road modeling. However, most existing procedural road modeling methods aimed at the visual effects of the generated roads, not the geometric or architectural fidelity that mostly determines the driving experience.

Geographic information systems (GIS) are computer-based systems widely used to store, manipulate, display, and analyze geographic information in many fields. With the rapid development and widespread use of GIS techniques, vast GIS data are captured through various digital data collection methods such as remote sensing via cameras, digital scanners and LIDAR.

As one kind of them, road GIS data which record the information of the real road network in the best possible way have also been used in many applications and facilitate our lives greatly, e.g., the automotive navigation system. Since real road GIS data contain road network information which is indispensable for some applications, especially for transportation, homeland security and defense applications, it will significantly reduce both the time and lab cost if 3D road network can be modeled from road GIS data directly and automatically. However, there are very few existing methods for GIS based automatic 3D high-fidelity road networks generation. Most GIS based modeling work and software focus on buildings [7, 8], vegetation and rural landscape visualization [9-11] rather than roads.

Therefore, a method that can automatically produce 3D high-fidelity road network models from real road GIS data will greatly benefit numerous applications involving road networks. This paper addresses this problem by proposing a novel method which is used in an ongoing project to automatically generate 3D high-fidelity road network models from existing road GIS data in compliance with a set of selected civil engineering rules. The proposed method consists of several steps, including road GIS data preprocessing, road representation parameterization, civil engineering rules based road surface

modeling, and intersection and interchange generation.

This paper is organized as follows: section 2 describes each step of the proposed method in detail; section 3 discusses the application fields and advantages of the proposed method, and finally this paper is concluded in section 4.

2.0 BODY
In this section, the whole road network modeling method is described using a road network which contains several road segments, road intersections and a traffic interchange as shown in Figure 1(a) as an example.

2.1 Road GIS Data Preprocessing

2.1.1 GIS Data Import
Although various data formats have been developed for GIS applications, such as GML (Geographic Markup Language) and TIGER (reference file format), shapefile format is the most widely used format and it is utilized in this research. A typical shapefile consists of a main file, an index file, a dBase file and a projection file. Among them, the first three files define the geometry and attributes in a shapefile. Three kinds of shape types are used to represent geometric shape features, which are point, polyline and polygon [12]. The main file contains the primary reference data with one record per shape feature; the index file stores the position and content length for each record in the main file; the dBase file contains the feature attribute for each record in the main file. A library named shapelib [13] is used in this project to read data from shapefile.

2.1.2 Road Network Topology Extraction
Since in existing road GIS data, roads are represented as 2D (latitude and longitude) centerlines in the form of polylines, i.e., connected line segments that consist of consecutive but discrete road centerline points as shown in Figure 1(b), road

network topology or connectivity information is not explicitly represented, that is, it is difficult to determine if two polylines are connected without explicitly comparing the points that compose the polylines. To expedite the automatic road generation process and to facilitate road navigation, an explicit representation of the road network or topology is necessary. In this research, a method proposed in [14] was employed to extract the topology information of the road network from raw road GIS data. The output of this method is a road network represented as a graph composed by road intersections (nodes) and road polylines (links) as shown in Figure 1(c).

2.1.3 Road Network Simplification
The raw road GIS data contain redundant representations for road links that have multiple names. That is, the same road with two or more different names is stored as two or more independent roads in the raw road GIS data. While this redundancy might be useful for other purposes, the same physical road should have only one 3D representation in this project. Hence road links with the same physical positions but different names are combined into one road link with multiple names, eliminating the redundancy of the network representation.

2.1.4 Road Classification
In order to obtain more information about road network, road links are classified into different categories according to their names which usually can be obtained from the road GIS data. Some keywords are identified to do the classification and totally six road categories are defined in this research, which are highway, local, ramp, bridge, tunnel, and unknown. For instance, keywords used to indentify local roads are a set including "LN", "ST", "RD", "DR", "AVE", "BLVD" and "PKWY". Keywords used for the road classification in this project are listed as follows:
- Highway:"I-" (e.g. I-64), "HWY".
- Local: " LN", " ST", " RD", " DR", "AVE", "BLVD", "PKWY".
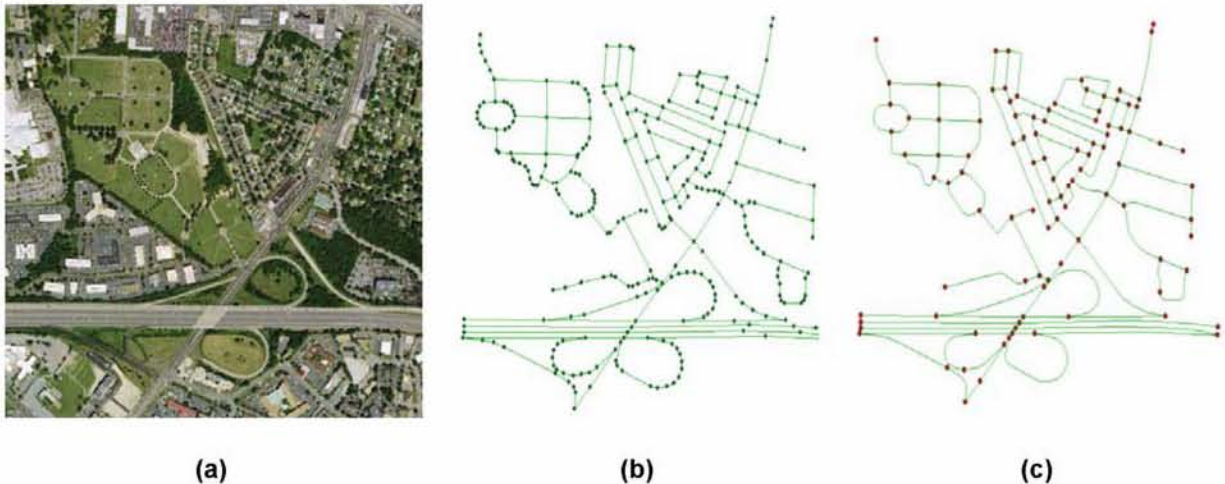
(a)   **(b)**   **(c)**

Figure 1 A road network example which contains several road segments, road intersections and a traffic interchange. (a) Satellite photo around VA-403 Norfolk, VA from USGS. (b) Road centerline and discrete road centerline points from road GIS data shown in ArcGIS for the same area. (c) Road network after topology extraction with extracted nodes indicated by red points.

- Ramp: "RAMP", 0-9+A-Z (e.g. 14B).
- Bridge: "BRIDGE".
- Tunnel: "TUNNEL".
- Unknown: "NULL".

2.2 Parametric Representation

2.2.1 Parameterization

As mentioned before, the road GIS data only contain discrete points of the road network in the form of polylines. This discrete representation has several drawbacks, with the most serious one being not supporting arbitrary resolution of representations. The proposed method converts the original discrete representation of the road network into parametric representations that have the advantages of supporting arbitrary resolution of levels of details (LOD) and reduced memory usage. Two standard parametric forms are defined as Straight Lines and Circular Curves.

- Straight Line (Line): A straight line connecting two points and specified by its ID, start point, end point, start side vector and end side vector.
- Circular Curve (Curve): Part of a circle and specified by its ID, position of center point, radius, start point, end point, start side vector, end side vector, start angle, end

angle and direction (clockwise / anticlockwise).

Among these parameters, side vectors indicate the extension direction of road surface. This representation of road centerline data has several advantages. First of all, it is relatively simple and easy to understand and implement. More importantly, it is well-suited to apply civil engineering principles, especially for superelevation generation of curve road for which the center point and radius are required.

2.2.2 Segmenting and Fitting

In order to divide the road links into segments that can be represented in standard segment forms, three types of critical points are identified to segment the road polylines: acute turn, s-turn and turn start/end [15] based on their geometric features. After the critical points are identified, road polyline links are partitioned into a set of segments that are groups of discrete points ready for segment fitting to obtain their appropriate analytic representations. Then least square methods [15] are employed to fit these road segments into straight lines and circular curves optimally. Based on the parametric

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representation of road network, different levels of details can be employed to generate the road model.

2.3 Civil Engineering Rule Based Road Surface Modeling

Since the road surface is the most significant feature of a road and its quality dramatically affects our driving experience, principles and rules on road surface design are of ultimate importance. To model this most critical component of roads realistically, namely, road surface, a basic set of civil engineering rules for road design are selected, including design speed, cross slope, superelevation, grade, etc. The road surfaces will be generated in compliance with these civil engineering rules. Among all of them, normal cross slope for most road surfaces and superelevation for some curved road surfaces are two major factors directly determining the main shape of the road surfaces. Besides these, method for pavement modeling and rendering is also discussed in this section.

2.3.1 Normal Cross Slope

Sloping on roadway cross section is employed to meet the drainage needs and direct water off the traveled way to facilitate road users and reduce accident potential. According to American Association of State Highway and Transportation Officials (AASHTO) standards [16], a plane model with a peak in the middle and a 2% cross slope downward toward both edges is preferred in this research for normal road surface modeling as shown in Figure 2.

2.3.2 Superelevation

The superelevation of a curved road segment is used to balance the centrifugal force that moves the vehicle traveling on this curve outward with gravity and side friction according to the laws of mechanics. Based on civil engineering rules [16], the superelevation rate can be determined based on the side friction factor, road radius and vehicle speed and in this research, the standard superelevation rates suggested by [16] are used for different range of curve

radius, road types and surface conditions. The centerline of the roadbed is used as the axis of rotation for superelevation and an illustration of a superelevation transition from normal crown to full superelevation can be found in Figure 2.
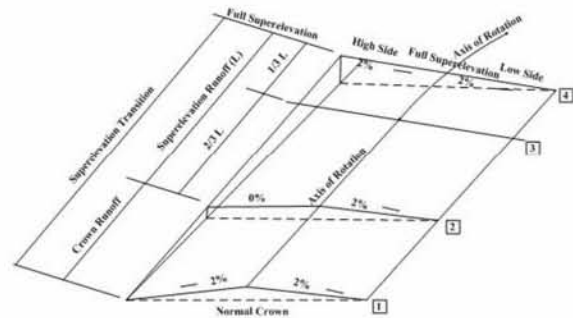

Figure 2 An illustration of a normal crown to full superelevation transition

2.3.3 Pavement

Road surfaces contain different types of pavements such as asphalt and concrete. Several methods can be used to render the road surface (pavements), which are texture mapping, programmable pixel shaders, and programmable vertex shaders. Besides visual simulation of the road surfaces, the geometry of the road surfaces can be further modified to reflect the variations on the road surface using programmable vertex shaders by adjusting the vertex positions. For instance, subtle variations of the road surface can be achieved by applying Perlin Noise and significant changes of the road conditions can be obtained through addition of holes to the road surface. We have generated a series of mathematical models for modeling different kinds of craters on planetary surface [17]. These craters can be further modified to simulate the wear and tear of road surface.

2.4 Intersection and Interchange

2.4.1 Intersection

The method discussed in [18] for junction synthesis was adopted, expanded and finally integrated into this research to
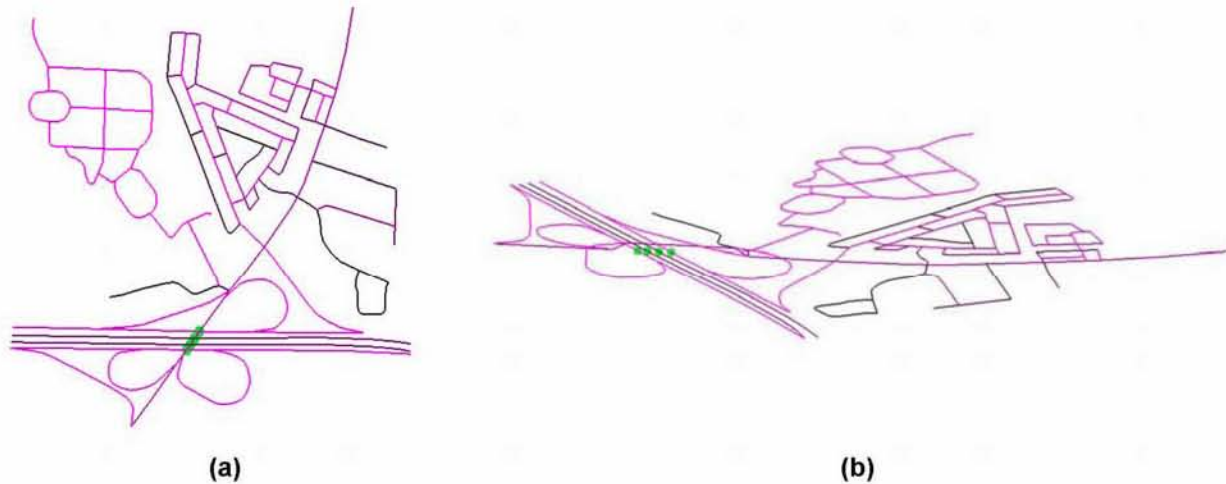
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Figure 3 3D exampled road network with generated interchange (overlapped positions are indicated by green points). (a) Top view. (b) Side view.

generate the road intersection. Compared with the original method that just considered synthesizing junctions from connected straight line road segments, our expanded method produces junctions from both straight and curved road segments with the help of side vectors. The resulting road intersection is represented by several parameters, including the position of the intersection center (node), the end point of the centerline and two boundary points for each connected segment. This process produces smooth transitions between road segments.

2.4.2 Interchange

Road interchanges are special road intersections that combine ramps and grade separations at the junction of two or more highways in order to reduce or eliminate traffic conflicts, improve driving safety and increase traffic capacity. Traffic interchange modeling is the most critical and challenging component of road network modeling due to its complexity and data deficiency that existing road GIS data are 2D and do not contain any height information (vertical position). Hence in order to generate 3D models of the interchanges, the overlapped positions in the interchanges are identified firstly and appropriate elevations are assigned to road links so that road links do not intersect or collide with each other. In

detail, since in the road GIS data, road intersections generally only occur at the end points of road links (polylines), if two road polylines contain the same point that is not the endpoint of either polyline or both polylines, this point is the location where these two road polylines overlap. And then, after overlapped position identification, the elevations of the overlapped road links are estimated based on mathematical formulations combining with observation of real traffic interchanges. Next the concept of "elevation level" is used to roughly represent the different height of road links and greater level values correspond to higher elevations. Finally after determining the elevation level for each overlapped road point, absolute elevations will be calculated based on the terrain elevation and level height, and linear interpolation is used to compute the elevations for road points located between two overlapped positions. A primary result of the interchange generation is shown in Figure 3 and reasonable relative elevation relationship is got via our proposed method.

2.5 Implementation

The proposed methods are implemented on the Microsoft XNA platform [19]. Road network models were created based on GIS data using the proposed methods and rendered with various shaders. At the same

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time, if needed, bridges and tunnels can also be generated with just some small modifications of common road segment generation program. Furthermore, considering about the environmental terrain modeling, digital terrain elevation and satellite image can also be combined seamlessly in this system to enhance the final effects. Figure 4 shows the generated 3D model for the examples road network.

3.0 DISCUSSION

Although civil engineering principles are emphasized in the proposed work, it is worth mentioning that we do not aim at generating a product that can be used for real road design and construction. Instead the intended audience and users of this work are professionals in the modeling and simulation industry, computer and video game industry, and other computer graphics applications that require realistic roadway models. The purpose is to provide rapid and efficient 3D road modeling for such applications that have higher requirements on high-fidelity road models, such as racing games and driving simulations. As such, not all civil engineering rules on road design will be utilized in the proposed work. It is also important to note that existing road GIS data does not provide complete information that is needed to generate 3D road models from the GIS data, for example, without elevation (height) information, it is difficult to determine the exact vertical locations of road network. In addition, some existing roads actually do not conform to the design standards (especially some old roads in urban areas). Considering all these factors, although the 3D road models to be produced by the method proposed in this paper are still reasonable approximations of real roadways and may not have the exactly the same structure of the real existing ones, they will have enough fidelity and resolution that are required by high-end modeling and simulation applications.
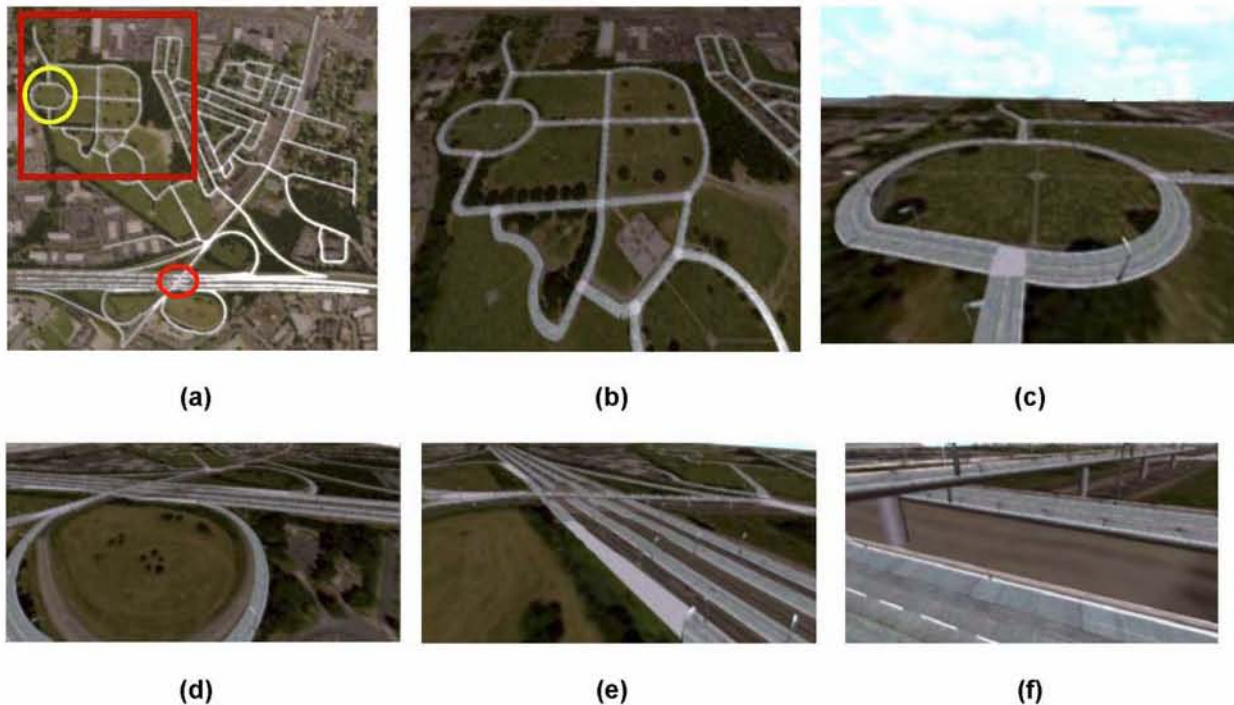
(a)   (b)   (c)

(d)   (e)   (f)

Figure 4 Experimental results (a) 3D road network generated for the examples road network. (b) Top view of the area indicated by the red rectangle in (a). (c) Side view of the area indicated by the yellow circle in (a). (d)(e)(f) Different views of the interchange part of the generated 3D road network model.

4.0 CONCLUSION

In conclusion, this paper worked on the automatic generation of 3D high-fidelity road network models from real road GIS data. The proposed method can apply to the modeling of the whole road network that is critical for applications that have stringent requirements on high fidelity road network, such as driving and transportation simulation. Also with minor modification, the proposed method can be extended for other areas, such as generation of subway system based on 2D subway maps.

5.0 REFERENCES

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Outline

- **Introduction**
- **Body**
    - Road GIS Data Preprocessing
    - Parametric Representation
    - Civil Engineering Rule Based Road Surface Modeling
    - Intersection and Interchange
    - Implementation
- **Discussion**
- **Conclusion**

Introduction

- **Road is an essential feature of civilization.**
- **Road models are widely used.**
  - Computer games
  - Virtual environment construction
- **2D/3D road models were generated manually.**
  - Creator, 3DMax and Maya
  - Massive labor & skilled artists
- **Procedural modeling**
  - Virtual effects
  - Geometric or architectural fidelity

Introduction

- **GIS: Geographic Information Systems**
  - Road GIS data
- **3D road network modeled from road GIS data**
  - Directly & automatically
  - Reduce both time & labor cost.
  - Few existing methods
- **Ongoing project**
  - Generate 3D high-fidelity road network models.
  - Existing road GIS data
  - A set of selected civil engineering rules

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Road GIS Data Preprocessing

- **Road GIS Data Import: Shapelib**

  - Road: polyline consisting of consecutive but discrete 2D centerline road points

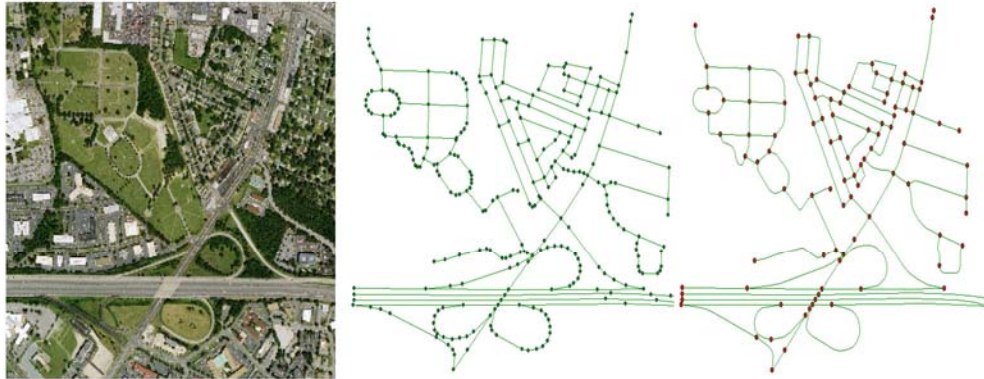- **Road Network Topology Extraction** (Jakkula, 2007)

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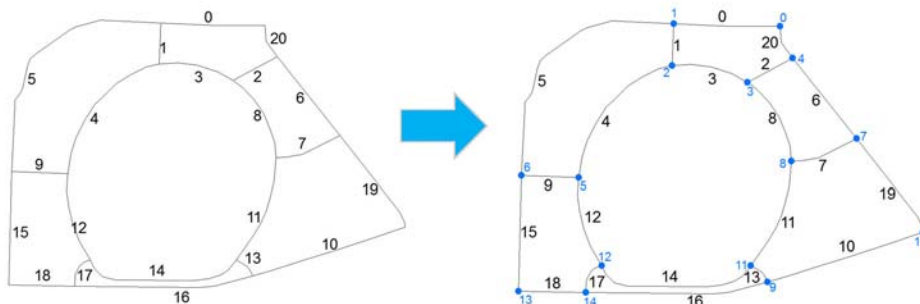
Road GIS Data Preprocessing

Figure 1. A road network example which contains several road segments, road intersections and a traffic interchange. (a) Satellite photo around VA-403 Norfolk, VA from USGS. (b) Road centerline and discrete road centerline points from road GIS data shown in ArcGIS for the same area. (c) Road network after topology extraction with extracted nodes indicated by red points.

Road GIS Data Preprocessing

- **Road Network Simplification**
  - Same physical positions but different names

- **Road Classification**
  - Highway:"I-" (e.g. I-64), "HWY".
  - Local: " LN", " ST", " RD", " DR", "AVE", "BLVD", "PKWY".
  - Ramp: "RAMP", 0-9+A-Z (e.g. 14B).
  - Bridge: "BRIDGE".
  - Tunnel: "TUNNEL".
  - Unknown: "NULL".

Parametric Representation

- **Parameterization:** converts original discrete road network into parametric representations.

- **Two Standard Forms (segment units)**

  - Straight Line (Line): A straight line connecting two points (its ID, start point, end point, start side vector and end side vector).

  - Circular Curve (Curve): Part of a circle (its ID, position of center point, radius, start point, end point, start side vector, end side vector, start angle, end angle and direction).
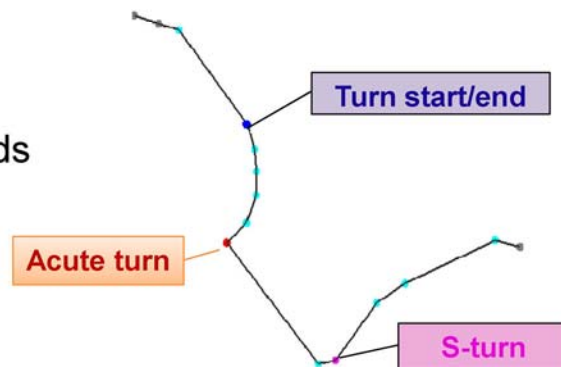
9/2/2010   9

Parametric Representation

- **Segmenting**: divides road link into segments that can be represented in standard segment forms.

  - Three types of critical points are identified.

  - Acute turn, s-turn and turn start/end (Wang, 2009)

- **Fitting**

  - Least square methods (Wang, 2009)

Turn start/end

Acute turn

S-turn

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Civil Engineering Rule Based Road Surface Modeling

- **Road Surface**
  - The most significant feature of a road
  - Its quality dramatically affects driving experience.

- **Standard**
  - American Association of State Highway and Transportation Officials (AASHTO) standard

- **A basic set of civil engineering rules**
  - Normal Cross Slope
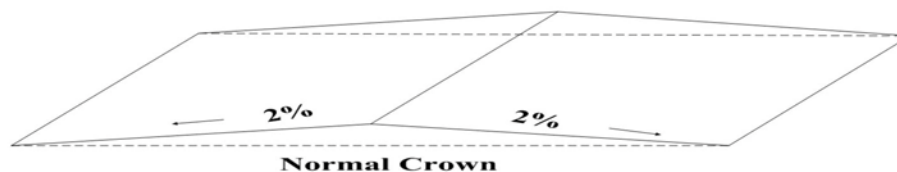 - Superelevation
  - Pavement
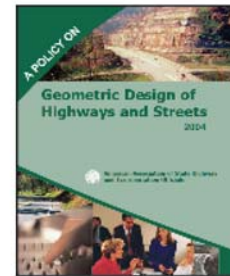
Normal Cross Slope

- **Slope**
  - Be employed to meet the drainage needs and directs water off the traveled way.

- **A plane model**
  - A peak in the middle and a 2% cross slope downward toward both edges is suggested and used.

Normal Crown

Superelevation

- Be used to balance the **centrifugal force** with **gravity** and **side friction** for **curve road segment**.
- **Superelevation rate**
  - The side friction factor, road radius and vehicle speed
  - Standard superelevation rates are used for different range of curve radius, road types and surface conditions.
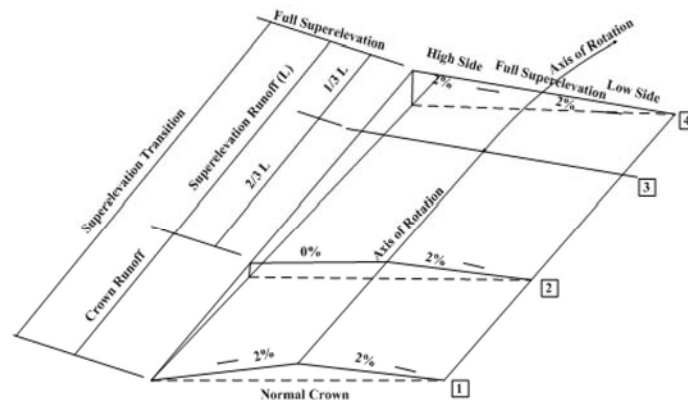
Superelevation

Figure 2. An illustration of a normal crown to full superelevation transition.

Pavement

- **Different types of pavements**: asphalt and concrete
  - Texture mapping
  - Pixel shaders & Vertex shaders
- **Variations on the road surface**
  - Subtle variations : Perlin Noise
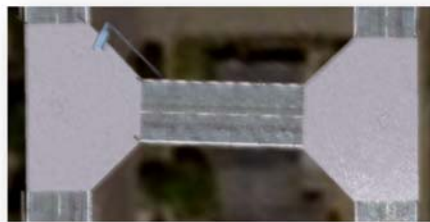 - Wear and tear : crater modeling (Wang, 2008)

9/2/2010   15

Intersection

- The method in (Sun, 2004) for junction synthesis
- Produced junctions from both straight and curved road segments.
- **The resulting road intersection**
  - The position of the intersection center (node)
  - The end point of the centerline
  - Two boundary points for each connected segment

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Interchange

- Special road intersection combining ramps and grade separations at the junction of two or more highways

- Reduce or eliminate traffic conflicts, improve driving safety and increase traffic capacity.

- The most critical and challenging component
  - Its complexity & data deficiency

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Interchange

- **Identify overlapped positions in the interchange.**

- **Determine elevation level for each overlapped road point.**
  - Elevation level
  - Mathematical formulations
  - Observation of real traffic interchanges

- **Calculate absolute elevation for each road point.**
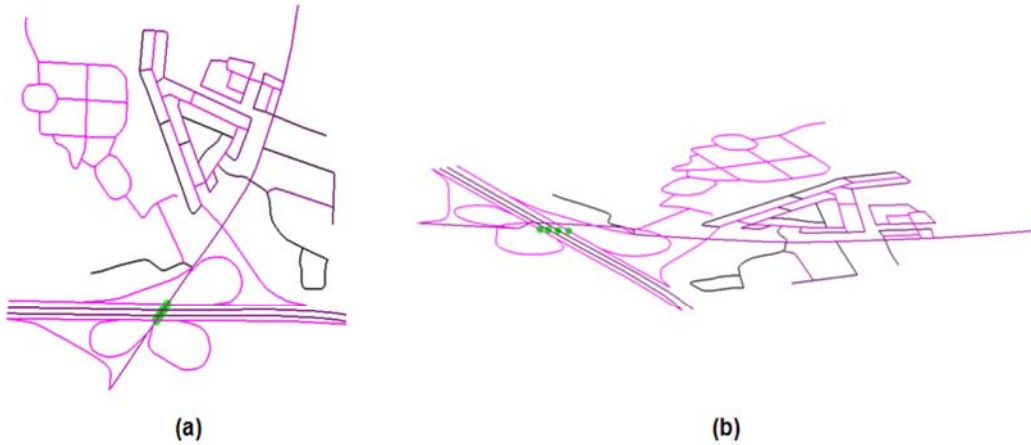 - Terrain elevation and level height
  - Linear interpolation

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Figure 3. 3D exampled road network with generated interchange (overlapped positions are indicated by green points). (a) Top view. (b) Side view.

Implementation

- Microsoft XNA platform
- Rendered with various shaders.
- Bridges and tunnels
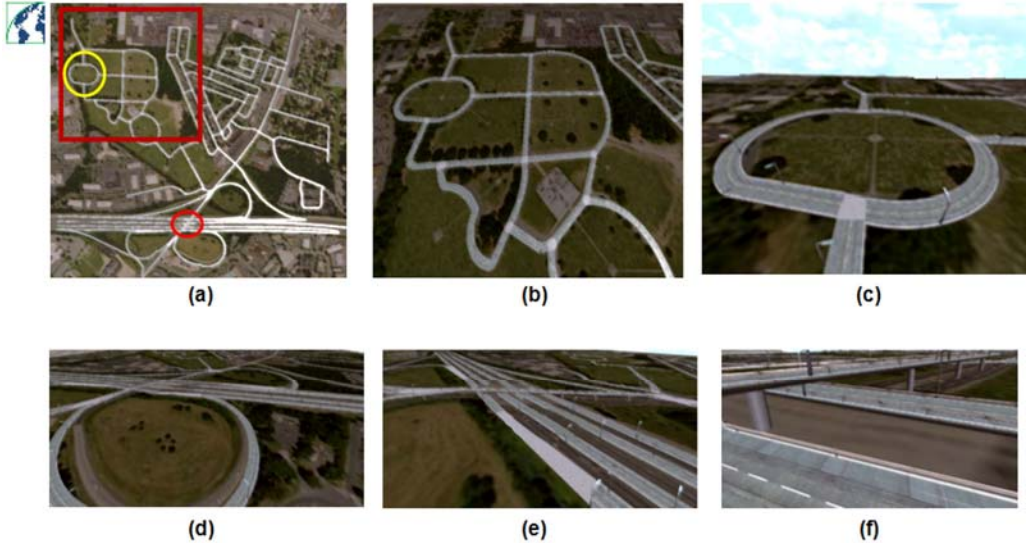- Digital terrain elevation and satellite image

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Figure 4. Experimental results (a) 3D road network generated for the exampled road network. (b) Top view of the area indicated by the red rectangle in (a). (c) Side view of the area indicated by the yellow circle in (a). (d)(e)(f) Different views of the interchange part of the generated 3D road network model.

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Discussion

- Do not aim at real road design and construction.
- Rapid and efficient 3D road modeling for computer graphics applications requiring realistic roadway models
  - Racing games and driving simulations
- Existing data do not provide sufficient information.
- Existing roads do not conform to the design standards.
- Reasonable approximations of real roadways
- May not have the exactly the same structure.

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Conclusion

- The automatic generation of 3D high-fidelity road network models from real road GIS data

- Apply to the modeling of the whole road network.

- Be extended for other areas.
  - Subway system

Questions/Comments

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Thank You !

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