USING HIGH-RESOLUTION DIGITAL ELEVATION MODEL FOR COMPUTER-AIDED FOREST ROAD DESIGN

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ABSTRACT:

The current forest road design systems are not capable of making computer-aided design judgments such as automated generation of alternative grade lines, best fitting vertical alignment for minimizing the total road costs, or consider environmental impact. A three dimensional (3D) forest road design model was developed as a decision support tool that provides a designer with a quick evaluation of alternative road paths. In the model, initial trial routes are generated by "tracing" the possible paths using computer cursor on a 3D image of the terrain. The model integrates two optimization techniques (linear programming and a heuristic approach) for selection of a vertical alignment with the lowest total costs, while conforming to environmental requirements. Improved 3D OpenGL accelerator is used to display and render 3D images of the terrain in real-time, based on high-resolution Digital Elevation Model (DEM) data. LIDAR (Light Detection and Ranging), one of the fastest growing systems in the field, can provide a high-resolution and accurate DEM of forested areas. It is expected to provide even better accuracy in the near future. The development of the road design model incorporating modern graphics capability, advanced remote sensing technologies, improved software languages, modern optimization techniques, and environmental considerations will improve the design process for forest roads.

AUSZUG:

Gegenwärtige Waldweg-Konstruktionssysteme eignen sich nicht zur computergestützten Designkontrolle, wie z.B. automatisiertes Erzeugung alternativer Gradlinien, optimaler vertikaler Ausrichtung zur Minderung der Gesamtkosten von Straßen oder Berücksichtigung von Umwelteinflüssen. Ein dreidimensionales (3D) Waldweg-Designmodell wurde entwickelt als ein Werkzeug, das den Entwickler durch schnelle Auswertung alternativer Straßenverläufe bei seinen Planungsentscheidungen unterstützt. Im Modell werden Ausgangsprobewege erzeugt, indem man mögliche Wege mit dem Computer-Cursor auf einem 3D-Bild des Geländes "verfolgt". Das Modell integriert zwei Optimierungstechniken (lineare Programmierung und heuristische Annäherung) zur Auswahl einer vertikalen Ausrichtung mit den niedrigsten Gesamtkosten in Übereinstimmung mit den Umgebungsbedingungen. Ein verbesserter 3D-OpenGL-Beschleuniger wird benutzt, um die 3D-Bilder des Geländes in Realzeit anzuzeigen und zu übertragen auf Basis hochauflösender Daten des Digital-Aufzug-Modells (DEM). LIDAR (Light Detection and Ranging), eines der sich am schnellsten entwickelnden Systeme auf diesem Gebiet, kann ein hochauflösendes und genaues DEM der bewaldeten Bereiche zur Verfügung stellen. Es wird erwartet, noch größere Genauigkeit in naher Zukunft zu erreichen. Die Entwicklung des Straßendesignsystems, das Leistungsfähigkeit moderner Graphikprogramme mit fortgeschrittenen Fernabfragetechnologien, verbesserten Software-Sprachen, modernen Optimierungstechniken und Berücksichtigung von Umweltbedingungen miteinander verbindet, wird eine Verbesserung des Designprozesses für Waldwege darstellen.

1. INTRODUCTION

Forest road design is a complicated problem relating economic and environmental considerations. Designers should evaluate sufficient number of alternative routes to locate a final route with the lowest total cost, while conforming to design specifications and environmental requirements. The current forest road design systems are not developed to provide a designer with large number of alternative paths. They are generally used to make the mathematical calculations required in manual road design. Besides, they are not capable of minimizing total cost of construction, maintenance, and transportation costs, or aiming for least environmental impacts.

With the growing availability of high-resolution DEM data and advanced features of high performance microcomputers, designing alternative road paths in the office has become a more realistic and practical exercise. It is difficult to generate DEM of a forested area that represents the actual ground condition with high accuracy. Airborne laser scanner technology generates a high-resolution and accurate DEM of forested areas, using a laser light detection and ranging (LIDAR) system (Reutebuch et al., 2003). LIDAR has been used over twenty years in variety of applications. Most recently, it has been used to provide DEMs for large scale and high-accuracy mapping (Kraus and Pfeifer, 1998; Means et al., 2000).

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LIDAR employs a powerful laser sensor positioned under an aircraft. The laser sensor consists of a transmitter and receiver. The distance from the sensor to points on the terrain below is measured based on the location and altitude of the aircraft. These two parameters are calculated using Global Positioning System (GPS) and Inertial Navigation System (INS) technologies. When a pulse hits the ground, the reflected light is collected by a receiver. The first return may locate the top of a tree, while the last return ideally locates the ground beneath the tree canopy.

The spatial resolution of the DEM highly depends on the ground cover. In a study conducted by Pereira and Janssen (1999), it was found that the vertical accuracy of LIDAR in open areas with hard surface is approximately 15 cm. However, in areas with very tall and dense canopy, the photogrammetric heights may have larger errors. Reutebuch et al. (2003) indicated that over mature forested areas LIDAR provides vertical accuracy of 25 cm, which is enough to generate an accurate DEM. As one of the fastest growing remote sensing technology, LIDAR is expected to provide even better accuracy in the near future.

In order to assist designers in locating forest roads, various computer-aided methods using DEMs have been introduced. Reutebuch (1988) developed a computer program, ROUTES, to estimate road gradient, length, and stationing along the possible road alternatives using a DEM. In the program, the designer could digitize the contours and use the digitizer puck to locate the road on a large-scale contour map. Although the graphical user interface (GUI) of ROUTES was primitive, the program worked well and provided the designers with the ability of quickly looking at alternative road locations at varying scales.

A computer program, PEGGER, was developed to automate initial forest road design through the use of a Geographic Information System (Rogers and Schiess, 2001). The performance of the program relied on DEMs, which must accurately represent the actual ground conditions. PEGGER was a tool for quickly analyzing many road alternatives based on a specified road gradient given by a user. It was not capable of considering environmental and economic constraints such as soil types, hydrology, property lines and slope classes. However, forest road design using PEGGER with accurate DEM data was expected to be more feasible and less time consuming than the traditional road design methods.

Coulter et al. (2001) developed a method of forest road design using high-resolution DEM data (1mx1m) from LIDAR. In the method, road elevations were assigned to each pixel within the road template to calculate earthwork from the difference between road and surface elevations. This method was only applicable to straight road segments and could not locate horizontal or vertical curves. It also could not calculate total road cost or consider environmental requirements. However, it was probably the first method showing that using high-resolution DEMs from LIDAR in forest road design may significantly decrease design time and effort spent both in the field and in the office.

A decision support system can be defined as an interactive system that assists a user to conduct decision making tasks by easily accessing decision models and data (Watson and Hill, 1983). Advances in the processing speed and real-time rendering and viewing of three-dimensional (3D) graphics on microcomputers permit locating a route interactively on a 3D display of a ground surface generated by a high-resolution DEM data. A 3-D forest road alignment optimization model, TRACER, aided by an interactive computer system, was developed as a decision support system. The model provides a designer with a quick evaluation of alternative road paths to locate the best path with minimum total road cost, while considering design specifications and environmental requirements. TRACER relies on a high-resolution DEM to provide terrain data for supporting the analysis of road design features such as ground slope, topographic aspect, and other landform characteristics. In the model, two optimization techniques are integrated: linear programming to minimize earthwork allocation cost and Simulated Annealing to optimize vertical alignment. In this paper, the features of the model were described and an application was presented.

2. MATERIAL AND METHODS

2.1 Input Data

Input data include DEM and attribute data, road design specifications, and environmental requirements. The DEM data is a set of scattered metric data points (X and Y coordinates and Z as elevation). In designing forest roads, the resolution of the DEM should be in the range of 1.0 m to 3.0 m to represent the actual terrain conditions (Akay, 2003). In this study, the DEM data set of 2.0 m resolution is developed using LIDAR data set collected from western Washington by Aerotec (1999). Bilinear interpolarion method is used to extract ground elevations from the DEM (Lemkow, 1977). First, the grid cell that contains the horizontal position of the current point is determined based on its coordinates, then elevation of this point is estimated by interpolating between the elevations of four corners on this grid cell. The attribute data, soil types and stream data, is represented in the same format as the metric data points. It is easy to incorporate other attribute data into the model if desired.

The road design specifications are geometric specifications, local site specifications, and economic data. The geometric specifications include road gradient, horizontal curves radius, vertical curve length, distance between curves, and safe stopping distance for driver safety. Road template specifications, turnout dimensions, distance between road sections, design speed, vehicle specifications, and traffic volume are also included in the geometric specifications. Local site specifications consist of swell and shrinkage factors of soils, vegetation cover, geological data, stand data, and distance to local resources of road construction materials. Economic data include the unit costs for road construction, maintenance, and transport activities. The environmental requirements considered in this study are minimum allowable road grade for proper drainage, minimum distance from the riparian zones and minimum stream-crossing angle for stream protection, and maximum height of cuts and fills for soil protection.

2.2 Displaying Terrain Image

The model uses graphics routines from NewCyber3D (2002) to display high-resolution image of the terrain in 3D, based on DEM data (Figure 1). The real-time 3D stereo display and stereo image composition is also supported by NewCyber3D. Above-below stereo display format is used to generate stereo scenes, which requires liquid-crystal glasses and an infrared emitter. The graphic programming runs in full-screen mode to be compatible with this format. At the standard sixty fields per

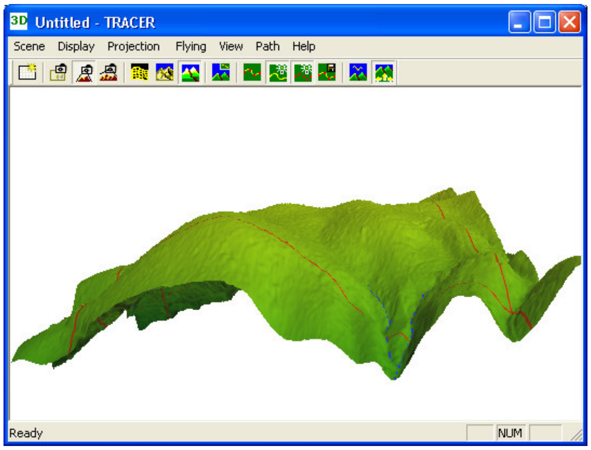

Figure 1. Displaying 3D image of the terrain

second, scanning each image takes half the duration of an entire field. Using a monitor operating at 120 fields per second, each eye sees 60 fields of image per second, while the other 60 fields are prepared for the other eye. Therefore, when the left eye can see an image, the right eye cannot (Lipton and Meyer, 1984).

2.3 Interactive Features

The alternative forest road paths are selected through real time interaction with 3D image of the terrain. The interactive features of the model are provided by NewCyber3D (2002), using an improved 3D OpenGL accelerator. The initial trial road path is "traced" by locating a series of intersection points on the terrain, using computer cursor (Figure 2). The model provides the designer with the road geometry information and attribute data in real time to locate control points with respect to road design specifications and environmental requirements. If a candidate intersection point is not acceptable by one or more constraints, the model warns the designer by changing the colour of the line between the previously selected intersection point and the candidate intersection point. The designer can zoom, pan, rotate, and scale the area in order to search intersection points around the terrain. The model has various interactive display features such as navigation control, bird-view, and real-time flythrough.

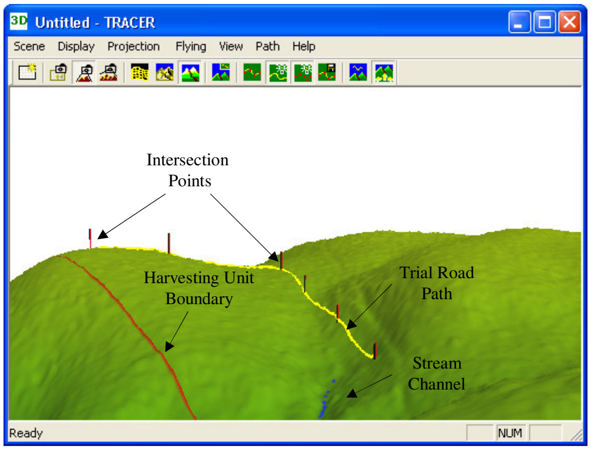

Figure 2. Selecting intersection points of a trial road path

2.4 Calculating Horizontal and Initial Vertical Alignment

After locating the trial path, the model automatically calculates the horizontal and initial vertical alignment considering road design specifications. Road gradient is restricted by the maximum allowable road grade considering the truck performance. The gradient is also limited by the minimum acceptable road grade to provide proper drainage.

In order to determine whether any type of curve is necessary, the model calculates the difference between two consecutive road grades (A) and horizontal deflection angle (Δ) for each intersection point along the roadway. In forest roads, it is not necessary to locate a vertical curve if A is less than or equal to a specified percentage of difference between grades ($A_{min.}$), which provides a log truck with a safe passage of the vertical curve. If A is greater than A_{min} and Δ is zero, the model locates a vertical curve. If A is less than or equal to A_{min} and Δ is greater than zero, then the model locates a horizontal curve. Otherwise, a straight segment (tangent) is located. If there is a case where A is greater than A_{min} and Δ is greater than zero, the model warns the designer to choose a different control point to avoid overlapping of vertical and horizontal curves.

To ensure a safe roadway passage along the vertical curves, the model is constrained to generate a minimum adequate curve length, which allows a log truck to pass a curve without bottoming out and provides safe stopping distance for driver safety. To provide safe continuous operation along the horizontal curve, the model is constrained minimum radius, acceptable road grade on horizontal curve, and minimum safe stopping distance.

2.5 Optimizing Vertical Alignment

After locating the horizontal alignment and initial vertical alignment, the model computes the total cost of construction, maintenance and transportation costs. The road construction activities considered in this study are construction staking, clearing and grubbing, earthwork allocation, drainage and riprap, surfacing, water supply and watering, and seeding and mulching. Road maintenance activities include replacing the aggregate, grading, maintaining culverts, cleaning ditches, and removing brush. Transportation cost varies with vehicle performance, equipment costs, gradient, and curvature. The cost of road design activities are estimated by multiplying their average unit costs by the quantity of design parameters (e.g. m^3, m^2, m).

The model searches for the optimum vertical alignment with minimum total cost among the large number of alternative alignments. Simulated Annealing (SA) algorithm, using a neighbourhood search, is employed to guide the search for the optimal vertical alignment. The model considers technically feasible grades within the specified elevation ranges of the intersection points. The SA algorithm was developed based on a metallurgical technique of annealing, in which a solid material is heated and cooled back slowly into an optimal state to produce the best product (Beasley et al., 1993). In this study, SA has been selected as an optimization technique because it generally provides a near-optimal solution and it is easy to implement into the model.

For each alternative vertical alignment, the model calculates earthwork volumes using average end-area method, minimizes earthwork costs using linear programming (LP), and estimates sediment production. The economic distribution of cut and fill quantities is determined by implementing the LP method of Mayer and Stark (1981). This method represents the earthwork allocation better than the other methods due to considering possible borrow and landfill locations and various soil characteristics along the roadway. Besides, it provides the optimal solution to the earthwork allocation problem. A linear programming code, using the idea of simplex algorithm (Bowman and Fetter, 1967), is developed to incorporate this method into the model.

The average annual volume of sediment delivered to a stream from the road segments is estimated by using the method of the Geographic Information Systems (GIS) based erosion delivery model, SEDMODL (Boise Cascade Corporation, 1999). Some of the road erosion factors considered in this model include geologic erosion rate, road surface type, traffic density, road width and length, average road slope, average precipitation factor, distance between road and stream, cut slope cover density, and cut slope height. SEDMODL reasonably predicts the sediment delivery and defines the road segments with high sediment production.

To develop additional road alignment alternatives, various feasible road paths can be traced out by the designer. For each alternative, the model follows the same procedure to find the optimal vertical alignment with minimum total cost. Therefore, the designer can quickly generate many alignments and select the optimal one among the alternatives in an efficient way.

3. RESULTS AND DISCUSSION

The model was applied to a study area of 55 hectares, located in the Capitol State Forest, Washington, the USA. The high-resolution DEM (1mx1m) of the study area was obtained from LIDAR (Aerotec, 1999). The attribute data including soil, hydrology, and geology data were provided by Washington Department of Natural Resources. Road design specifications (Table 1) and cost data in US dollars (Table 2) were obtained from the local sources in Pacific North West (PNW) (Kramer, 200; USDA Forest Service, 1999).

Initial road path was generated by establishing six intersection points on the 3D image of the terrain based on DEM data from LIDAR, while considering road design specifications and environmental requirements (Figure 2). The unit cost of this initial path was $36.88/m. Then, using optimization techniques, the model located the optimal vertical alignment with the minimum unit cost of $27.74/m (Figure 3). Therefore, total road cost was reduced about 25% by the optimization model. Total amount of sediment delivered to streams from the road section was estimated as 0.84 ton/km.

Table 1. The road specifications used in the example

Road Specifications	Values
Road width	4 m
Cut slopes	1:1
Fill slopes	1.5:1
Minimum curve radius	18 m
Minimum length of a vertical curve	15 m
Minimum differences between grades	5 %
Minimum road grade	± 2 %
Maximum road grade	16 %
Minimum distance from road to streams	10 m
Maximum cut and fill height at centerline	2 m
Design speed	55 km/hr

Table 2. Local unit cost data for road construction in PNW

Cost Items	Costs
Construction staking	$ 778/km
Clearing and grubbing	$3700/ha
Earthwork	
Excavation	$1.6/m^3
Haul	$1.3/m^3-km
Embankment	$0.6/m^3
Disposal	$0.1/m^3
Borrow material	
Excavation	$1.8/m^3
Haul	$1.3/m^3-km
Embankment	$0.6/m^3
Surfacing	
Base course	$3.9/m^3
Traction surface	$11.8/m^3
Drainage and riprap	
Culvert	$25 meter
Riprap	$10/m^3
Watering	$3/kilo liter
Seeding and mulching	
Material	$0.5/kg
Application	$550 /ha

The results indicated that total construction cost was the largest cost component, followed by maintenance and transportation costs (Table 3). Within the construction cost components, surfacing cost was the largest, followed by earthwork allocation cost. Total cost of maintaining culverts and ditches and clearing bushes was the largest cost component in the maintenance costs.

During the search process, the model calculated 147 feasible solutions out of 1200 automatically generated vertical alignment alternatives. The solution process took about 15 minutes. The most of the computation time was spent on calculating earthwork allocation using LP for each vertical alignment alternative. The time spent on earthwork allocation increases as the number intersection points along the roadway increase.

Table 3. Total cost summary table

Cost Components	Costs ($)
Total Construction Cost	
Earthwork Cost	2109.09
Construction Staking Cost	177.29
Clearing Grabbing Cost	737.05
Drainage Cost	406.85
Seeding Mulching Cost	369.99
Surfacing Cost	3221.65
Water Supply Watering Cost	859.87
Riprap Cost	483.91
Total Maintenance Cost	
Rock Replacement Cost	319.45
Grading Cost	84.16
Culvert, Ditch, Brushing Costs	1060.62
Total Transportation Cost	1166.16

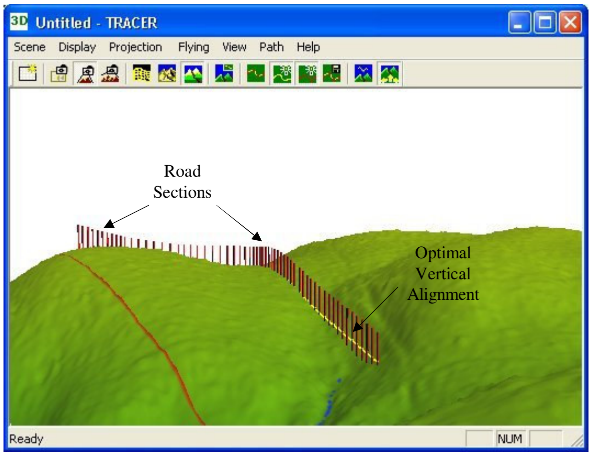

Figure 3. Optimal vertical alignment on 3D image of the terrain

Increasing the number of intersection points may also decrease the driver safety and comfort due to frequent changes on the roadway grade. However, using more intersection points would reduce the earthwork volume that leads to significant reduction in earthwork allocation cost and total construction cost since the road profile becomes closer to the ground profile.

Profile and plan view of the road alignment was shown in Figure 4 and Figure 5, respectively. The model required two horizontal curves and one crest vertical curve along the roadway. The radiuses of the horizontal curves (e.g. 62.9m and 50.9m) and the length of the vertical curve (66.23m) were acceptable for safe traffic passage. The length of road section was approximately 396 m with gradient of 2 to 12% (Figure 4).

4. CONCLUSIONS

Using high performance microcomputers, improved software languages, advanced remote sensing technologies, modern optimization techniques, and high-resolution DEM data has significantly improved the designer efficiency in designing preliminary forest roads in the office. In this study, a 3D forest road alignment optimization model was developed as a decision support system. Using this model, a designer can quickly evaluate alternative paths and locate the best path with minimum total road cost. In the model, an initial horizontal alignment is located interactively on the 3D image of the terrain generated based on a high-resolution DEM from LIDAR. During the last couple of decades, LIDAR has been used in variety of applications. Most recently, it has been used to generate high-resolution DEMs of the forested areas with sufficient accuracy. The model also relies on available GIS layers of attribute data to represent topographic conditions. Available GIS data collected from the forested areas currently cannot represent the actual topographic condition with a high accuracy; however, quality of GIS data is improving as remote sensing technologies advance.

In the model, the optimal vertical alignment is determined automatically, using the combination of two optimization techniques: LP method for determining the economic distribution of cut and fill quantities and SA algorithm for locating the optimal vertical alignment. LP method guaranties the global minimum cost for earthwork allocation problem, while SA provides good/near-optimal solution for the optimal vertical alignment selection problem.

The results from the brief example were instructive in presenting how a decision support system equipped with interactive features, advanced GIS and remote sensing technologies, and environmental considerations can improve the design process for forest roads. It provides a road designer with a number of alternative alignments to evaluate quickly and systematically. The model has several limitations for further developments such as improving the graphic interface, optimizing the horizontal alignment, and calculating earthwork allocations where the unit costs vary with the quantity of the cut and fill.

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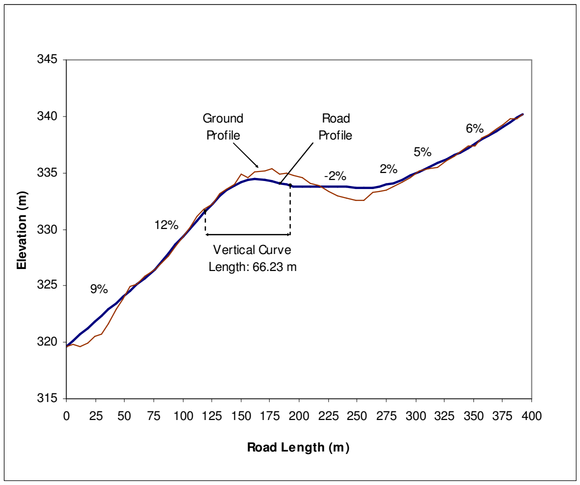

Figure 4. Profile view of the forest road

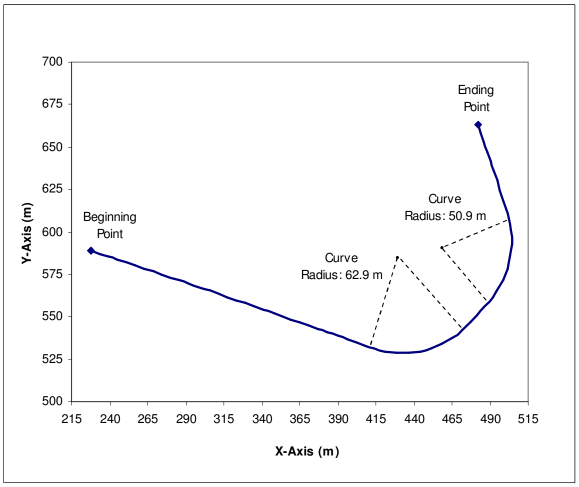

Figure 5. Plan view of the forest road

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