SURFACE MODELLING FOR ROAD NETWORKS USING MULTI-SOURCE GEODATA

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ABSTRACT:

Road systems are the fundamental component in the geographic information systems. This kind of civil infrastructures has large coverage and complex geometry. Thus, the modelling process leads to handling huge data volume and multi-source datasets. A reasonable process should be able to reconstruct separate parts of road networks and combine the surfaces together. Hence, the reconstruction of complete three-dimensional road networks needs scrutiny when a large area is to be processed. This paper proposes a scheme to focus on this issue using an integrated strategy with multi-source datasets. The modelling processes combine different data sources to refine road surfaces to keep the continuities in elevation and slope. The proposed scheme contains three parts: (1) data pre-processes, (2) planimetric networking, and (3) surface modelling. In the first part, datasets are registered in the same coordinate system. In the next step, topographic maps provide the roadsides to derive the geometric topology of road networks. Finally, those centerlines combine airborne laser scanning data to derive road surfaces. Considering the data variety, some road segments generated from aerial images are also included in the proposed scheme. Then, the successive process integrates those models for the refinement of road surfaces. The test area is located in Taipei city of Taiwan. The road systems contain local streets, arterial streets, expressways, and mass rapid transits. Some roadways are multi-layer and cross over with different heights. The final results use three-dimensional polylines and ribbons to represent geometric directions and road surfaces. Experimental results indicate that the proposed scheme may reach high fidelity.

1. INTRODUCTION

Based on the viewpoint of decision support for modern cities, the reconstruction of a virtual environment is an essential task. The applications include urban planning, traffic simulation, true orthorectification (Zhou et al., 2005), hazard simulation, communication, etc. Since the road models are one of the most prominent components in the urban information systems, the reconstruction of the model becomes increasingly important. In general, the traditional topographic map is a kind of widely used dataset that describes road geometries. It can efficiently build single-layer road models. However, this civil infrastructure is developed rapidly in modern cities for the traffic demand, and road types become more complex including local streets, arterial streets, expressways, freeways, and mass rapid transit. Single-layer road networks have changed to multi-layer systems and topomaps may be insufficient to describe complex roads. The elevation information of road surfaces needs to be considered for the separation of overpasses.

Some researches focused on the surface modelling processes with different strategies and data, e.g. aerial photos, laser-scanning data, GPS data, topomaps, and so on. Cannon (1992) proposed a scheme to locate the three-dimensional road profiles integrating GPS and INS data. A related work also had been made to estimate the slope information of road profiles using GPS data (Han and Rizos, 1999). Some studies preferred to derive road information in spectral domain. They analyzed road shapes of centerlines or boundaries to derive road geometries with vehicle-based images (Yan et cl., 2008), aerial photos (Treash and Amaratunga, 2000; Hinz and Baumgartner, 2003; Dal Poz et al., 2004), satellite images (Yan and Zhao, 2003; Doucette et al., 2004; Hu et al., 2004a; Kim et al., 2004; Karimi and Liu, 2004; Yang and Wang, 2007), airborne laser scanning data (Clode et al., 2007). Some proposed semi-automatic approaches basing on the matching technique to reliably extract road geometries with manual editing from high-resolution satellite imagery (Hu et al., 2004a; Kim et al.,2004). Easa et al. (2007) focused on the automatic image processing to extract edge lines for calculation of geometric parameters to describe horizontal alignments from high resolution images.

On the other hand, an integrating strategy had been proposed to deal with this issue using aerial images and laser scanning data (Hu et al., 2004b; Zhu et al., 2004). Zhang (2003) integrated aerial photos and geo-database to derive and update three-dimensional road data. Moreover, geo-database and laser scanning data also could be a combination. Hatger and Brenner (2003) calculated the profile geometries of centerlines from the geo-database and digital surface models. The segment-based method used region growing to detect road areas for the calculation of geometric parameters to refine the geo-database. Furthermore, Cai and Rasdorf (2008) also combined two datasets, airborne laser scanning data and planimetric centerline

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data, to establish three-dimensional centerlines. Those elevation differences of multi-layer areas were marked with an additional attribute.

Other researches based on the mapping concepts to regard road surfaces as some parts of terrain. Thus, some filtering techniques were developed to extract ground information from airborne laser scanning data for DEM (digital elevation model) generation. The performances of those filtering methods had been compared by Sithole and Vosselman (2004). In some cases, single-layer road network could be regarded as a part of bare earth. Hu (2003) assumed that road profiles could be piecewise continuous and extract road points with the elevation threshold from discrete point clouds. Vosselman (2003) used laser scanning data to reconstruct single-layer road models referencing cadastral maps. This process derived road points within road areas first and generated models with triangular irregular network (TIN) surface. The refinement step assumed that road surfaces without slope, curvature, or torsion and smoothed them with the second order constrained polynomial functions. Additionally, Sithole and Vosselman (2006) handled the multi-layer condition which point clouds of overpasses were marked with the analyses of slope and elevation difference. They regarded those marked areas as the extended parts of terrain so that there was at least one side should connect to the ground. Oude Elberink and Vosselman (2006) paid attention to multi-layer interchanges using laser scanning data and topographic maps. Those roads were TIN-based models, and the multi-layer parts were separated into different elevations. Chen and Lo (2009) proposed a scheme to fuse airborne laser scanning data and topographic maps. The planimetric geometry and elevation of each road segment were established. The road models were represented as vector-based ribbons.

As a summary, the integration of heterogeneous datasets seems to be a popular way to reconstruct three-dimensional road models, especially topomaps and laser scanning data. Most studies focused on the modelling processes for single-layer road systems, and few of them discussed about multi-layer parts. The reconstruction of road systems using a robust method for the large coverage is still an ongoing topic. Although the proposed scheme (Chen and Lo, 2009) reconstructed multi-layer models, this sequential modelling process was a local approach to smooth the model surfaces. In a rigorous way, we may need to consider a method to handle complete road networks and preserve the capacity for model updating.

This investigation proposes an approach to model three-dimensional road networks using laser scanning data and topographic maps. Because some countries may have complete information of road boundaries and centerlines, others may use CAD data to describe roads using piecewise polylines in planimetric domain without geometric topology. Therefore, this investigation needs to compute topology of road networks and derive road elevations from discrete point clouds. In this planimetric part, each road segment would be generated its centerline and connect to others for network topology with conjunction points. The successive processes then include laser scanning data to derive road surfaces of each segment and refine all conjunction points to maintain the continuities in elevation and slope. When road systems encounter changes over time, new roads for example, they are needed to rebuild according to the latest dataset. Those new parts are digitized from aerial photos in this modelling process and refined their elevations with existed models to keep the system coincidence. The results are to be represented as three-dimensional ribbons.

2. METHODOLOGY

Based on the viewpoint of surface modelling, we integrate multi-source datasets to reconstruct complete surface modelling. In this investigation, we assume that the vertical and horizontal alignments of each road segment are continuous within a local area. Moreover, a global approach implements B-spline surface fitting refines the elevations of network conjunctions by keeping the continuities. The local approach sequentially modifies the elevation of each road segment. The proposed scheme has also considered the multi-layer condition. The processes have three parts: (1) registration, (2) planimetric networking, (3) model surfacing. The first part is to register all datasets, i.e. topomaps, laser scanning data, and three-dimensional boundaries. The next step then produces the networks using roadsides from topographic maps. The third part computes the model surface of each road segment and combines all roads from different sources to refine their vertical and horizontal profiles to keep the continuities in elevations and slope. The workflow shows in Figure 1.

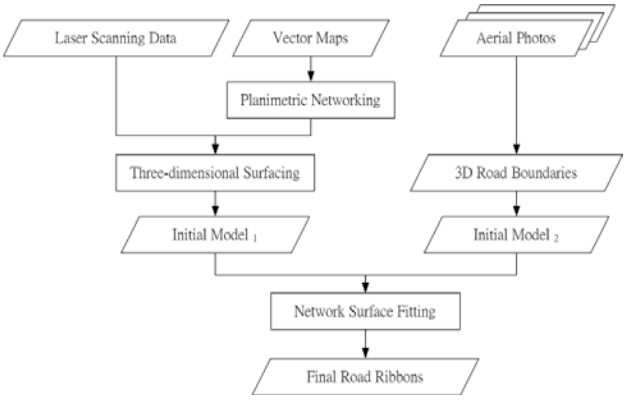


Figure 1. Workflow

2.1 Planimetric networking

In traditional CAD-based topographic maps, there are several road levels like local streets, arterial streets, expressways, etc. This kind of data records those boundaries using piecewise polylines. In addition, the topomaps may lack some information, e.g. attributes, topology, and centerlines. To directly use the topomaps for centerline generation is still difficult if those boundaries are independent without pair relationship. Therefore, this step uses those existed boundaries to compute centerlines for the reconstruction of network topology.

First of this part, the planimetric process separates those boundaries into many simple straight lines. Those pieces then connect to each other according to the empirical thresholds of distance and angle for the development of complete boundary lines. The second step pairs those produced edges to position centerlines. All the planar conjunctions, i.e. crossroads, are automatically added a node point to split those centerlines and establish the topology, besides overpasses. The networking procedure would detect those multi-layer parts with boundary analysis (Chen and Lo, 2009) and mark which centerlines go through those areas.

2.2 Three-dimensional surfacing

After planimetric networking, laser scanning data is employed for road surfacing. The airborne LIDAR data records plenty discrete points with accurate elevation information. This surfacing step, basing on the planimetric geometry, extracts those points on the road surfaces and computes their elevations. Chen and Lo (2009) assumed that the local relief of road surfaces should be continuous for traffic. They then analyzed the elevation histogram and extract the candidate points on the roads to fit surfaces. The proposed scheme contains two parts: (1) initial modelling and (2) profile refinement. The initial process calculates the surface elevations from discrete points along each produced centerline. Those original road surfaces then are modified their elevations to keep the model continuities in elevation and slope.

2.3 Initial Modelling

Those existed airborne laser scanning data describe accurate elevations with considerable quantities of points. The laser beam also has the opportunity to penetrate canopies to detect elevations in occluded areas. However, this kind of data has no distinct boundaries. To directly use discrete points for surface modelling is a difficult work. Chen and Lo (2009) proposed a two-way method to extract road points. They assume that the road surface profile is smooth and continuous in a local area so that the maximum number of elevation histogram of road points may locate within a certain interval. One process, thus, extracts points with a designed threshold to fit surfaces at each vertex of centerlines. The used equations, i.e. linear and quadratic polynomial functions, are shown in Equation (1) and (2). The unknown parameters are the s11~ s26. Those two hypotheses are automatic selected according to the analysis of the standard deviation during the fitting procedure. In some conditions, road surfaces may be interfered by cars or canopies, this threshold may lead to remove too many points to calculate surfaces. The other process then selects the locally lowest point to be the surface elevation. In the first way, the cross-section is a curve to represent the reality of horizontal profiles by surface fitting. On the other hand, the second way provides a flat road surfaces.

$$S_1(Z) = s_{11} + s_{12}X + s_{13}Y \tag{1}$$

$$S_2(Z) = s_{21} + s_{22}X + s_{23}Y + s_{24}XY + s_{25}X^2 + s_{26}Y^2 \tag{2}$$

where X, Y,and Z are coordinates of the LIDAR points; and S_{11}~S_{26} are parameters of the surface function.

2.4 Profile refinement

This investigation describes each road segment with two nodes and several vertices, i.e. conjunction points of networks and consecutive center points, respectively. In the previous step, we independently derive the elevation of each vertex from original point clouds. Nevertheless, some parts of each vertical profile may be discontinuous, erroneous, and empty. The following process then transforms the coordinates (X, Y, Z) to mileages (Stations) and fine-tunes the vertical profiles with three mathematical models. The linear, quadratic, or cubic functions are used to refine its vertical profile. The mathematical models are formulated in Equation (3), (4), and (5), respectively. The modification process would select an optimal function according to the minimum standard deviation. Those errors and empty values of each road segment are detected and re-computed.

After vertical refinements, the continuities of horizontal profiles may be interfered. In this process, the surface fitting then includes those consecutive vertices to smooth their elevations. Equation (1) and (2) are considered in the smoothing process. However, if a road segment is too long, the used models may be insufficient to describe the characteristics of vertical profiles. Chen and Lo (2009) considered that road systems are designed and organized by low-ordered polynomial models everywhere so that the theoretical models can easily represent each sub part of one vertical profile. They created some pseudo nodes for each road segment and smooth the geometry of cross-sections with Equation (1) or (2). The profile refinement is an iterative process until the elevation change of each road segment is smaller than the designed tolerance.

$$L_1(H) = p_{11} + p_{12}M \tag{3}$$

$$L_2(H) = p_{21} + p_{22}M + p_{23}M^2 \tag{4}$$

$$L_3(H) = p_{31} + p_{32}M + p_{33}M^2 + p_{34}M^3 \tag{5}$$

where p_{11}~p_{34} are parameters of the line function; M is the mileage of each road segment; and H is vertex height.

2.5 Network surface fitting

This study focuses on the modelling procedure with multiple roads using different data and keeps the results continuous in elevation and slope. For this purpose, we propose to use B-spline surface fitting to modify all conjunction points of road networks. The elevation correction of each road segment is then re-arranged to its internal vertices. In this step, we simplify the format of those produced road models for surface fitting. The conjunction points are selected and computed their new elevations using B-spline curve function, i.e. Equation (6), to maintain the continuities in elevation and slope. After the fitting process, all the conjunctions have new height values, and elevation changes then bring to each road segment and modify the elevations of internal vertices. The iteration stops when the elevation change of all road systems is smaller than the threshold. In short, the proposed scheme makes the capability to reconstruct three-dimensional road models combining different data sources.

$$C(u) = \sum_{i=0}^{n} f_i(u)P_i \tag{6}$$

where P_j are control points and f_j is a basis function.

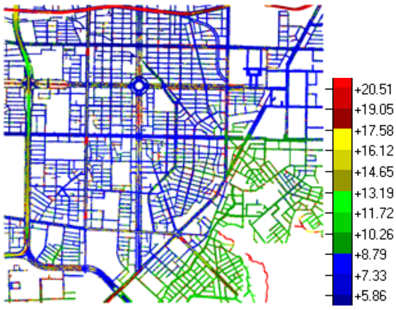
3. EXPERIMENTAL RESULTS

The scheme was validated using data for single and multiple layer road systems in Taipei City of northern Taiwan. The area has the coverage of 3,200m*6,600m. The test site includes arterial streets, local streets, expressways, and mass rapid transit in an urban area. The test datasets include topographic maps, airborne scanning data, and three-dimensional boundaries. The scale of the topographic maps is 1:1000. They contain several feature layers, such as buildings, roads, power lines, etc. In Taiwan, road boundaries are recorded as independent planimetric polylines without topology or transportation attributes, as shown in Figure 2. As shown in Figure 3, the LIDAR data was derived from a Leica ALS50 system in March 2007. The flight altitude ranged from 1200 to 1500 m. The laser pulse rate was 70 kHz, and the point density was about 10 points/m^2. The random error of laser points in elevation is better than 0.15m (ITRI, 2006). The third type dataset is the three-dimensional road boundaries which were digitized from aerial images. The spatial resolution of used DMC images is about 17 cm. Figure 4 shows edited road boundaries in aerial images.

LIDAR road points are incorporated to provide height information for three-dimensional surface modelling. A threshold for the maximum elevation histogram is used to determine which method will be used for road surface initialization, i.e., either surface fitting or lowest point selection. The radius of a buffer circle is set to be half the roadwidth. Based on the experience, this percentage threshold of elevation histogram of initial surface modelling would be 30%. The reason is that the space interval of the along-track vertices is densified to 0.5m. Those local slopes of the vertical profiles are assumed to be less than 45°, i.e., the elevation change is smaller than 1.5m. Since the slope of a road is seldom larger than 45°, the threshold is reasonable that adapts for general applications. Possible interference could be the presence of dense vehicles that make the point clouds deviate from the road surface. This could lead to unreliable results. For more precise surface modelling, the spanning distance between pseudo nodes is set to be 200 m, according to the rules of roadway designs. Next, the vertical profiles, cross-sections, and intersections are smoothed according to either height difference or iterative times. Figure 5 shows the reconstructed three-dimensional road models.

To evaluate the reconstructed road models, reference LIDAR road points are extracted manually. The normal height differences between the reference points and the reconstructed surfaces are compared to calculate the relative error assessment. The index of modelling error is expressed as the root mean square error (RMSE). The generated results indicate that the RMSEs for the modelled surfaces of test sites are lower than 0.15 m. Those values indicate that the iteratively local approach may lead to modelling errors within the range of random error of the raw data. The slopes of reconstructed models in vertical profiles and cross-sections are estimated and shown in Figure 6 and 7, respectively.

Figure 2. Road boundaries in topographic maps



(unit: m)

Figure 3. Sub part of laser scanning data

Figure 4. Digitized road boundaries in aerial images

Figure 5. One part of reconstructed models (Overpass)

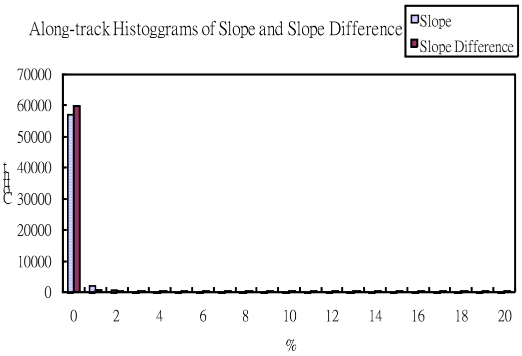


Figure 6. Histogram of slope and slope difference of along-track profiles

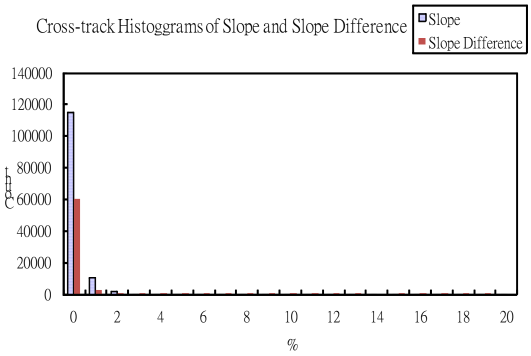


Figure 7. Histogram of slope and slope difference of cross-track profiles

4. CONCLUSIONS

Without considering the landuse changes, the proposed scheme integrates topographic maps, airborne laser scanning data, and three-dimensional road boundaries for 3D surface modelling. In the modelling process, road surfaces are initialized from the raw LIDAR data. Additionally, we proposed a network surface fitting process to refine those model surfaces from multi-source datasets to maintain the continuities in elevation and slope. The test site includes local streets, arterial streets, and expressways to validate the ability of the proposed scheme. According to the experimental results, the three-dimensional surface modelling accuracy reaches 0.149 m. In addition, the modelling results indicate that this approach reaches an error, which is within the random error of the raw data.

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