THREE-DIMENSIONAL ROAD EXTRACTION COMBINING A STEREOSCOPIC PAIR OF LOW-RESOLUTION AERIAL IMAGES AND A DTM

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ABSTRACT:

This paper proposes a semiautomatic method for road extraction. The proposed method combines a stereoscopic pair of low-resolution aerial images with a polyhedron generated with a digital terrain model (DTM). The problem is formulated in object space by means of an objective function that models the object 'road' as a smooth curve belonging to a polyhedral surface. The proposed objective function depends on radiometric information accessed in the image space via a collinear relationship between road points in the object space and corresponding points in the image spaces of stereoscopic images. The polyline that provides the best representation of a selected road is obtained via the optimization of the objective function using a dynamic programming algorithm. The optimization process is iterative. An operator is required to supply an initial polyline approximating the selected road. The obtained results show that the proposed method is robust even when faced with anomalies along roads, such as obstructions caused by shadows and trees.

1. INTRODUCTION

Methods for road extraction from aerial and satellite imagery are essential for capturing and updating the spatial information. Several studies have been conducted on this subject beginning with the pioneering studies of Bajcsy and Tavakoli (1976) and Quam (1978). The majority of the studies of road extraction have involved models and approaches formulated in the image space. Most common semiautomatic strategies are road trackers (McKeown e Denlinger, 1988, Kim et al., 2004) and curve-fitting methods (Kass et al., 1987, Neuenschwader et al., 1997, Agouris et al., 2000, Göpfert et al., 2011). Conversely, automated methods of road extraction require a highly sophisticated integration of context-based information and prior knowledge (Baumgartner et al., 1999; Hu et al., 2007, Poullis e You, 2010).

Currently, there are few existing object-space methods (e.g., Grüen e Li, 1997 and Dal Poz et al., 2010, 2012) for road extraction. These previously developed methods are based on a single image (mono mode) combined with a digital terrain model (DTM) or utilize two or more images (stereo mode) from one or more sensors. The stereo mode method can integrate a DTM into the extraction, which can render a more stable process. Both mono and stereo modes can address occlusions and false road hypotheses more efficiently than the use of image space extraction methods alone (Grüen e Li, 1997, Hinz et al., 2001, Hinz e Wiedemann, 2004). An advantage of delineating roads in object space is the facilitated introduction of restrictions during extraction, particularly the vertical smoothness of the road centerline, which cannot be forced into image space models and strategies.

In this paper, a semiautomatic method for road extraction in object space is proposed that combines a stereoscopic pair of low-resolution aerial images with a DTM-generated polyhedron. This method is suitable for modelling roads with linear features. In practice, a road can be modelled as a linear feature if its width in the image falls within the range of 1-3 pixels. When roads are within this range of pixels, the image under consideration is classified as having a low resolution in the context of road extraction methods (Baumgartner et al., 1999). The semiautomatic method proposed here extends the method of Dal Poz et al. (2012) by introducing a geometric restriction in which the extracted polyline must belong to the surface of a polyhedron generated from a TIN (Triangulated Irregular Network). The remainder of this article is organized in the following sections: Section 2 describes the principles of the proposed model, Section 3 analyses the results, and Section 4 presents the conclusions.

2. METHOD

The proposed method is based on an object space road model formulated by Dal Poz et al. (2012) for a stereoscopic pair of aerial images. Subsection 2.1 provides a brief description of the pre-existing object space road model. Subsection 2.2 describes the modified model and the search-space sampling method.

2.1 Road model based on stereoscopic aerial images

Assuming that a road in a low-resolution image can be represented by the polyline $P^i = \{p_1, ..., p_n\}$, where pi is the ith vertex, one can generate a mathematical model using an objective function (Equation 1) and the inequality constraint (Equation 2) as follows (Grüen e Li, 1997):

$$E = \sum_{i=1}^{n-1} \left(\left[E_{p1} - \beta E_{p2} + \gamma E_{p3} \right] \times \left(1 + \cos(\alpha_1 - \alpha_{i+1})\right) / \left| \Delta_{s_i} \right| \right) \quad (1)$$

$$C_i = \alpha_i - \alpha_{i+1} < T \quad (2)$$

In these equations, E_{p1} is a function that depends on the vertex p_i and expresses road pixels as being lighter than their neighbouring pixels; E_{p2} is a function that depends on two

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consecutive points (p_{i-1} and p_i) of polyline P^i and specifies that grey or colour levels of roads typically do not vary within short distances; E_{p3} is a function that depends on vertex p_i and expresses that the road is a lighter linear feature; α_i is the direction of the linear segment defined by points p_{i-1} and p_i; β and γ are positive constants; $|\Delta_{si}|$ is the distance between points p_{i-1} and p_i; and T is an angular threshold that limits the change of direction between two successive segments of polyline P^i.

According to Equation 1, only three consecutive points (p_{i-1}, p_i, p_{i+1}) of polyline P^i are simultaneously interrelated, and thus, this relationship can be decomposed into a sum of *n-1* subfunctions $E_i(p_{i-1}, p_i, p_{i+1})$, as shown in Equation 3:

$$E = \sum_{i=1}^{n-1} E_i(p_{i-1}, p_i, p_{i+1}) \tag{3}$$

The model solution is a polyline $P^i = \{p_1, ..., p_n\}$ that represents a road and corresponds to the maximum value of the objective function given by Equation 3. In object space, this objective function can be formulated in terms of vertex point coordinates that belong to the corresponding polyline. Thus, using the collinearity equation one can establish the mathematical relationship between the line (L_i) and column (C_i) coordinates of vertex p_i and the object space coordinates of P_i. By specifying P_i using the ellipsoidal height h_i and defining the coordinates E_i and N_i in the Universe Transverse Mercator (UTM) system, Equation 3 can be expressed as:

$$E = \sum_{i=1}^{n-1} E_i(P_{i-1}(E_{i-1}, N_{i-1}, h_{i-1}), P_i(E_i, N_i, h_i), P_{i+1}(E_{i+1}, N_{i+1}, h_{i+1})) \tag{4}$$

The objective function expressed in Equation 4 is ambiguous because there is an infinite number of polylines in object space that become a single polyline when projected into image space. To remove this ambiguity and obtain a single solution, Dal Poz et al. (2012) developed an objective function specifically for an aerial imagery stereoscopic pair, which is defined as the sum of the objective functions for the left- and right-hand images (both low resolution):

$$\begin{aligned} \mathrm{E}^T &= E^l + E^r = \\ &\sum_{i=1}^{n-1} E_i^T (P_{i-1}(E_{i-1}, N_{i-1}, h_{i-1}), P_i(E_i, N_i, h_i), \\ &\quad P_{i+1}(E_{i+1}, N_{i+1}, h_{i+1})) \end{aligned} \tag{5}$$

In Equation 5 (Figure 1), E^l is the objective function (Equation 4) that correlates road R in the object space with road *r* in the left-hand image; E^r is the objective function (Equation 4) that correlates the road centreline *R* with the road centreline *r'* in the right-hand image; and E_i^T is obtained by grouping like terms of E^l and E^r. The mathematical model presented in Equation 5 is designated the *stereo road model*.

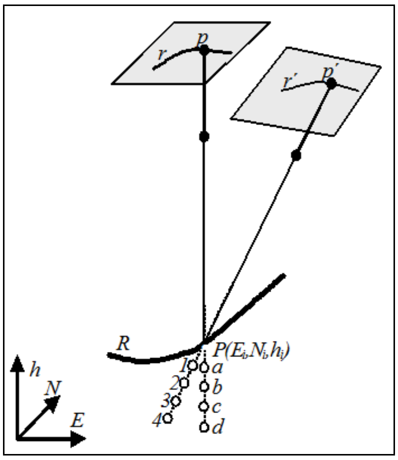
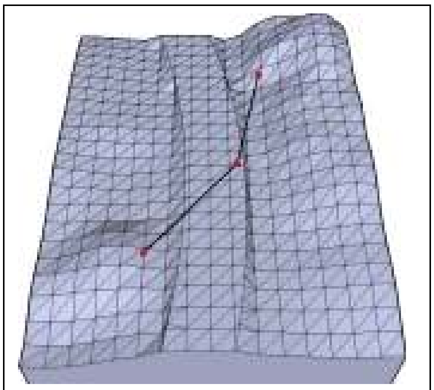


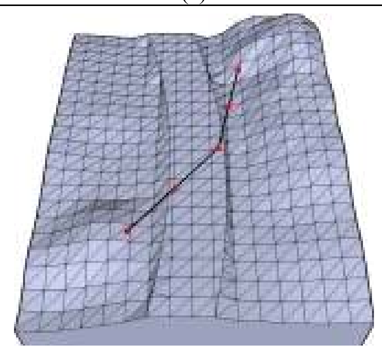
Figure 1. Road model principle for a pair of stereoscopic images (Dal Poz et al. 2012)

2.2 Proposed road extraction method

The extraction process is initiated by defining a polyline in object space from several seed points that are provided by the operator and sparsely placed along the road that will be extracted. As a general rule, a small number of seed points is required along segments with a low curvature, whereas segments with a large curvature will require a greater number of seed points. Because the operator must visualize the road to provide seed points, the adopted strategy measures seed points in one image of the stereoscopic pair and projects them over the DTM using a monorestitution algorithm (Makarovik, 1973).



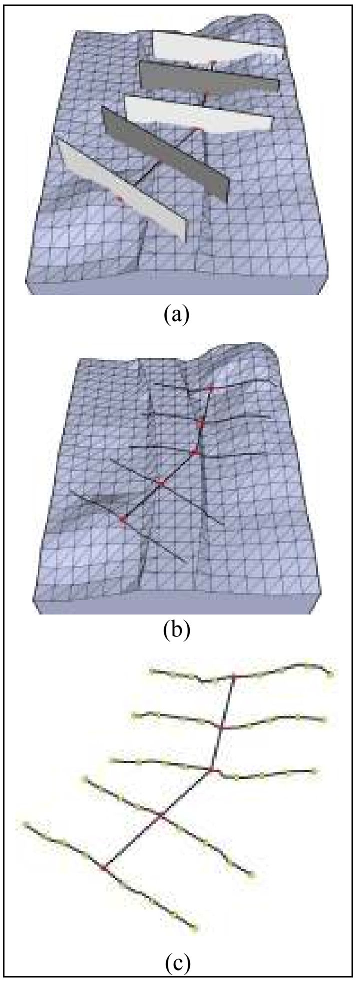
(a)



(b)

Figure 2. (a) Initial polyline with three seed points. (b) Densification

The initial polyline (Figure 2a) is then gradually densified and refined over iterative optimization cycles in object space until it adequately describes the road centreline. Densification is performed by linearly interpolating mid-points between each pair of pre-existing adjacent vertices (Figure 2b).



(a)

(b)

(c)

Figure 3. (a) Planes that are perpendicular to the densified polyline. (b) Search polylines defined by intersecting the planes with the DTM. (c) Sampled search polylines

The vertices resulting from the polyline densification are used as references to sample candidates for the optimal vertex. If m candidate vertices are tested for each of the n vertices of the densified polyline, then m^n candidates for the optimal polyline will be generated in the search-space at each iteration. It is therefore recommended that the lowest possible number of candidates for each vertex is tested. Accordingly, the search-space is limited to a *search polyline* (Figure 3b) obtained by intersecting the DTM-generated polyhedron with planes that are perpendicular to the densified polyline (Figure 3a). Candidate vertices are symmetrically and regularly sampled along the search polylines (Figure 3c). The extension of the search polylines is dependent on the spatial proximity of the operator-defined seed points. To maximize the convergence radius and guarantee an accurate result, a multi-resolution strategy is adopted whereby lower-resolution polylines are employed in initial iterations (with a width of the same order as the road, thereby ensuring a wider search region) and a higher resolution is adopted in later iterations (ca. 1/3 of the road width). This process enables the correct positioning of the optimal polyline upon the road.

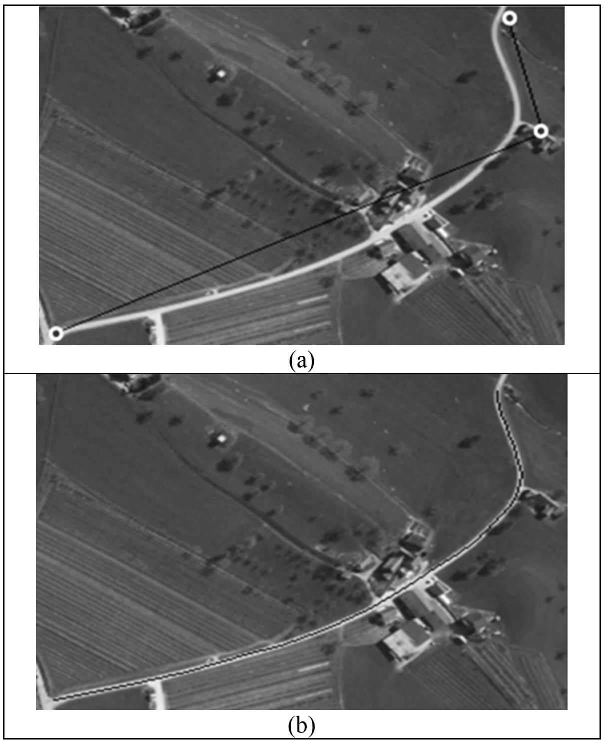
In the example shown in Figure 3c, eight vertices (yellow dots) are sampled symmetrically at regular intervals along the search polyline. Each central vertex (red dots) corresponds to a vertex of the densified polyline (Figure 3b). Vertex sampling along each search polyline is performed using the 3-D parametric form of the linear equation. Each vertex $P_i(E_i, N_i, h_i)$ is computed as a function of the line parameter t_i, which describes the distance between the vertex being sampled ($P_i(E_i, N_i, h_i)$) and the central vertex. Therefore, because each vertex $P_i(E_i, N_i, h_i)$ will depend only on the distance t_i, Equation 5 can be rewritten as:

$$E^T = \sum_{i=1}^{n-1} E_i^T \left(P_{i-1}(t_{i-1}), P_i(t_i), P_{i+1}(t_{i+1}) \right) \tag{6}$$

According to Equation 6, only three variables (t_{i-1}, t_i, t_{i+1}) are simultaneously interrelated as opposed to nine variables as in Equation 5. This structure enables us to use a "time-delayed" discrete dynamic programming algorithm (Ballard e Brown, 1982; Amini et al., 1990) because the underlying condition of this optimization algorithm — few variables are simultaneously interrelated — is fully satisfied.

3. EXPERIMENTAL RESULTS

In the following we present preliminary results based on two stereoscopic pairs of low-resolution aerial sub-images. We used a TIN-based DTM with an average resolution of 1 m. The results were evaluated both visually and numerically. The visual evaluation was performed by analysing and overlaying the extracted polylines onto one of the stereoscopic pair of sub-images. The numerical evaluation was performed by calculating the completeness and correctness parameters. Definitions and formulations of these quality indexes can be found in Heipke et al. (1997).



(a)

(b)

Figure 4. (a) Seed points. (b) Extracted road centreline

Figure 4a shows a road at a high contrast with the surrounding lateral regions and a very smooth geometry. The primary anomalies are its intersection with another road segment and a small group of buildings along its length. These anomalies cause certain small margin segments to be absent and lead to small variations in road width. Figure 4b demonstrates the performance of the proposed method when applied to this low-complexity segment. This road segment was successfully extracted, as indicated by the maximum score (100%) of the completeness index. However, the correctness index was 83%.

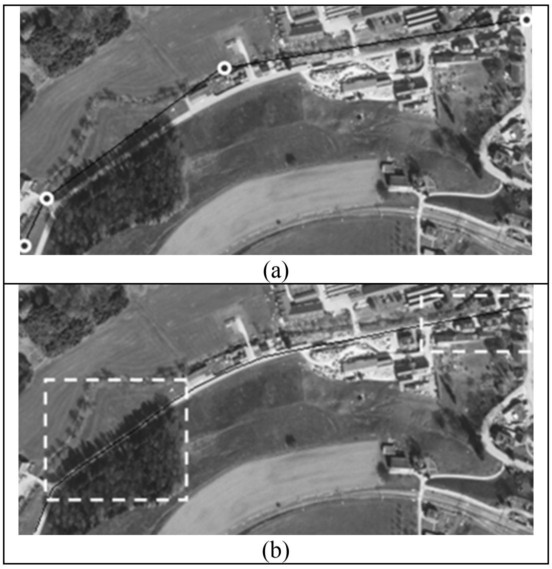


Figure 5. (a) Seed points. (b) Extracted road centerline

The road segment in Figure 5a shows a long curve with two occlusion regions: one is caused by buildings and projected shadows (Figure 5b, smaller rectangle), and the other is caused by a forest patch that largely obstructs a long road segment. Four seed points were chosen, including two placed close together roughly in between the two central seed points to help capture the road signal in the segment obstructed by the forest. The result of this extraction is satisfactory, although a portion of the centreline is coincident with one of the road borders. This placement effect is a consequence of the method, which is most efficient when modelling roads up to 3 pixels wide, which is narrower than the analysed segment. The completeness and correctness parameters were 100% and 77%, respectively.

4. CONCLUSIONS

The present study described a semiautomatic method for road extraction using a stereoscopic pair of low-resolution aerial images and a DTM based on DP optimization in object space. The DTM allows the search for the optimal polyline to be restricted along a narrow band that is overlaid upon the model. It also allows for the elimination of candidate polylines that do not meet the vertical smoothness criterion, i.e., those polylines with a vertical deflection angle that violates a user-defined threshold.

To preliminarily evaluate the performance of the proposed method, two experiments were designed using two stereoscopic pairs of low-resolution aerial sub-images and a 1-m-resolution DTM. The results were qualitatively and quantitatively analysed (the quantitative assessment was based on completeness and correctness indices). Visually, the extracted polylines were of good geometrical quality, although the correctness parameter fell below 80% in one case.

REFERENCES

Agouris, P., Gyftakis, S., Stefanidis, A., 2000. Uncertainty in image-based change detection. In: *Accuracy 2000*, Amsterdam, pp. 1-8.

Amini, A. A., Weymounth, T. E., Jain, R. C., 1990. Using dynamic programming for solving variational problems in vision. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 12(12), pp. 855-867.

Bajcsy, R.; Tavakoli, M., 1976. *Computer recognition of roads from satellite picture*. *IEEE Transactions on Systems, Man and Cybernetics*, 6, pp. 76 – 84.

Ballard, D. H., Brown, C. M., 1982. *Computer Vision*. Prentice Hall, Inc., Englewood Cliffs, New Jersey, 523p.

Baumgartner, A., Steger, C., Mayer, H., Eckstein, W., Ebner, H., 1999. Automatic Road Extraction Based on Multi-Scale, Grouping and Context. *Photogrammetric Engineering and Remote Sensing*, 65(7). pp. 777–785.

Dal Poz, A. P., Gallis, R. B. A., Silva, J. F. C., 2010. Three-Dimensional Semiautomatic Road Extraction from a High-Resolution Aerial Image by Dynamic Programming Optimization in the Object-Space. *IEEE Geoscience and Remote Sensing Letters*, 7, pp. 796-800.

Dal Poz, A. P., Gallis, R. A. B., Silva, J. F. C., Martins, E. F. O., 2012. Object-Space Road Extraction in Rural Areas Using Stereoscopic Aerial Images. *IEEE Geoscience and Remote Sensing Letters* (accepted).

Göpfert, J., Rottensteiner, F., Heipke, C., 2011. Using snakes for the registration of topographic road database objects to ALS features. *ISPRS Journal of Photogrammetry and Remote Sensing*, 66, pp. 858-871.

Gruen, A., Li, H. Semi-automatic linear feature extraction by dynamic programming and LSB-snakes. *Photogrammetric Engineering and Remote Sensing*, 63(8), pp. 985-995.

Heipke, C., Mayer, H., Wiedemann, C., 1997. Evaluation of automatic road extraction. In: *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Stuttgart, 32, part 3-4w2, pp. 151-160.

Hinz, S., Baumgartner, A., Mayer, H.; Wiedemann, C., Ebner, H., 2001. Road Extraction Focusing on Urban Areas. In: *Automatic extraction of man-made objects from aerial and space images*, Rotterdam, pp. 255 – 265.

Hinz S., Wiedemann C., 2004. Increasing Efficiency of Road Extraction by Self-Diagnosis. *ISPRS Journal of Photogrammetry and Remote Sensing*, 70(12), pp. 979–986.

Hu, J., Razdan, A., Femiane, J. C., Cui, M., Wonka, P., 2007. Road network extraction and intersection detection from aerial images by tracking road footprints. *IEEE Transaction on Geosciences and Remote Sensing*, 50(12), pp. 4144-4157.

Kass, M., Witkin, A., Terzopoulos, D., 1987. Snakes: Active Contour Models. In: *1st International Conference on Computer Vision*, London, pp. 259-268.

Kim, T., Park, S-R., Kim, M-G,. Jung, S., Kim, K-O., 2004. Tracking road centerlines from high resolution remote sensing images by least squares correlation matching. *Photogrammetric Engineering and Remote Sensing*, 70(12), pp. 1417-1422.

Makarovik, B., 1973. Digital Mono-Plotters. *ITC Journal*, 1, pp. 101-122.

Mckeown, D. M., Denlinger, J. L., 1988. Cooperative methods for road tracking in aerial imagery. In: *Workshop of Computer Vision and Pattern Recognition*, pp. 662-672.

Neuenschwader, W. M., Fua, P., Iverson, L., Szekely, G., Kubler, O., 1997. Ziplock snakes. *International Journal of Computer Vision*, 25(6), pp. 191-201.

Poullis, C., You, S., 2010. Delineation and geometric modeling of road networks. *ISPRS Journal of Photogrammetry and Remote Sensing*, 65, pp. 165-181.

Quam, A., 1978. Road tracking and anomaly detection in aerial imagery. In: *DARPA Image Understanding Workshop*, pp. 51-55.