GENERATION OF DIGITAL SURFACE MODEL FROM HIGH RESOLUTION SATELLITE IMAGERY

Chunsun Zhang [a, *], Clive Fraser[b]

[a]Geographic Information Science Center of Excellence (GIScCE), South Dakota State University, 1021 Medary Ave, Brookings SD 57007, USA-(chunsun.zhang)@sdstate.edu
[b]Dept. of Geomatics, The University of Melbourne, Parkville, Victoria, Australia-(c.fraser)@unimelb.edu.au

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ABSTRACT:

We discuss an improved approach for digital surface model (DSM) generation from high-resolution satellite imagery (HRSI) in this paper. The HRSI systems, such as IKONOS and QuickBird have initialed a new era of Earth observation and digital mapping. The half-meter or better resolution imagery from Worldview-1 and the planned GeoEye-1 allows for accurate and reliable extraction and characterization of even more details of the earth surface. In this paper, the DSM is generated from HRSI using an advanced image matching approach which involves an integration of feature point, grid point and edge matching algorithms, makes use of the explicit knowledge of the image geometry, and works in a coarse-to-fine hierarchical strategy. The DSMs are generated by combination of matching results of feature points, grid points and edges. This approach produces reliable, precise, and very dense 3D points for high quality digital surface models which also preserve discontinuities. Following the DSM generation, the accuracy of the DSM has been assessed and reported. To serve both as a reference surface and a basis for comparison, a lidar DSM has been employed in a testfield with differing terrain types and slope. The experimental results have shown that the developed approach achieved very good quality results of DSM with general height accuracy is around 4m over topographically diverse areas.

1. INTRODUCTION

With the launch of the IKONOS and QuickBird, which produce high-resolution satellite imagery below 1m resolution in the panchromatic mode and 4m resolution in multi-spectral mode, a new era in earth observation, digital mapping and application development has begun. The half-meter or better resolution satellite imagery from Worldview-1 and the planned GeoEye-1 allows for accurate and reliable extraction and characterization of even more details of the earth surface. The possibility of the high-resolution satellite sensors, such as IKONOS and QuickBird to change their viewing angle in one orbit, gives them the capability to obtain stereo or even triple-overlapped images from the same orbital pass. Therefore, imagery collected from high-resolution satellite sensors can alleviate temporal variability concerns as the momentary separation between in-track scene capture allows consistent imaging conditions. These superior characteristics make high-resolution satellite imagery well suited for DSM generation (Zhang, 2005; Poon et al., 2005; Krauss et al., 2005; Sohn et al., 2005; Zhang and Gruen, 2006; Poon et al., 2007) and feature extraction (Hu and Tao, 2003; Di et al., 2003; Zhang et al., 2005). This paper deals with IKONOS Geo stereo imagery for accurate digital surface models generation. After this introduction, we briefly describe the sensor model for image georeferencing. Then, we concentrate on our image matching approach. The approach was developed for automatic DSM generation and provides dense, precise and reliable results. Our approach uses a coarse-to-fine hierarchical solution with a combination of several image matching algorithms. Afterwards, the experiment is conducted and the results is presented using IKONOS Geo stereo imagery in a test site of Hobart, Australia, with large height range and very

variable terrain relief and land cover. Finally, the detailed DSM accuracy evaluation is given using a lidar DSM as reference.

2. IMAGE ORIENTATION WITH RPC

IKONOS imagery is collected by a linear array scanner with the pushbroom sensor, and is composed of consecutive scan lines where each line is independently acquired and has its own time dependent attitude angles and perspective centre position. The imaging geometry is characterized by nearly parallel projection in along-track direction and perspective projection in cross-track direction. To describe mathematically the object-to-image space transformation, the rational function model has been universally accepted and extensively used (Baltsavias et al., 2001; Jacobsen, 2003; Grodecki and Dial, 2003; Fraser et al., 2002; Fraser and Hanley, 2003; Poli, 2004; Eisenbeiss et al., 2004). The rational function model is the ratio of two polynomials and is derived from the physical sensor model and on-board sensor orientation (Grodecki and Dial, 2003). The rational polynomials coefficients (RPCs) are supplied with the IKONOS imagery.

Because RPCs are derived from orientation data originating from the satellite ephemeris and star tracker observations, without reference to ground control points (GCPs), they can give rise to geopositioning biases. These biases can be accounted for by introducing additional parameters (Fraser and Hanley, 2003; Fraser et al., 2006). After the bias compensation process, bias-corrected RPCs can be generated by incorporating bias compensation parameters into the original RPCs, allowing bias-free application of RPC positioning without the need to refer to additional correction terms (Fraser and Hanley, 2003;

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* Corresponding author.

Grodecki and Dial, 2003; Fraser et al., 2006). It has been shown in previous research that with bias-corrected RPCs, 1 pixel level geopositioning accuracy can be achieved from high-resolution satellite imagery (Dial and Grodecki, 2002a; Fraser and Hanley, 2003; Fraser and Hanley, 2005; Baltsavias et al., 2005; Fraser et al., 2006). Previous research has shown that sub-pixel accuracy is usually obtained from IKONOS imagery shorter than 50km (Dial and Grodecki, 2002b).

3. THE IMPROVED APPROACH FOR IMAGE MATCHING

Image matching has been an active topic in photogrammetry and computer vision for decades. One of the important applications of image matching in photogrammetry is for automatic generation of digital surface model. The fundamental goal of image matching is to automatically find the conjugate features (points, lines, curves, regions, etc) on overlapping images. A large number of approaches have been published, and for DSM generation, some packages are commercially available. However, a fully automatic, precise and reliable image matching method, to adapt to different images and scene contents, does not yet exist. The limitations arise mainly from an insufficient understanding and modeling of the underlying process and lack of appropriate theoretical measures for self-tuning and quality control. The difficulty of image matching comes from, for example, radiometric distortion, geometric distortion, occlusion, repeated pattern and lack of features. The recent research trend in image matching is towards hierarchical solutions with a combination of several algorithms and automatic controls.

We have developed an image matching approach for automatic DSM generation from high-resolution satellite images. The approach uses a coarse-to-fine hierarchical strategy with several image matching algorithms, essentially combines the matching results of the feature points, grid points and edges. Thus, it can provide dense, precise, and reliable results. The general scheme is presented in Fig. 1.
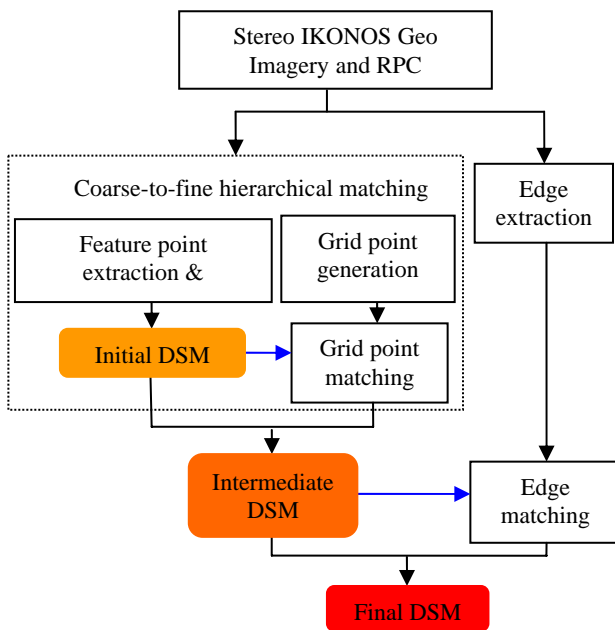

Figure 1. Image matching strategy and work flow for DSM generation from high-resolution satellite imagery.

The coarse-to-fine hierarchical strategy is used this approach where image matching follows an image pyramid approach. That is, the solution of correspondences is found from the top of the image pyramid progressively to the bottom of the pyramid which is the image of the original resolution. During the process, the result from a higher level of the pyramid is used as an approximation and adaptive computation of the matching parameters and search range at the subsequent lower level. Image matching continues until the lowest level of the pyramid is reached, where the highest accuracy results are also obtained. Moreover, an initial DSM is generated from the feature points. The DSM is then refined progressively by incorporating more features such as grid points and image edges. Again, as in the image pyramid approach, the resulting DSM from previous feature matching is served as a guide in matching successive features, while the DSM itself will be augmented with the new features, resulting in a denser and denser DSM which allows for better characterization of the terrain. The algorithms for the extraction and matching of feature points, grid points and image edges are described below. More details can be found in Zhang et al. (2007).

Feature points are very important in image matching and DSM generation (Hsia and Newton, 1999). First, a new version of the Wallis filter (Baltsavias, 1991) is applied to optimize the images for feature point extraction and subsequent image matching. This filter enhances features in images and therefore enables improved feature point extraction. Furthermore, since the filter is applied in both images using the same parameters, naturally occurring brightness and contrast differences are corrected. Following the image enhancement process, feature points are extracted using the well-known Foerstner operator.

We exploit pixel grey value similarity and geometrical structure information in feature point matching. This is done in two steps, where different matching algorithms are employed at each step. Following feature point extraction, candidate conjugate points are then located by cross correlation in which the normalized correlation coefficient is used for the similarity measure. This measure is largely independent of differences in brightness and contrast due to normalization with respect to the mean and standard deviation. This information is then used as prior information in the following step for structural matching. The locally consistent matching is achieved through structural matching with probability relaxation (Zhang and Fraser, 2007).

With the computed similarity measures, a matching pool for candidate conjugate points is constructed and a similarity score is attached to each candidate point pair. Although the correlation coefficient is a good indicator of the similarity between points, problems still exist in determining all correct matches. Firstly, there is the difficulty of how to decide on a threshold in correlation coefficients to select the correct matches. The existence of image noise, shadows, occlusions, and repeated patterns exacerbates this problem. Furthermore, matching using a very local comparison of grey value difference does not necessarily always deliver consistent results in a local neighbourhood. In order to overcome these problems, the structural matching algorithm with probability relaxation proposed in Zhang and Baltsavias (2000) has been adopted. The detailed computation of structural matching with probability relaxation is given in Zhang et al. (2007).

Feature point matching is very efficient and suitable in texture-rich regions with grey value variation. On the other hand, in

image regions with poor texture or no texture information, few or even no feature points can be extracted. Thus, feature point matching will lead to holes on the DSM in these areas. To solve this problem, grid points can be used and grid point matching has been introduced (Hsia and Newton, 1999; Gruen and Zhang, 2005; Baltsavias et al., 2005). Grid points are determined at given positions, uniformly distributed over the whole image. As for feature points, the grid points are matched using cross-correlation and structural matching with epipolar constraint following the coarse-to-fine concept. Since grid points may appear in regions with poor texture, shadows or occlusions, the search for the match of a grid point has a higher possibility to yield ambiguity or no matching candidate. To increase the reliability of the grid point matching, the DSM generated from feature point matching is employed to constrain the matching candidate search. This will further reduce the search space and thus decrease ambiguity while speeding up the matching process.

Image edges are important features. Edges are rich, particularly in man-made environment, and associate with ridge lines and break lines on terrain. Thus, 3D edges play important role in characterizing surface discontinuity, and are essentially an important component of a DSM. In addition, edges are critical in feature extraction, object recognition, 2D/3D reconstruction of man-made objects, etc. In this paper, the edge extraction and matching algorithms developed in Zhang and Baltsavias (2000) is employed. This method was developed for automated 3D reconstruction of man-made objects from airborne and spaceborne images (Zhang, 2003; Baltsavias and Zhang, 2005). The advantages of this method are that it exploits rich edge attributes and edge geometrical structure information. The rich edge attributes include the geometrical description of the edge and the photometrical information in the regions immediately adjacent to the edge. The epipolar constraint is applied to reduce the search space. The similarity measure for an edge pair is computed by comparing the edge attributes. The similarity measure is then used as prior information in structural matching. The locally consistent matching is achieved through structural matching with probability relaxation. More details of the matching strategy can be found in Zhang and Baltsavias (2000) and Zhang (2003).

Edges are extracted using the Canny operator and then fitted to generate straight line. For each straight edge segment, the position, length, orientation, and photometric robust statistics in the left and right flanking regions are computed. The photometric properties include the median and the scatter matrix.

The epipolar constraint is employed to reduce the search space. With the approximated height information derived from feature point and grid point matching, an epipolar band of limited length is defined. Any edge included in this band (even partially) is a possible candidate. The comparison with each candidate edge is then made only in the common overlap length, i.e. ignoring length differences and shifts between edge segments. For each pair of edges that satisfy the epipolar constraints above, their rich attributes are used to compute a similarity score. Therefore, the similarity score is a weighted combination of various criteria. The detailed computation can be found in Zhang and Baltsavias (2000).

Following the computation of similarity measurement, we construct a matching pool and attach a similarity score to each candidate edge pair. Since matching using a local comparison of edge attributes does not always deliver correct results, the

structural matching using probability relaxation, similar to that in point matching, are conducted. The method seeks the probability that an edge in one image matches an edge in the other image using the geometrical structure information and photometric information of neighboring image edges. Therefore, the correspondences of both individual edges and edge structures are found. As in point matching, the computed edge similarity scores are used as prior information in structural matching. The compatibility function is evaluated using the differences between the relational measurements of two edge pairs in the stereo images. For the details of the definition of relational measurements and evaluation of compatibility function, we refer to Zhang and Baltsavias (2000) and Zhang (2003).

4. EXPERIMENT RESULTS

We have applied the matching approach to a set of along track IKONOS Geo stereo images in order to extract a DSM in a test site around Hobart, Australia. This scene encompasses a total area of 120 km2 and consists of a variety of land cover types, including mountainous forest (to a height of 1200 m above sea level), hilly suburban neighbourhoods, parks, urban housing and commercial buildings (Fig. 2). The images were acquired towards the end of the southern hemisphere summer season. Note the cloud cover in the lower left side of the Fig. 2. A more complete description of the scene and the image data can be found in Fraser and Hanley (2005).
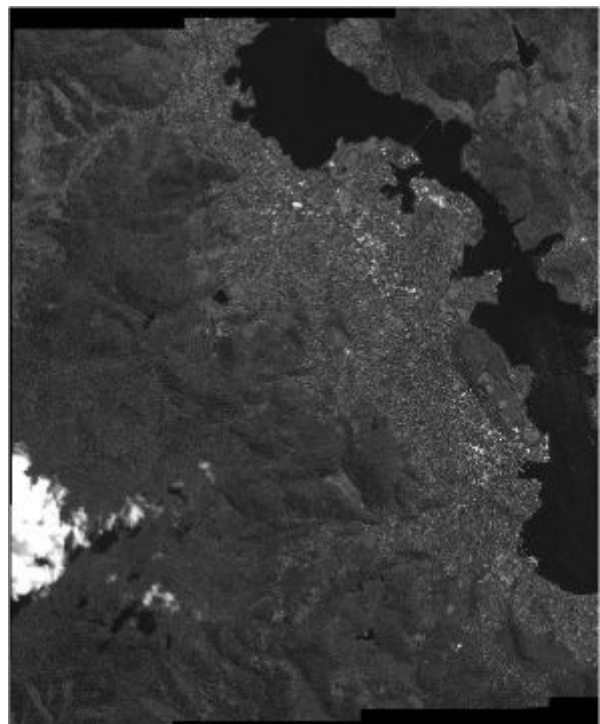

Figure 2. IKONOS image of Hobart, Australia.

First, the vendor-supplied RPCs were refined with the bias compensation model using ground control points. This process corrected the bias in the original RPCs and improved the geopositioning accuracy. The bias-corrected RPC are then used in image matching and for DSM extraction. The process began with feature point matching, and the DSM was progressively

augmented with the results from grid matching and edge matching. The matched points and edges were transformed to 3D object space through space intersection using the bias-corrected RPC. Fig. 3 illustrates the generated DSM with a ground sampling distance of 5 meters using the proposed image matching strategy. This DSM is generated from the matched points using bi-cubic interpolation approach. Visual inspection reveals that good results have been achieved. The very dense terrain points enable delineation of the terrain in more detail. By combining results of multi feature matching, particularly the edge features, the fine structures of the terrain including streets, large buildings and other infrastructure are also modelled.
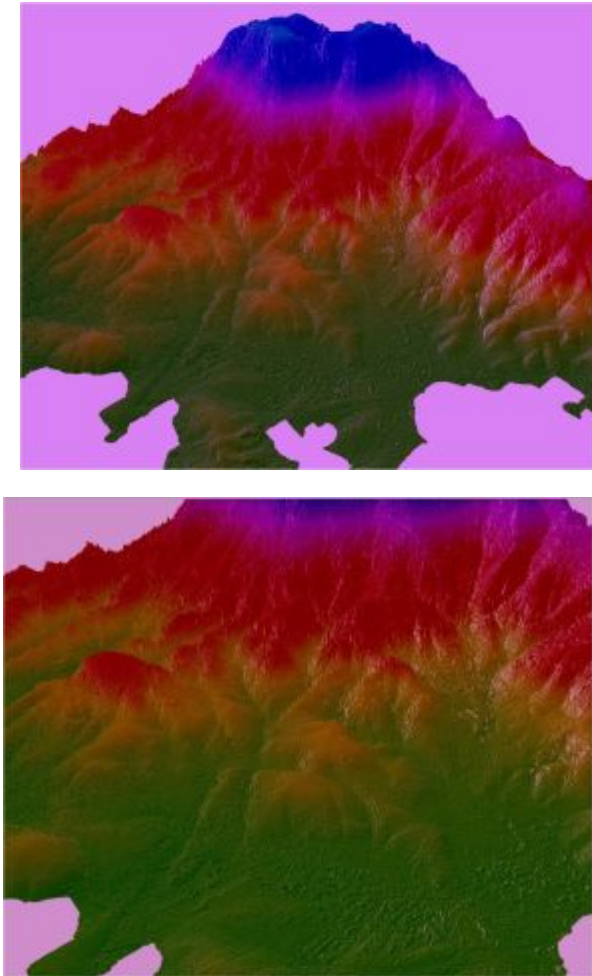

Figure 3. Two views of the generated DSM from IKONOS Geo stereo imagery over Hobart, Australia.

Quantitative evaluation of the DSM was performed by comparison with a lidar DSM. The lidar DSM is located within the Hobart test site, covers a long strip and contains a diversity of land cover including buildings and suburban housing in central and Southern Hobart (Fig. 4). The elevation of range is about 300m. The lidar data has a 1.25m average ground spacing. The planimetric accuracy for the first-pulse was better than 1m, with standard error of heighting being estimated at 0.25m (AAMHatch, 2004). First, the DSM heights from IKONOS stereo imagery were compared with against the lidar height data. This assessment reveals that the RMS discrepancy was around 4m, indicating that the generated DSM is indeed a good representation of the actual terrain. However, the assessment does not provide an insight into variability of accuracy associated with areas of different land cover.
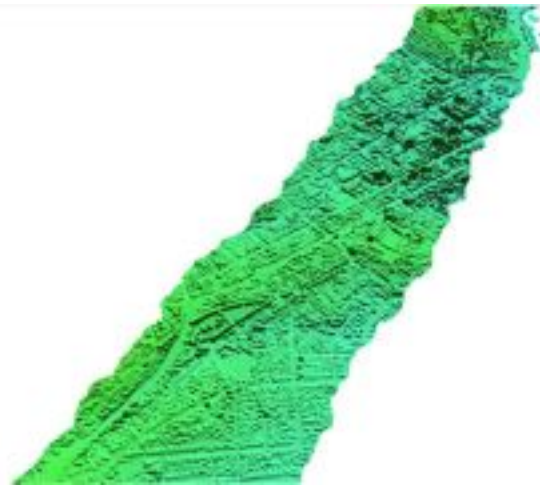

Figure 4. Reference lidar DSM with 2m grid spacing.

In order to take into account the influence of topographic variation and land cover variability on the modelled surface, the lidar strip area was divided into separate sub-areas. These comprised urban and rural areas, with a further subdivision into regions within these two categories. Table 1 gives the DSM accuracy evaluation results. The accuracy of the generated DSM is generally in the range of 2.0 to 6.0m. Height accuracy is better in bare ground areas, while the accuracy degrades in built-up urban areas. The accuracy is worse in forest areas, since image matching is susceptible to difficulties in forest due to the poor contrast of image contents and shadows. The generated DSM is usually higher than lidar reference in forest areas, partially due to the fact that the laser can penetrate into forest canopies. In urban areas, the large discrepancy can be also contributed from lidar when the laser erroneously strikes the vertical profile of an object (e.g. building walls) and is misinterpreted as surface.

5. DISCUSSION AND CONCLUSION

We have demonstrated algorithms and programs for automatical generation of DSM from high-resolution satellite imagery, consisting of a combination of feature points, grid points, and edges. Key components presented are methods to explore IKONOS Geo stereo imagery for producing dense and detailed DSMs over large areas. First, the vendor-supplied sensor model coefficients must be refined using a bias compensation model to achieve sub-pixel geopositioning accuracy. Then the DSM is automatically generated by a sophisticated image matching approach. The matching approach involves an integration of feature point, grid point and edge matching algorithms, makes use of the explicit knowledge of the image geometry, and works in a coarse-to-fine hierarchical strategy. The coarse-to-fine strategy allows for the matching process following an image pyramid approach, while progressively reconstructing the surface model from feature points, grid points to edges. This strategy reduces search space, provides more reliable results, and speed up the process. For the matching of each feature, a two-step scheme is employed in which the candidates are first found using normalized correlation coefficient (for points) or by comparing the attributes (for edges), while the final matches are located by a structural matching algorithm with probability relaxation. This scheme avoids a hard threshold in deciding

matches which usually causes commission and omission errors, while providing consistent results in a local neighborhood. The integration of multi features for DSM generation is another advantage of the proposed approach. The grid point matching allows for bridging gaps or holes in regions with poor or no texture. The integration of edges in the DSM is particularly useful and preserves the discontinuity of the terrain that allows for better characterization of terrain.

Land cover	RMSE(m)	Mean(m)	Abs Max(m)
Urban			
CBD	4.0	1.6	38.6
Residential	2.6	0.8	22.8
University	2.8	0.1	27.0
Building	2.9	1.1	21.3
Sporting fields	2.7	0.2	14.6
Park	3.1	1.2	29.8
Gardens	2.9	0.9	34.9
Rural			
Bare ground	2.1	0.5	8.7
Sporting fields	2.6	0.2	12.9
Forest	6.3	1.8	43.6

Table 1. Margin settings for A4 size paper

Experiments have been conducted. We have presented the result of processing of IKONOS Geo stereo images over a test site in Hobart, Australia with accurate ground control points, nearly 1300m height range and variable land cover. The result was compared with reference data from airborne laser scanning. The general height accuracy is around 4m over topographically diverse areas. The quality and accuracy of the generated DSM improves in the open rural areas. The largest errors are usually found in forest areas or urban centers. There are also contributing errors from the reference data.

6. ACKNOWLEDGEMENTS

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