Stereo Elevation Determination Techniques for SPOT Imagery

Doug C. Brockelbank
Alberta Research Council, Calgary, Alberta T2N 1N4, Canada
Ashley P. Tam
Department of Surveying Engineering, University of Calgary, Calgary, Alberta T2N 1N4, Canada

ABSTRACT: Techniques used to extract accurate elevation information from stereo SPOT satellite images are described and compared. Feature- and area-based stereo image matching models and a hybrid model are implemented and tested with SPOT imagery. The feature-based model uses a relaxation labeling approach in a top-down structure to find feature disparities. The area-based model uses a top-down approach to correlate a grid of image patches. The hybrid model uses feature matches to guide area-based matching. Match point disparities found by the models are converted to elevations and interpolated to form a complete digital elevation model (DEM). A quantitative evaluation of the DEMs is used to compare the performance of the three methods.

INTRODUCTION

The generation of digital elevation models (DEM) for land surfaces has traditionally been accomplished by area based correlation techniques (Panton, 1978; Gruen and Baltsavias, 1986). However, attempts at DEM generation have also used point-of-interest matching (Hannah, 1989) and feature matching (Greenfeld and Schenk, 1989). Feature matching has traditionally been used in close-range stereo depth mapping environments (Barnard and Thompson, 1980; Grimson, 1985). The question of whether one approach is better suited to DEM production (Day and Muller, 1989) will be addressed by this paper.

A feature-based model for DEM generation is compared to an area-based model and a hybrid model is also considered. The implementation of the models and the experimental design are unbiased. This results in a fair comparison which indicates that the area-based model is more accurate than the feature-based model for DEM generation. The extra processing required for the hybrid model does not seem to be justified because the results are no more accurate than the area-based model.

COMPONENTS

The three stereo models are made as similar as possible to allow valid comparisons between the models. The models are

- Feature Based,
- Area Based, and
- Hybrid.

The models for stereo matching are implemented from a common pool of components. This section briefly describes each of the following components used to implement the stereo models:

(1) Satellite Parameter Estimation,
(2) Disparity Prediction,
(3) Feature-Based Stereo Matching,
(4) Area-Based Stereo Matching, and
(5) Generation of DEM.

SATELLITE PARAMETER ESTIMATION

The satellite parameter estimation component is used to calculate the SPOT sensor position and orientation parameters during the nine seconds required to capture each image. At least eight manually collected ground control points are required along with satellite ephemeris data to estimate the satellite parameters (Tam, 1990). The satellite parameters can be used to geometrically transform the raw SPOT images (level 1A processing) to a regular grid image with a single scale. Obviously, this type of transformation is an approximation because a DEM is not used (Otto, 1990).

This approximate transformation can also be used to associate a position on the image with a ground location. When two matching positions from the images in a stereo pair are simultaneously projected into the ground, an accurate position and elevation of the point can be calculated. This is done by finding the midpoint of the parallax of the projected rays (Tam, 1990) as shown in Figure 1.

DISPARITY PREDICTION

One factor that satellite parameters and ground control cannot model is local elevation changes in the land surface. Elevation changes cause a relative shift of parts of the image with respect to their surroundings. The objective of stereo matching is to find this shift. Before the stereo matching models can find this shift, another level of registration is required to get the two images aligned along the horizontal axis so that all shifts are only in the horizontal direction. This step, called epipolar alignment, reduces the search area for matching image points to a straight line. The horizontal shift is also modeled approximately to reduce the search space for the stereo matcher to a small segment along a straight line.

Match control points, selected manually from the two raw SPOT images, are used to eliminate vertical shift and predict horizontal shift of corresponding points in the two images. Cubic polynomials are used to model the horizontal and vertical disparity between match control points in the two images of the stereo pair. The polynomials are calculated using the least-squares method (Zhang and Zhou, 1989). In this implementation, overlapping patches are used to make the polynomial approximation of disparity more accurate.

Each polynomial patch is calculated with a least-squares approximation. A system of ten simultaneous linear equations from the partial derivatives of the least-squares equation are used. The least-squares equation is

$$\Sigma\{(a_0 + a_1r + a_2c + a_3rc + a_4r^2c + a_5rc^2 + a_6r^2 + a_7c^2 + a_8r^3 + a_9c^3) - (disparity)\}^2 = 0,$$

where the variables r and c are the row and column coordinates of the match control points from the first image, *disparity* can be either the horizontal or vertical difference in position of matching points, and the a_i are the unknown coefficients to be solved. (Note: the nearest nadir image in the stereo pair will be referred to as the first image.)

PHOTOGRAMMETRIC ENGINEERING & REMOTE SENSING,
Vol. 57, No. 8, August 1991, pp. 1065-1073.

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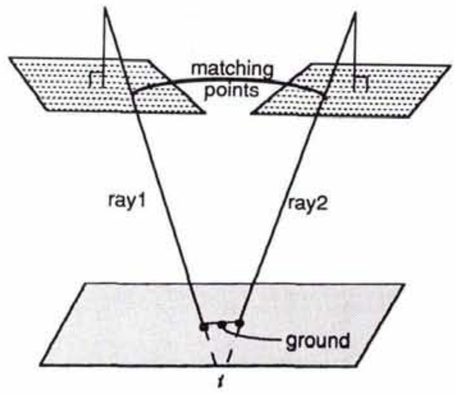

FIG. 1. Parallax calculation.

The difference in position of matching points collected from two sets of stereo SPOT imagery of Dinosaur National Monument (DNM) and Red Deer is shown in the Table 1. The root-mean-square (RMS) difference between corresponding points from the two images is given for the match points at three stages.

(1) The raw SPOT coordinates are registered globally by a horizontal and vertical shift,
(2) The estimated satellite parameters are used to register the images, and
(3) A set of cubic polynomial patches are used for fine adjustment of the image registration.

FEATURE-BASED STEREO MATCHING

Feature extraction is performed on the raw SPOT images using the second directional derivative edge operator (Haralick, 1982). Edge strength and orientation are calculated and one addition has been made to the edge detector. Rather than having a constant threshold which always yields edges greater than a certain strength, a context sensitive threshold has been added. Context sensitive thresholding uses the local intensity gradient of the image as the threshold. The effect of using the image gradient as the threshold is a more even distribution of edges over the entire image. In areas of high gradients, there will be a high threshold and only the strongest edges will be found. Conversely, in areas of low gradients a low threshold will be used, allowing weaker edges to be detected rather than completely ignoring the area. The reason for using a context sensitive threshold in this application is that satellite images often have some very strong edges and large areas with faint edges. Finding an even distribution of elevations over an area requires starting with an even distribution of edges. Edges found for the DNM and Red Deer stereo pairs are shown in Figure 2.

The feature-based matching method used here can be described in three main steps which are

- feature map construction,
- set pool construction, and
- top-down match resolution.

The feature-based matcher operates in a topocentric coordinate system. Edge positions and orientation are geometrically transformed with the estimated orbital parameters to the topocentric coordinate system. The patch polynomials, described previously, are then used for epipolar alignment and horizontal disparity prediction. The edge points are thinned and linked together at their end points using their strength and orientation information. A feature map is built for each image from the joined edges. A set pool is constructed for each feature in the first image. Each set pool contains all possible features from the second image which could match the feature from the first image. Set pools contain only features on the same epipolar line with approximately the same orientation and strength. Search window locations are defined by the horizontal disparity polynomial patches. Match resolution is accomplished in a top-down structure by processing the strongest half of the features first and then the weakest half. Matching stronger features first was found to be more effective because their matches are more easily and accurately found (El-Hakim, 1989). Iterative relaxation labeling is the technique used to resolve matches (Barnard and Thompson, 1980) within the top-down structure.

TABLE 1. RMS OF DISPARITIES AFTER TRANSFORMATIONS (PIXELS).

transformation	DNM Vertical	DNM Horizontal	Red Deer Vertical	Red Deer Horizontal
raw SPOT coordinates	22.6	37.7	139.5	75.2
estimated satellite parameters	1.78	9.39	3.27	7.67
cubic polynomial patches	1.12	1.82	1.25	1.30

AREA-BASED STEREO MATCHING

The area-based matching technique used here requires that the stereo SPOT images be epipolar. This is accomplished by geometrically transforming (Zhang and Zhou, 1989) and resampling (Schlien, 1979) the second image into the coordinate system of the first image. The second image is also normalized to have approximately the same mean shade as the first image. These transformations are similar to the transformations described in Gruen and Baltsavias (1986), but here they are carried out globally on the whole SPOT image rather than independently on each correlation patch. The results is that this algorithm is comparatively fast. The implementation described in Gruen and Baltsavias (1986) may be more accurate, but this algorithm is not over parameterized and is probably more robust because there are not so many parameters to constrain and solve.

This method for area-based matching can be described in two main steps for ease of understanding. The steps are

(1) match grid construction,
(2) top-down matching:
    (a) match possibilities search, and
    (b) match resolution.

A match grid is used in this implementation because it is not necessary, possible, or efficient to find the elevation for every point on a SPOT image. Instead, a regular grid with an interval the same size as the smallest matching patch is constructed for the first SPOT image. During matching, the grid stores the horizontal and vertical disparities of resolved matches and the predicted disparities for points that are still unmatched. At first, all the predicted disparities will be zero because the second image has been transformed approximately into the coordinate system of the first image.

The top-down structure of the area-based matcher is implemented by using different sized correlation patches. In this implementation, 19-pixel-square and then 9-pixel-square patches are used to correlate the image points on the grid. The first level of matching, with the large patch size, has more context to eliminate matching ambiguities easily. The second level of matching, with the small patch size, is used to refine matches made in the first level.

A patch from every grid location on the first image is correlated with positions in the second image search area. The vertical and horizontal search area is ±3 and ±7 pixels, respectively, for

(a) (a)

(b) (b)

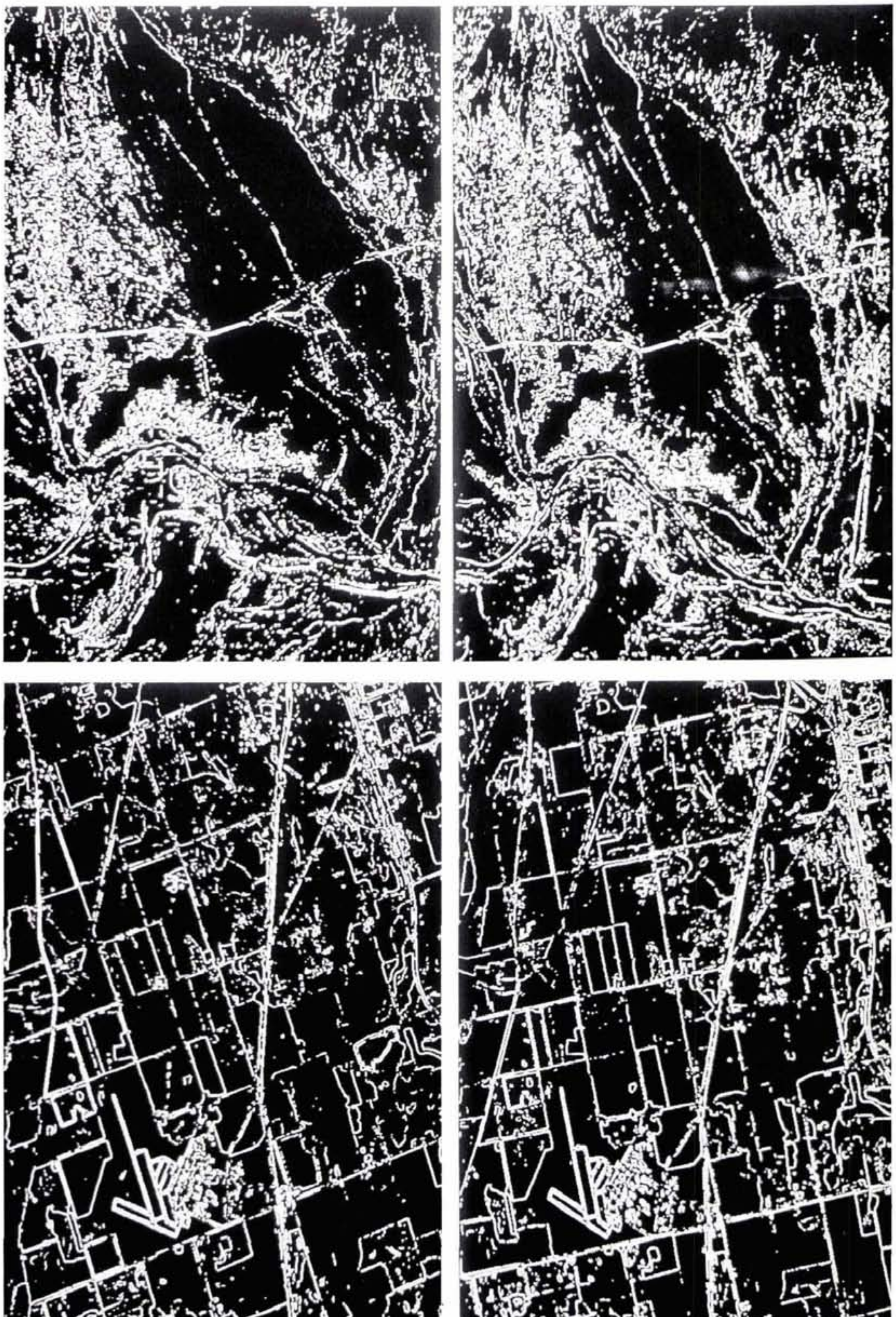

FIG. 2. Edge detection: (a) DNM, (b) Red Deer.

the first level and ± 1 and ± 2 for the second level. Only grid locations having a certain threshold of texture in the first image are used for matching. Possible matches are eliminated for the following four reasons:

(1) a high RMS difference in pixel intensities between the patches on the two images;
(2) the projection of the raw SPOT image coordinates to the ground coordinate system indicating a large parallax;
(3) the elevation of the current possible point being much different from the known elevations of the surrounding points; and
(4) during the second level of top-down matching, the elevation of the current point being much different from the elevation found for this point at the previous level.

If there is more than one possible match left after the elimination, then a final resolution step is needed. The minimum product of elimination reasons (1) and (2) is used to choose the most probable match.

DEM Generation

Both matching methods just described create a list of raw SPOT match point coordinates as their final result. These match points are used to generate a complete DEM at a given resolution level in the UTM coordinate system. Elevations are calculated for the manual and automatically found match points. The remaining unknown elevation points are interpolated. A process of smoothing is used to reduce the quadratic variation of the DEM surface (Grimson, 1981) because large jumps in elevation are probably due to incorrect matches.

MODELS

Three models of stereo image matching are used in this experiment, namely the Feature-Based Model, the Area-Based Model, and the Hybrid Model. A short summary of each model is given in this section. Figure 3 shows how the various components are combined to make the three stereo models.

Feature-Based Model

The feature based model is implemented with components (1), (2), (3), and (5) as described in the components section. This model detects edges in the two images. The edges are transformed into a topocentric coordinate system and used to build feature maps. Patch polynomials are used to predict horizontal and vertical feature disparities. Set pools are constructed containing all possible matches for features from the first image. The feature matches are resolved using iterative relaxation labeling. A top-down structure controls the matching process by matching the strongest features first. The matches are found only to a pixel level of localization.

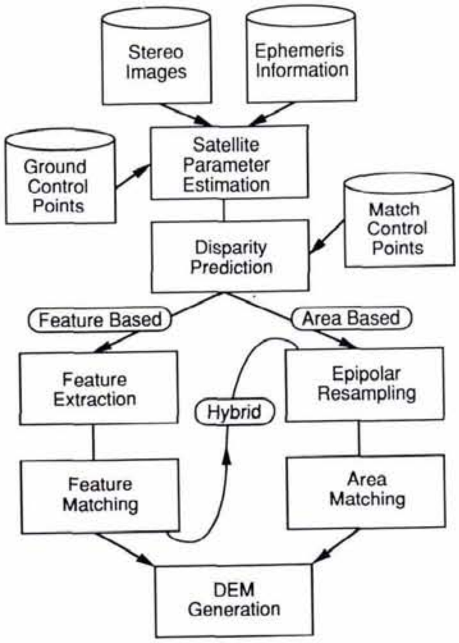

FIG. 3. Stereo models.

Area-Based Model

The area-based model is implemented with components (1), (2), (4), and (5) as described in the components section. Patch polynomials are used to resample the second image into the coordinate system of the first image. A grid of positions from the first image is selected as match points. A top-down structure is used to match these points first with a large patch size and then a smaller patch. Match processing attempts to find a low RMS difference in patch intensities between the two images. A low parallax of the two possible matching points is also sought along with a smooth elevation profile for the local area. The second level of matching with the smaller patch size is used to refine the first level matches by finding sub-pixel localization.

Hybrid Model

The hybrid model is implemented with all the components described in the components section. Actually, this model is implemented as a two-stage process. The feature-based model and the area-based model are used in turn in the hybrid model. The feature-based model is used exactly as previously described. The disparity points from the feature-based model are used to predict match locations for the area-based model. The area-based model starts as it normally would, but, when the matching grid is constructed, the feature matches are used to form match prediction polynomials. The information from feature matching should let the hybrid model find matches quicker and sometimes even find new matches that were outside of expected search areas. One drawback is that any errors made by the feature matcher will be repeated in the hybrid model.

TEST RESULTS

This section discusses experimental test results based on two sets of stereo SPOT satellite images. A portion of these stereo images are shown in Figure 4.

- Dinosaur National Monument (DNM), Colorado, captured on 11 Sep 1987 and 15 Sep 1987.
- Red Deer, Alberta, Canada, captured on 23 Aug 1988 and 31 Aug 1988.

Satellite Parameter Estimation

The estimated satellite parameters and resulting accuracy of the bundle adjustment for the test imagery are important components in accuracy determination. A complete analysis of these components is not included in this paper, but the results are included. To determine the accuracy of the Satellite Parameter Estimation algorithms, eight ground control points are used in the bundle adjustment for the DNM imagery. These points are used in a complex process for satellite position and orientation estimation which is then used to define the relation between the image coordinates and the ground coordinate system (Tam, 1990). The image characteristics and RMS error of control and check points are given in Table 2 for the DNM and Red Deer imagery.

Stereo Matching

The stereo image match verification procedure and results are discussed in this section. The DEM is checked for elevation accuracy by comparing the DEM with elevations from match test points. The match test points are simply an independent set of manually selected match points from the stereo imagery. They are chosen monoscopically on a high resolution computer work station. Only integer values are allowed for their coordinate

(a) (a)

(b) (b)

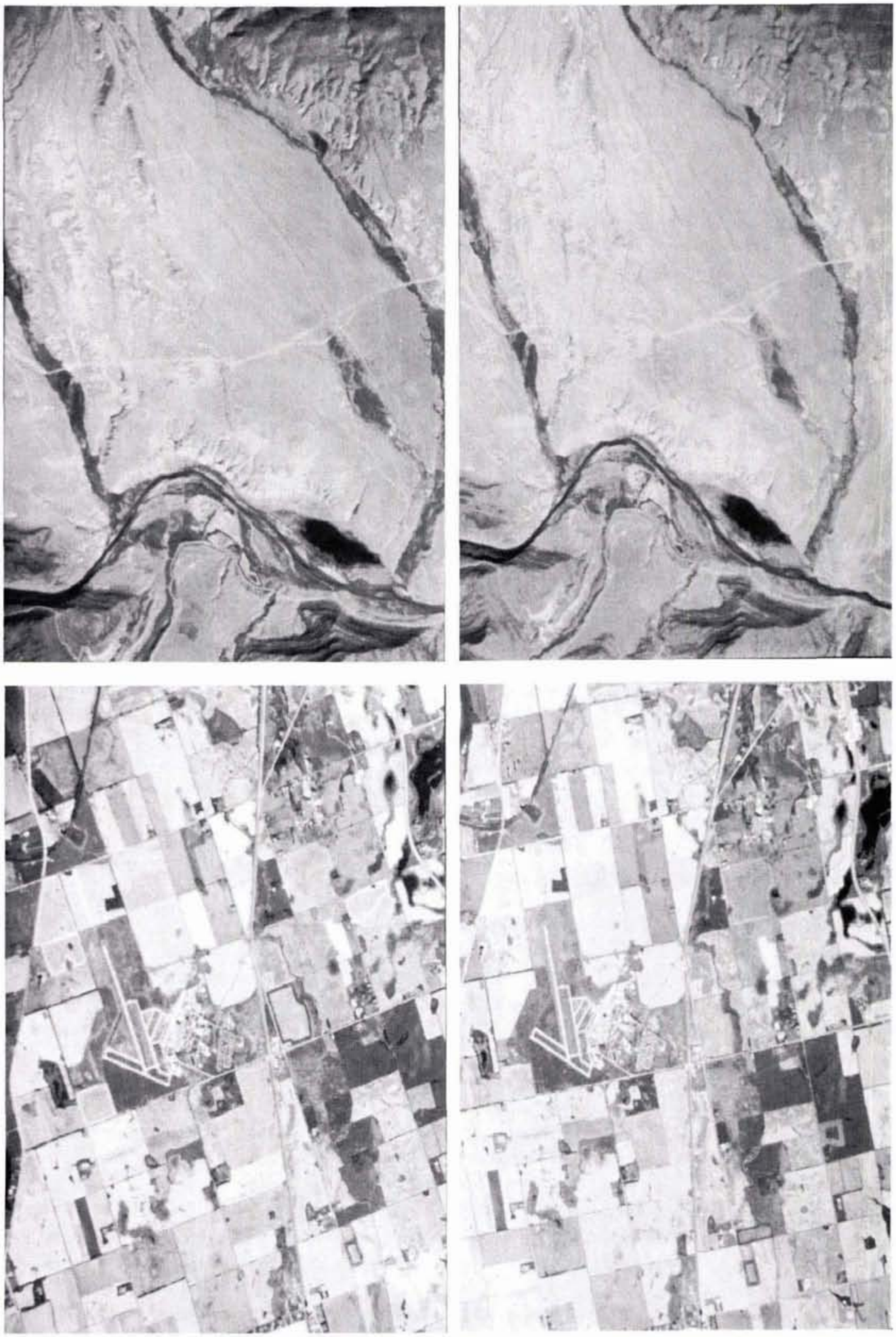

FIG. 4. SPOT stereogram images: (a) DNM, (b) Red Deer.

positions. The expected accuracy of the match test points is 0.5 pixels.

The DEM is tested by calculating the terrain coordinates (X, Y, Z) for the set of independent match test points. These elevations

TABLE 2. IMAGES AND CONTROL.

	DNM	Red Deer
View Angles (degrees)	L: 11.3 R: −20.8	L: 25.5 R: −26.2
Base-to-Height Ratio	0.58	0.97
Elevation Range(metres)	1231.4	205.7
# Ground Control Points	8	9
RMS x,y,z in metres	1.3 0.8 3.9	0.7 0.9 1.1
#Check Points	39	88
RMS x,y,z in metres	12.8 13.3 11.7	8.5 9.6 8.2

TABLE 3. DNM - RMS OF PARALLAX (METRES).

	# Matches	X	Y	Z
match test points	26	2.05	2.80	3.72
feature-based matches	7635	3.32	4.54	6.01
area-based matches	5077	1.53	2.09	2.77
hybrid matches	12712	2.74	3.74	4.96

are compared to the elevation values on the interpolated DEM. The RMS error is calculated for the differences between the DEM and the match test point elevations.

A portion of the Dinosaur National Monument stereo pair (1,001 by 990 pixels) is the first test area. The DEM was calculated with the aid of 182 match control points. Testing uses 26 independent match points to check the DEM. The RMS of the parallaxes for the match point are given in Table 3. The distribution and density of automatically determined elevations points from the DNM scene are shown for the feature-based, area-based, and hybrid models in Figure 5. The RMS errors in metres between the Dinosaur National Monument DEM and elevations from the manually selected match test points are given in Table 4.

The second test imagery is a portion of the Red Deer stereo pair (3263 by 2654 pixels). The DEM was calculated with the aid of 140 match control points. Testing uses 58 independent match points to check the DEM. The RMS of parallaxes for the match points are given in Table 5. The distribution and density of automatically determined elevations points from the Red Deer scene are shown for the feature-based, area-based, and hybrid models in Figure 5. The Red Deer DEM was tested against three sources of elevation data. Manually chosen match test points, ground control point elevations read from 1:50,000-scale topographic maps, and Alberta Survey Control points. The RMS errors in metres between the Red Deer DEM and these elevations are given in Table 6.

For the sake of completeness, the error caused by matching must be combined with the error calculated from the satellite parameter estimation stage. In a simplified approach, this is done by adding the square of their RMS errors and taking the square root. The RMS errors in metres for the area-based matcher on the DNM and Red Deer DEMs are given in Table 7.

DISCUSSION

STEREO MATCHING EVALUATION

There are identifiable factors that affect the accuracy of the DEM. It is possible that the difference in accuracy for the two stereo pair scenes can be attributed to these factors. The most important factors affecting matching are

- the side-looking view angles of the satellite,
- the amount of match control used to aid the matching process,
- the terrain variation, and
- the scene quality and feature distribution.

The left and right side viewing angles for the DNM and Red Deer scenes are given in Table 2. The number of match control points used with the Dinosaur National Monument stereo pair was 182 for approximately 99 square kilometres of land surface. The Red Deer imagery was processed with 140 match control points over approximately 866 square kilometres of land surface. The Dinosaur National Monument scene (Figure 4a) is extremely rough in terms of terrain height while the Red Deer scene is quite flat. The Red Deer imagery appears to have a dense and even distribution of features over the scene due to a patchwork of fields and roads as shown in Figure 4b. Conversely, the Dinosaur National Monument scene is an undeveloped area with few visible features in some areas.

The satellite viewing angles for the Dinosaur National Monument stereo pair are closer together than those for the Red Deer pair. This results in less distortion of the images and thus easier matching. The apparent advantage of smaller angle difference for the Dinosaur National Monument stereo pair is off balanced by a less accurate parallax calculation. This is due to the less precise intersection of the image rays when projecting into the ground coordinate system. This means that the satellite orientation probably has little effect on DEM quality for these two stereo image pairs.

The number of match control points used to guide the stereo matching process is much higher for Dinosaur National Monument than for the Red Deer scene. The extra match control is required for the Dinosaur National Monument scene because of its rougher terrain and poorer features.

The terrain variation and feature quantity and quality would suggest that the best matching results should be obtained from the Red Deer stereo pair as they are. This indicates that the most important factors in stereo matching are terrain variation and visible feature quantity and quality. In terms of combined error, the Red Deer DEM is even more accurate than the DNM DEM because of superior ground control and satellite parameter estimation for the Red Deer scene.

The result obtained with the area-based model on these two scenes compares favorably with other implementations. The area-based model found a DEM with an RMS accuracy of 16.8 m and 11.8 m for the DNM and the Red Deer scenes, respectively. Accuracy values of 10 m to 18 m RMS were reported in Kauffman and Wood (1987). Vincent *et al.* (1988) reported a 18.4-m RMS accuracy. Day and Muller (1989) reported an RMS elevation accuracy between 11.24 m and 14.43 m. Arai *et al.* (1989) reported an RMS accuracy of 24.2 m for rough terrain.

MODEL EVALUATION

The results of stereo matching and DEM calculation show that the area-based matcher performs better than both the feature-based matcher and the hybrid matcher. The DEMs calculated by the area-based model are more accurate than the DEMs calculated by the other two models.

One important point to note is that the feature-based matcher is significantly less accurate than the other two matchers. The accuracy of the area-based matcher and the hybrid matcher are very close in most respects. This can be explained. The feature-based matcher finds matches only at feature locations. These

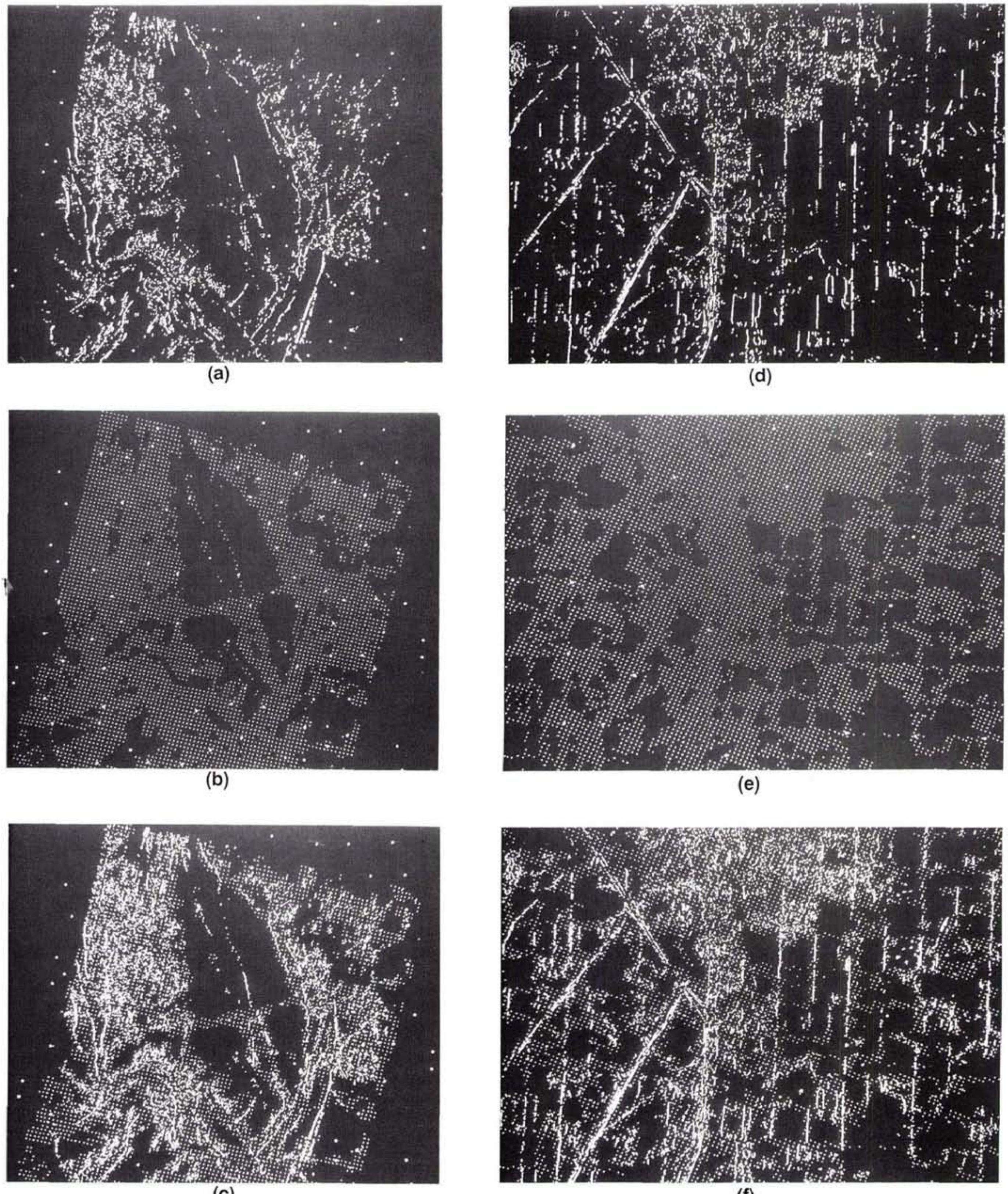

FIG. 5. Sparse DEMS: DNM - (a) Feature-Based, (b) Area-Based, (c) Hybrid.
Red Deer - (d) Feature-Based, (e) Area-Based, (f) Hybrid.

TABLE 4. DNM DEM ACCURACY (RMS METRES).

test points	Stereo Model		
	Feature	Area	Hybrid
26 Match Test Points	16.8	12.1	12.7

TABLE 5. RED DEER -RMS OF PARALLAX (METRES).

	# Matches	RMS of Parallax		
		X	Y	Z
match test points	58	3.70	4.39	3.46
feature-based matches	51484	3.70	4.40	3.39
area-based matches	26463	1.92	2.28	1.76
hybrid matches	77974	4.89	5.81	4.57

TABLE 6. RED DEER DEM ACCURACY (RMS METRES).

Test points	Stereo Model		
	Feature	Area	Hybrid
58 Match Test Points	10.1	8.52	8.90
15 Map Test Points	8.84	7.45	7.95
29 Alberta Land Survey	8.46	4.55	4.82

TABLE 7. ELEVATION ACCURACY OF DEMS (RMS METRES)

	Error Source		
	Satellite	Matching	Combined
DNM	11.7	12.1	16.8
Red Deer	8.2	8.52	11.8

feature locations are not distributed evenly over the entire image (see Figure 2a). For example, a road or river covers a very narrow long piece of the image. The elevations found at feature points must be used to interpolate the elevations over large parts of the image that are void of features. The interpolated elevations are not representative of the true land surface. The other two models use area-based matching which searches on a regular grid over the entire image. Although a complete coverage of elevations points is not found on the entire grid, there is a much more even distribution of matches over the image (see Figure 5). Any features in the image implicitly help the area-based matching method to decide on a match because the feature contains information about a sharp change in image shading.

The feature matcher and the hybrid feature matcher have a higher RMS error in the terrain coordinate calculation due to the following two reasons:

- The feature extraction stage produces edges at a resolution level equal to the input images. The edges are extracted identically from both images, but the position an edge is found at could be incorrect by up to half a pixel. This quantizing effect of edge detection introduces one source of error. This source of error could be reduced by using an edge detector with sub-pixel localization of the edge (Nalwa and Binford, 1986).
- Feature-based matchers are only able to match features at the resolution level at which the features were found. The reason for this is that feature or edge information is discrete. This differs from the area-based model which can localize a match to a sub-pixel resolution level because the image patches being matched are actually representing continuous information.

CONCLUSION

The discussion revealed some flaws in feature-based matching in the domain of satellite images and DEM generation. Edge detection is an intermediate step in the feature matching method which adds an error to the resultant DEM by inaccurate localization of feature positions. Also, the matching stage in the feature-based matching method is not as accurate as area-based matching because features are discrete while the area-based matching uses information which represents continuous data. This means features can only be matched at the resolution at which they were found, but area-based matching operates with sub-pixel accuracy. Of course, if features are found with high precision, this will not affect feature-based matching.

The advantage of feature matching is that image features usually occur where there are changes in ground slope. Areas with abrupt changes in ground slope, known as breaklines, are very important to DEM calculation. Unfortunately, features might not be found over large areas of land surface with a rolling elevation pattern. The feature stereo model will find discontinuities in the elevation map, and perhaps with a better interpolation method this would suffice. However, area based matching will find many of its matches around features on the land surface, and more subtle shading changes will also be used to find elevations. The feature matcher cannot find these subtle shade changes, or, if it does, it cannot match the vast number of them with any degree of certainty. Feature-based matching is likely more suited to the robot vision environment where physical models can be combined with stereo matching to define depth.

The hybrid model of stereo matching used in this experiment performed nearly as well as the area-based model. The hybrid model finds the same even and complete coverage of matches that area-based matching finds, but it is hindered by the less accurate feature-based matches being included in the DEM. In the hybrid model the feature matches used to guide the area matching allow a quicker convergence to the correct matches, although this statistic was not collected. It is doubtful whether all the extra processing of feature matching is required for the hybrid matching method to find its matches.

The area-based stereo matching method has certain advantages in the satellite image domain. There is less intermediate processing of the images and thus less introduction of error into the final result. Area-based matching has the ability to match very subtle features on the land surface because of the context existing in large image patches. Because the image patches used for area-based matching are representations of continuous data, matching can be taken to sub-pixel accuracy. Area-based matching gives an even coverage of matches over the DEM, resulting in less interpolation and a more accurate result.

Many applications for digital elevation models can be found in route planning, major construction developments, and environmental studies. DEMs can add another dimension to geographic information systems. Figure 6 shows the original SPOT image draped on the Dinosaur National Monument DEM.

ACKNOWLEDGMENTS

In January 1989, Applied Terravision Systems (Calgary) and Alberta Research Council launched a Joint Research Venture on the generation of DEMs from stereo SPOT satellite images. The objective of this 16-month project was to develop a DEM gen-

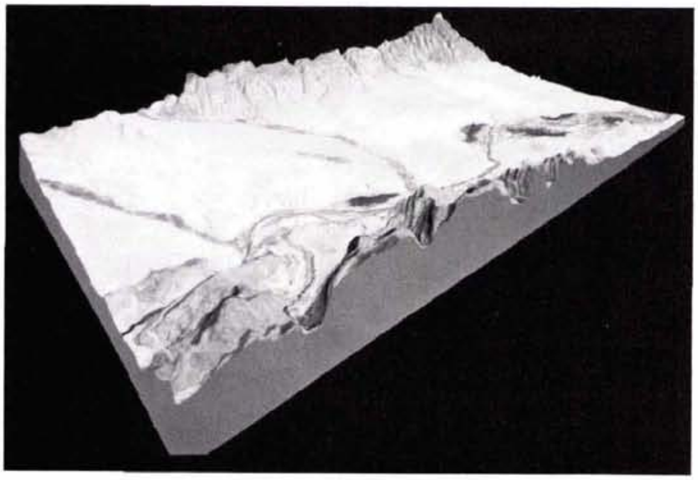

FIG. 6. Dinosaur National Monument DEM.

eration package for enhancing the capability of the LANDSCAN system developed by Applied Terravision Systems. The DEM generation package runs on Sun and Apollo work stations and a two-week turn around time is required to produce a DEM from stereo imagery. Persons from Coles Gilbert Associates and the University of Calgary, Department of Surveying Engineering also participated in this project. All funding for this project was shared by Applied Terravision Systems and the Alberta Research Council, Advanced Computing and Engineering Department. SPOT Image Corp. and the Canada Centre for Remote Sensing provided the test imagery.

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(Received 30 July 1990; accepted 3 October 1990)