POTENTIAL OF USING AUTOMATICALLY EXTRACTED STRAIGHT LINES IN RECTIFYING HIGH RESOLUTION SATELLITE IMAGES

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ABSTRACT

The quick advance in remote sensing technologies provides the ability to acquire high quality metric information. This is achievable by forming the relationship between image coordinates and ground coordinates as 2D and 2D-to-3D transformation models. Most of these models are based on point features. Although point-based transformation models are well developed, it is time-consuming and costly to measure point coordinates manually. In addition, automatic point extraction algorithms especially in satellite images are far inferior in quality. This makes other feature-based transformation models more attractive. Linear features have greater potential than other features not only in automation but also in representation and modelling. This study investigates rectifying satellite images with different resolutions and orientations using line-based transformation models. In addition, the relative relationships between linear features are imposed by incorporating geometric constraints. Straight lines are extracted using an automated linear feature extraction algorithm. Experiments are conducted with different sets of straight lines and their results are reported and analyzed. The research reveals that line-based transformation models provide equivalent results to those obtained using point-based transformation models especially when geometric constraints are forced. In addition, combined point/line-based transformation models were also investigated and the results are similar to those achieved with point or line features only.

KEYWORDS: Satellite images; Rectification; Straight lines; DLT; parallel projection.

INTRODUCTION

Recent high-resolution satellite imaging systems, such as IRS, SPOT5, IKONOS, and QuickBird, have initiated interesting data sources for earth observation. The panchromatic mode of these satellites could reach the accuracy standards for large-scale mapping especially in urban areas. This is achievable through rigorous and non-rigorous transformation models including: the parallel projection transformation model, the extended parallel projection transformation model, and the DLT transformation model. Although significant development has been accomplished in invistigating and analyzing such models (Sadeghian et al. (2004), Shaker et al. (2005), Morgan et al. (2006), Baltsavias et al. (2006)), most of these studies are point-based.

Recently, line-based transformation models have stimulated a great interest in image registration. Several studies have included linear features in image registration and orientation (Lee and Bethel (2004), Schenk (2004), Mulawa et al. (1998), Mikhail and Weerawong (1997)). The advantages of employing linear features in image registration are highlighted in Habib et al. (2004). Linear features add more information, they have higher semantic than point features, and they are easier to detect than point features. Additionally, geometric constraints are more likely to exist among linear features, which eventually improve the adjustment process. Moreover, linear features are represented by segments. Such representation can be delineated easily in digital images either manually or automatically.

Straight lines were used in Habib et al. (2005) to register multi-source satellite images together for change detection applications. The dataset includes IKONOS, KOMPSAT, LANDSAT7, and SPOT images. First, a set of straight lines are manually digitized. Then, the images are registered through the affine and the similarity transformation models. Results disclose that the affine transformation model could be used to register satellite images with narrow angular field of view. In addition, the study revealed that the 2D the similarity transformation model is suitable for applications with low-accuracy standards.

The line-based projective transformation model was used to rectify different satellite images in Barakat et al. (2004). The parallel projective point-based, line-based, and combined point/line-based transformation models are examined in rectifying LANDSAT7, SPOT4, IRS-1D, and IKONOS images. Results for the LANDSAT7, SPOT4, IRS-1D, and IKONOS showed an average Root Mean Squares error (RMS) of 16, 13, eight, and two meters respectively. In all experiments, the combined point/line-based projective transformation model demonstrated approximately the same results as if each feature is used separately. However, the study focused on using the projective transformation model only. The projective transformation model assumes that both the image and ground spaces are planner surfaces and do not consider any elevation variation.

Additional investigations have been conducted to rectify IKONOS images using linear features. The Line-Based Transformation Model (LBTM) was used to model the relationship between object space and image space linear features in Shaker (2004). The principle of the LBTM model is that the line unit vector components of a line segment could replace the point coordinates in the representation of the ordinary 2D and 3D affine and conformal models. Experiments with synthetic and real data were performed. For the real data, a group of 12 Ground Control Lines (GCLs) were established by connecting some GCPs in the data set. A set of 16 ground points was used as checkpoints. An average RMS of several meters in the X and Y coordinates using four to 12 GCLs was observed. Additionally, investigation on image-to-image registration through the LBTM was proposed in Shi and Shaker (2006). In both studies, the researchers reported a significant problem that affects the results significantly due to unit vector representation. They suggested the incorporation of GCPs to solve this problem.

Elaksher (2008) studied the rectification of a single panchromatic IKONOS image using linear features. Different 2D and 2D-to-3D line-based transformation models were developed and analyzed. The research concluded that line-based transformation models provide about 1.5 meter horizontal accuracy for the IKONOS image. However, the study was carried out with manually digitized linear features. In this paper we investigate using automatically extracted linear features, including geometric constraint between linear features, and combing both points and straight lines in the rectification process. The study is carried out with SPOT5, IKONOS, and QucikBird panchromatic images.

METHODOLOGY

Linear Feature Extraction

Since manual linear feature digitization is very expensive and time consuming, automatic linear feature extraction algorithms are of great need. However, the development of such algorithms has been recognized as one of the most challenging tasks in the image processing and computer vision communities. The problem arises as a result of occlusion, noise, weak contrast, and diverse object textures. In this research, we adopt the following lines extraction algorithm. Firstly, the Canny edge detector algorithm, Canny (1986), is executed to extract edge pixels. Secondly, edge pixels are thinned by means of the algorithm presented in Rosenfeld and Kak (1982). Finally, edge pixels are accumulated in corresponding cells of the Hough space, Hough (1962), using the following strategy. For each edge pixel a local line is fitted using its neighbouring pixels. If the local line is accepted, i.e. the total fitting residual is smaller than a predefined threshold, the number of lines in the 2D line parameter space corresponding to this line is increased by one. Given all points that contributed to a certain cell, a nonlinear least squares adjustment model is used to adjust the line parameters. Extracted lines are grouped and joined based on the differences in their parameters. The algorithm is carried out recursively and it terminates when no more lines could be joined.

Line-based Transformation Models

In recent years, linear control features have been adopted to replace point control features. Hence, photogrammetric models need to be expanded to accommodate linear features. In this case, the relationship between one linear feature in object space and its corresponding line in image spaces is derived rigorously using the camera orientation parameters. The will-known 2D line representation is shown in equation 1, (Mikhail et al. 2001). This form is not valid for straight lines passing through the origin. In addition, this representation implies that the line is of infinite length; hence, no specific point is used. In this research the line-based parallel projection (3D affine) transformation model, equation 2, the line-based extended parallel projection transformation model, equation 3, and the line-based DLT transformation model, equation 4, are used. These transformation models are driven from the point-based transformation models as described in Elaksher (2008). Hence, the transformation parameters are the same as those calculated via the point-based models.

$$ax + by + 1 = 0 \quad (1)$$

where x and y are the planemetric coordinates of any point on the line, and a and b are the line parameters.

$$a_1 = \frac{a_2 p_1 + b_2 p_5}{a_2(p_3 z_1 + p_4) + b_2(p_7 z_1 + p_8) + 1}$$
$$b_1 = \frac{a_2 p_2 + b_2 p_6}{a_2(p_3 z_1 + p_4) + b_2(p_7 z_1 + p_8) + 1} \quad (2)$$

$$a_1 = \frac{a_2(p_1 + p_4 z_1) + b_2(p_8 + p_{11} z_1)}{a_2(p_3 z_1 + p_6) + b_2(p_9 z_1 + p_{12}) + 1}$$
$$b_1 = \frac{a_2(p_2 + p_5 z_1) + b_2(p_9 + p_{12} z_1)}{a_2(p_3 z_1 + p_6) + b_2(p_9 z_1 + p_{12}) + 1} \quad (3)$$

$$a_1 = \frac{a_2 p_1 + b_2 p_5 + p_9}{a_2 p_4 + b_2 p_8 + z_1(a_2 p_3 + b_2 p_7 + p_{11}) + 1}$$
$$b_1 = \frac{a_2 p_2 + b_2 p_6 + p_{10}}{a_2 p_4 + b_2 p_8 + z_1(a_2 p_3 + b_2 p_7 + p_{11}) + 1} \quad (4)$$

where p1, p2, ..., p12 are the transformation parameters, a1 and b1 are the line parameters in ground space, a2 and b2 are the line parameters in image space, and z1 is the average elevation of the line in ground space. Equations 2, 3 and 4 emphasize assigning a single height value for each line.

A major advantage of linear features is the existence of many useful geometric relationships between them. These relationships can be identified easily, and corresponding equations are developed as mathematical constraints. These constraints are used to improve the quality and reliability of the rectification outputs. In this research, two geometric relationships are proposed. Equations 5 and 6 are used for parallel lines, like road edges, and perpendicular lines, for example building boundaries, respectively.

$$\begin{bmatrix} a_i - a_j \\ b_i - b_j \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} a_i \\ b_i \end{bmatrix} \begin{bmatrix} a_j & b_j \end{bmatrix} = 0 \quad (6)$$

where ai and bi are the ground parameters for line i, aj and bj are the ground parameters for line j.

Moreover, satellite images, especially in urban areas, contain both points and linear features. This encourages combining both points and linear features in the rectification process of satellite images. In such scenarios, the transformation parameters of both the point-based and the line-based transformation equations are identical. This overcomes carrying more constraint equations between the transformation parameters in the least squares adjustment process as in Barakat et al. (2004). After composing the transformation equation for both line-based and combined point/line-based transformation models, the transformation parameters for each model are computed by the least squares adjustment technique. Inputs to the model are the a and b parameters for both ground and image lines, the elevation value of each line, and approximate values of the transformation parameters.

DATASET DESCRIPTION AND EXPERIMENTS

Dataset Description

Three satellite images covering Al-Moqatam Plateau, Cairo, Egypt are used in this research. The elevation range in the area is about 175m. The first image is a SPOT5 panchromatic image, the second image is an IKONOS panchromatic image, and the third image is a QuickBird panchromatic image. Table 1 summarizes the meta-data provided with the original three images.

Table 1. Meta-data for the SPOT5, IKONOS, and QuickBird satellite images

	SPOT5	QuickBird	IKONOS
Date of acquisition	18 February 2004	7 September 2002	6 February 2003
Pixel size (m)	2.5	0.65	0.98
Latitude of image center (°)	29.96N	30.04N	30.17N
Longitude of image center (°)	31.27W	31.22W	31.24W
Off nadir angle (°)	25.64	14	27.73
Average image azimuth (°)	110	104	126

A set of 12 GPS surveyed points and a block of 1:4500 aerial photos, scanned at 25μm resolution, are used to provide control information. The GPS survey was carried out with two dual-frequency GPS receivers. Once the survey was completed, the GPS baselines were processed in the Trimble® software. Five centimetres planimetric accuracy and nine centimetres vertical accuracy are noticed in the GPS baseline adjustment results. After the GPS survey was completed, the image correspondence of each GPS point is identified manually, tie points are digitized, and the aerial photos are triangulated in the ERDAS IMAGINE OrthoBase® environment. The image triangulation shows an average accuracy of ten centimetres in the horizontal and vertical directions. Such accuracy enables collecting ground control points and lines for the satellite rectification process.

Accuracy of Extracted Lines

In the next step, linear features are automatically extracted through the algorithm presented in section 2.1. The average posterior estimate of the reference variance ($\hat{\sigma}_o^2$) for the end points of each line is computed and used to compute covariance matrix of each line following the procedure described in Mikhail and Ackerman (1976). Lines with $\hat{\sigma}_o^2$ greater than one pixel are eliminated and not used in the rectification processes. Table 2 summarizes the average values for $\hat{\sigma}_o^2$ and the average variances for the parameters of each line. Results in table 2 reveal that the image space accuracy of the extracted linear features are within one pixel. Hence the accuracy of the extracted linear features in image space is comparable to the accuracy to which points can be located in image space. This adds to other advantages of linear features and supports the employment of linear features in rectifying satellite images. Figures 1 through 3 show the automatically extracted straight lines, with $\hat{\sigma}_o^2$ less than one pixel, in the QuickBird, IKONOS, and SPOT5 images respectively.

Table 2. Evaluation of the line extraction algorithm

	SPOT5	QuickBird	IKONOS
No. of extracted lines with $\hat{\sigma}_o^2$ less than one pixel	74	193	102
Average $\hat{\sigma}_o^2$ for end points (pixels)	0.98	1.12	.97
Average σ_a^2 (pixels)	1.21	0.85	1.17
Average σ_b^2 (pixels)	1.02	1.13	0.95

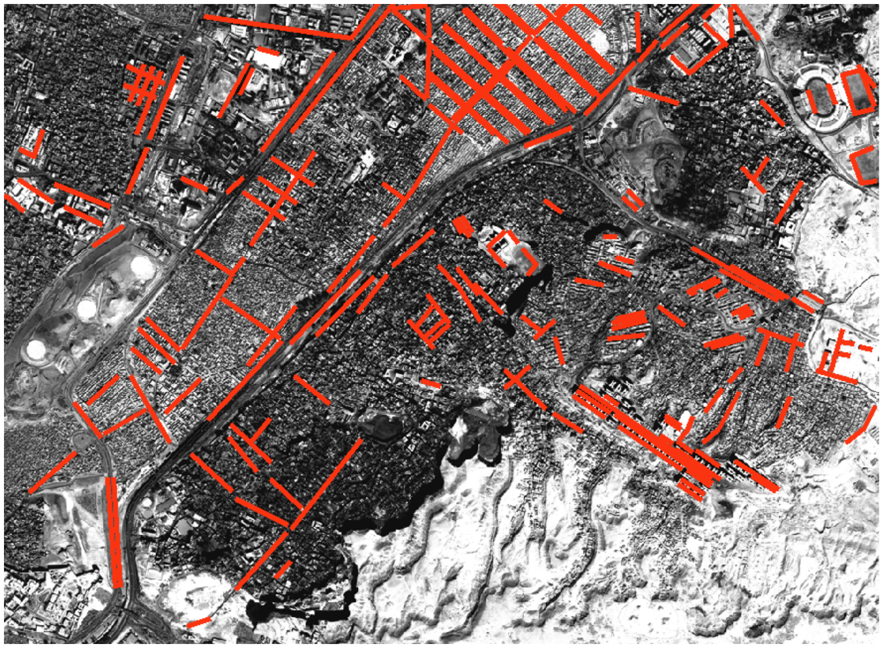

Figure 1. Automatically extracted lines in the QuickBird image.

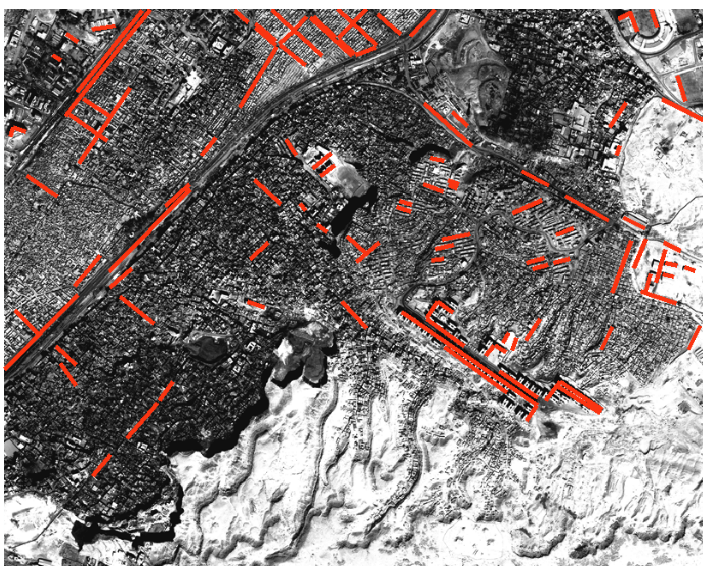

Figure 2. Automatically extracted lines in the IKONOS image.

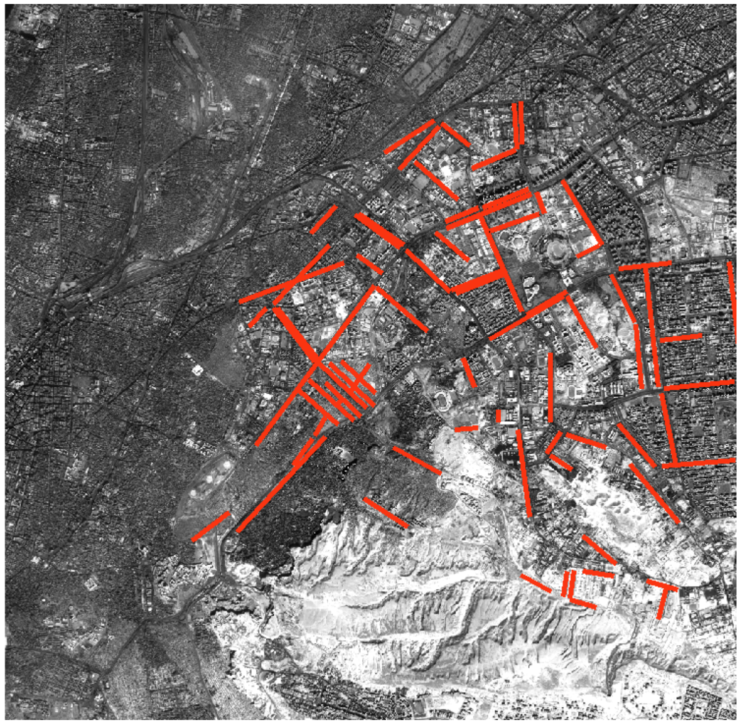

Figure 3. Automatically extracted lines in the SPOT5 image.

Image Rectification Experiments

Four sets of experiments are conducted in this research. In the first set, 40 GCPs are used to compute the transformation parameters for the point-based transformation models. An independent group of 90 check points (CPs) are used to evaluate the results. The image coordinates of the GCPs and the CPs are manually measured in each satellite image and their ground coordinates are computed from the aerial images. The results of this set serve as a reference for comparison with other sets of experiments.

Table 3. RMS results for point-based transformation models (pixels)

	SPOT5	QuickBird	IKONOS
Parallel projection	1.21	1.19	1.21
Extended Parallel projection	1.03	0.95	0.99
DLT	0.81	0.89	0.93

In the second and third sets, the line-based transformation models are examined and analyzed. The second set of experiments are carried out without incorporating the geometric constraints, while in the third set of experiments the geometric constraints are included. Only horizontal straight lines are considered in the rectification process. For each pair of corresponding image/ground line, two observation equations are formed. The transformation parameters are calculated by solving the entire system of observation equations iteratively, due to its non-linearity, with the least squares adjustment technique. Results are evaluated through the RMS of the 90 CPs in figures 4, 5, and 6.

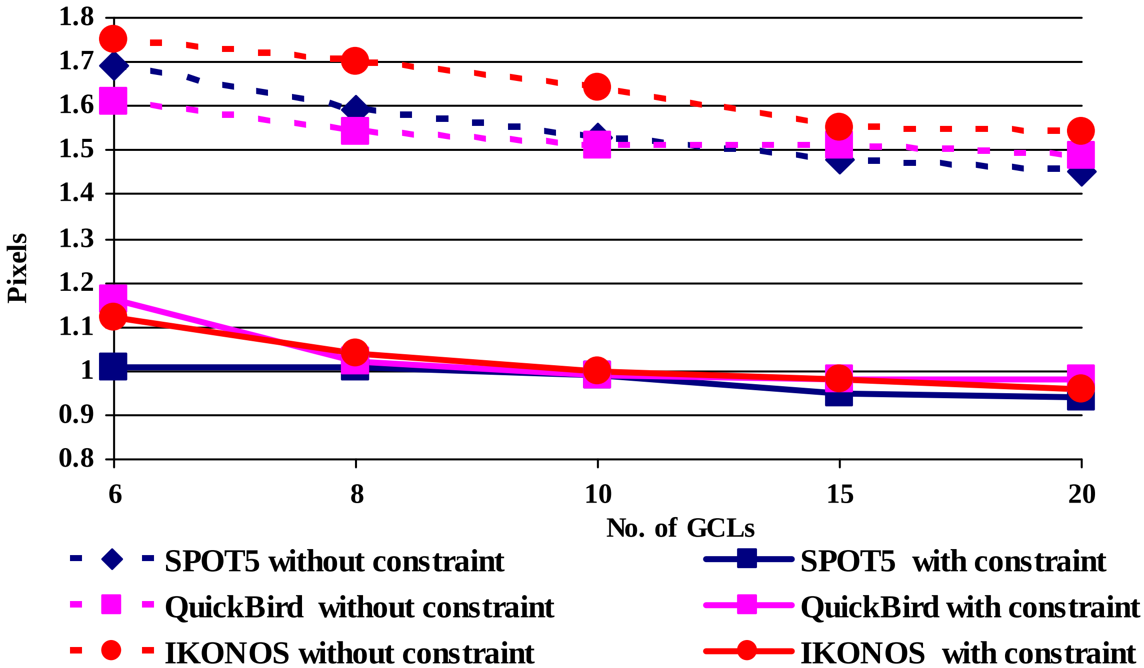

Figure 4. RMS results for the line-based parallel projective transformation model (pixels).

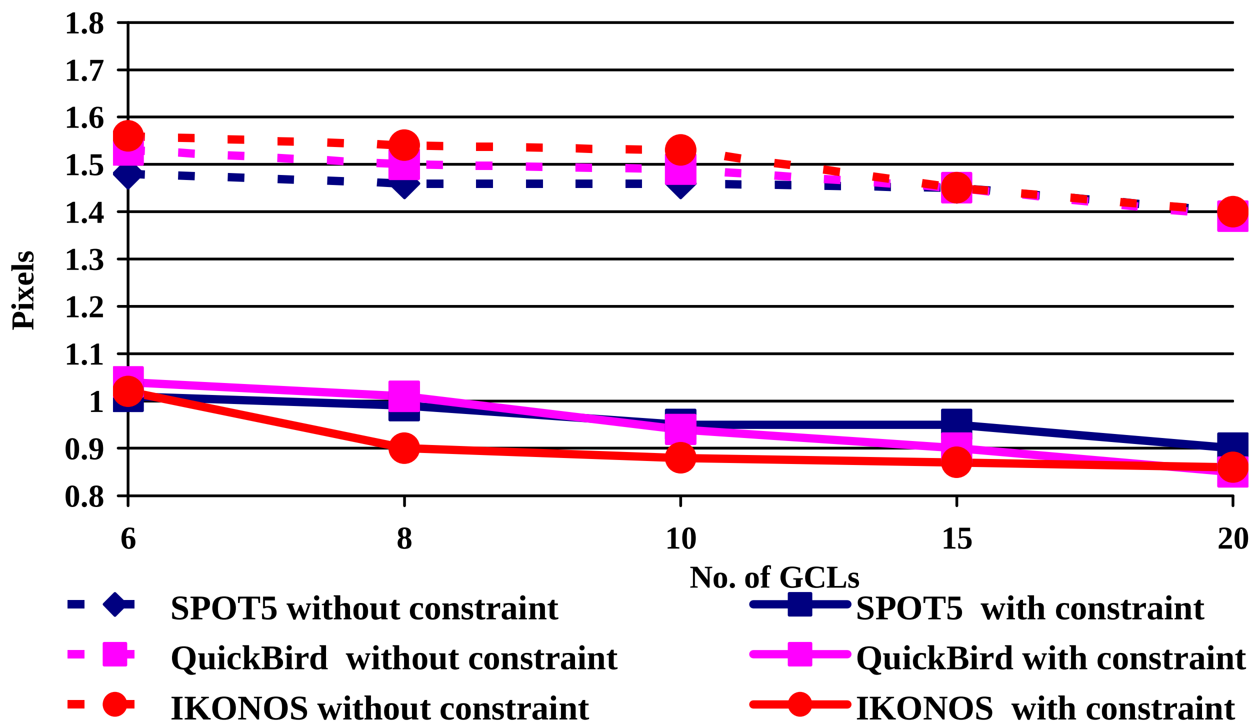

Figure 5. RMS results for the line-based extended parallel projective transformation model (pixels).

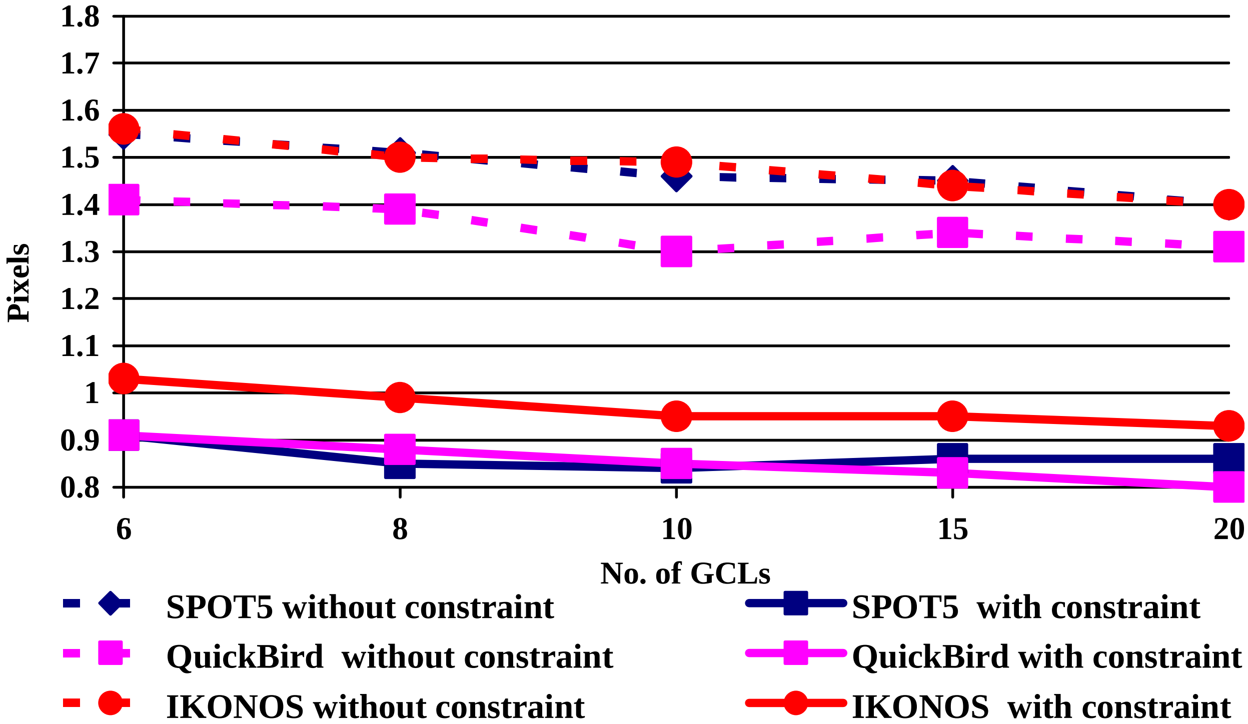

Figure 6. RMS results for the line-based DLT transformation model (pixels).

In the fourth set of experiments, the GCPs are combined with the GCLs to compute the transformation parameters. In this set of experiments, the geometric constraints between the linear features are applied. Table 4 summarizes the RMS for this set of experiments. The computed parameters for the point-, line-, and point/line-based projection transformation models are compared in table 5.

Table 4. RMS results for combined point/line-based transformation models with geometric constraints (pixels)

	SPOT5	QuickBird	IKONOS
Parallel projection	0.99	1.05	1.08
Extended Parallel projection	1.01	1.03	1.02
DLT	0.84	0.93	0.97

Table 5. The parameters of the parallel projection, extended parallel projection, and DLT transformation models (IKONOS image)

	Parallel projection			Extended Parallel projection			DLT		
	Line-based with constraints	Point-based	Line/Point Based with constraints	Line-based with constraints	Point-based	Line/Point Based with constraints	Line-based with constraints	Point-based	Line/Point Based with constraints
p_1	1.136	1.137	1.137	1.134	1.134	1.134	1.136	1.136	1.136
p_2	0.001	0.001	0.001	0.002	0.002	0.002	0.003	0.003	0.003
p_3	-0.087	-0.087	-0.087	-0.084	-0.081	-0.082	-0.0839	-0.0840	-0.0840
p_4	-0.222	-0.201	-0.214	-0.451	-0.398	-0.398	-0.451	-0.398	-0.405
p_5	-0.058	-0.058	-0.058	-0.058	-0.058	-0.058	-0.058	-0.058	-0.058
p_6	1.091	1.090	1.091	1.091	1.091	1.091	1.091	1.091	1.090
p_7	-0.202	-0.202	-0.202	-0.204	-0.204	-0.204	-0.203	-0.203	-0.202
p_8	0.201	0.200	0.200	0.201	0.201	0.201	0.201	0.201	0.201
p_9				$-2\ e^{-7}$	$-2\ e^{-7}$	$-2\ e^{-7}$	$-2\ e^{-7}$	$-2\ e^{-7}$	$-2\ e^{-7}$
p_{10}				$3\ e^{-7}$	$3\ e^{-7}$	$3\ e^{-7}$	$3\ e^{-7}$	$3\ e^{-7}$	$3\ e^{-7}$
p_{11}				$-7\ e^{-6}$	$-6\ e^{-6}$	$-6\ e^{-6}$	$-8\ e^{-6}$	$-6\ e^{-6}$	$-6\ e^{-6}$
p_{12}				$-3\ e^{-6}$	$-2\ e^{-6}$	$-2\ e^{-6}$			

RESULT ANALYSIS

Several remarks are observed from the conducted experiments. Firstly, the presented linear feature extraction algorithm is able to extract sufficient and well distributed linear features. The pixel accuracy of these lines provides high quality and reliable control features for the rectification process. Secondly, the line-based transformation models without constraints demonstrate an average RMS of about 1.7 pixels. Those results are similar to the results obtained in Elaksher (2008) via manually extracted linear features. Thirdly, including the geometric constraints between linear features provides higher accuracy up to half a pixel in most cases. The results are within one-pixel and are comparable to the point-based RMS. For the three satellite images, we can reach one pixel accuracy with 10 GCLs. Fourthly, insignificant differences in the RMS are observed between the results of the line-based parallel projection, extended parallel projection, and DLT transformation models. This is noticed with the inclusion or exclusion of the geometric constraints between the linear features. Fifthly, comparing the parameters in table 5 shows that the differences between the transformation parameters for the parallel projection, extended parallel projection, and DLT are insignificant. The absolute values of p9, p10, and p11 for the DLT and the extended parallel projection models are less than 1e-5. The value of the parameter p12 for the extended parallel projection is also less than 1e-5. Consequently, the differences between the RMS for the parallel projection, extended parallel projection, and DLT transformation models are insignificant. The combined point/line-based transformation models gives similar results to those obtained with either points or lines. Different combinations were tested and the same accuracy is observed.

CONCLUSIONS

Digital photogrammetry has the ability to develop different forms of image rectification algorithms based on points, lines, or areal features. This research investigates the use of line-based transformation models in satellite image rectification. A main advantage of linear features is the ability to automate the entire rectification process. This is practically important due to recent advancements in automating line extraction algorithms. These algorithms are showing major progress in extracting meaningful and dependable linear features, unlike point detection algorithms. Without loss of generality, we propose the use of straight lines, and attempt to utilize them in a similar manner as point features. The developed line-based transformation models are tested on SPOT5, IKONOS, and QuickBird images for an area with an average relief of 175 meter. Ground reference is provided from high-resolution large-scale aerial photos. However, other sources of control information for linear features could be existing GIS information, large-scale maps, or GPS surveys. Straight lines are automatically extracted from the satellite images with a pixel accuracy. Ground to image relationship is established through line-based parallel projection, extended parallel projection, and DLT transformation models. Since these transformation models take into account the elevations of the straight lines, only horizontal lines are considered. In addition, geometric constraints are used to enforce the relationship between parallel and orthogonal straight lines. The experiments demonstrate that the same accuracy is achieved with either manually digitized or automatically extracted linear features. In addition, in order to achieve the same accuracy as the point-based transformation models, we need to include the geometric constraints between linear features. Results recommend using reasonable number of GCLs to achieve an RMS of one-pixel. Furthermore, the line-based parallel projection, extended parallel projection, and DLT transformation models provide comparable results. The combined point/line-based transformation models are also investigated and similar results to those obtained with either points or lines are observed.

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