Image-to-image registration is a prerequisite step for many important applications in different disciplines. In the field of remote sensing, the launch of new high-resolution satellites raises the need for a fast and dynamic technique for image-to-image registration in order to obtain full benefit from these satellites, especially for applications such as Earth monitoring and map updating. This paper presents the utilization of the Line-Based Transformation Model (LBTM) for image-to-image registration following the successful use of the LBTM for the rectification of high-resolution satellite images using linear features as control features.

The developed model is similar in structure to some other point-based transformation models. However, line segments on linear features are used first to recover the model transformation coefficients. Based on the recovered coefficients, the whole image is registered using the ordinary point-based form of the model. Line segments on linear features have been chosen due to their existence in images regardless of the type of the land-use covered by the images and because line segments can be easily extracted from the images. Moreover, control points may not exist or a complete match between points on images cannot be achieved. Different forms of the developed model are discussed and results using different high-resolution satellite images from both IKONOS and QuickBird satellites are presented. The experimental results of the new technique show high integrity of the new model and indicate that image-to-image registration by LBTM is reliable.

1. Introduction

Image-to-image registration in its simple term is the process of transforming each pixel on an image (master image) to its corresponding pixel in another image (reference image). This process can be performed by selecting enough points in one image and the corresponding points in the counterpart image. Then, by applying a transformation function, the transformation coefficients can be recovered and the master image can be resampled to the reference image. Several approaches have been proposed for image-to-image registration (Ton and Jain 1989, Chen and Lee 1992, Brown 1992, Boardman et al. 1996). However, these approaches face several challenges because they are driven by linking points in the master and the reference images and under many circumstances accurately identifying discrete conjugate points may not be possible. This is because images may be taken from different
sensors, and the radiometric and geometric properties of the images may differ based on imaging methodology and conditions (Habib and Alruzouq 2004). Moreover, the number of the identified points is often not sufficient and the points distribution is not always uniform (Chen and Lee 1999).

Consequently, other features such as linear features have been used as control features in order to cope with the misidentification problem of the points and to register images accurately. Linear features have been chosen due to several factors, which can be summarized as follows: (a) Linear features can be easily identified in the image by many automatic extraction tools. (b) It is easier to implement an automatic feature extraction algorithm instead of extracting point features, since linear features have more attributes than point features. (c) Information from linear features can be used even without a complete match between image and object linear features. (d) Linear features can be presented by either a set of points on the feature or a set of feature descriptors, which means that many geometric constraints and additional information can be contributed to the solution (Kanok 1995). Finally, (e) linear features add more information, increase redundancy, and improve the geometric strength of adjustment (Habib et al. 2003).

Dare and Dowman (2001) introduced an improved model for feature-based registration. The model integrates multiple feature extraction and feature matching algorithms to identify common features in the multi-sensor images. As a result, the number of accurate tie points that can be derived, can be significantly increased. The derived tie points are used with a selected transformation function and a resampling method is applied to register the master image. The model was tested with small and large images and the results show that the model is working significantly well. However, Dare and Dowman (2001) found that increasing the number of the tie points did not always improve the accuracy of the results and more accurate registration results can be achieved when a more appropriate transformation function is used.

Chen and Lee (1999) proposed a strategy to initialize the registration using linear feature matching. This strategy, which comprises feature extraction, feature description, similarity assessment and matching, was tested between airborne scanner image and aerial photo for rolling terrain, and the experimental results prove that the proposed scheme is reliable. However, uncertainty about the reliability of the scheme was raised for images covering rugged terrain and large-scale images.

Habib and Alruzouq (2004) established a new approach for automatic image registration. The new approach used end points of straight lines as feature primitives and the Modified Iterative Hough Transform as the matching strategy to estimate the parameters involved in the transformation function. The established approach has two advantages: it does not need complete correspondence between the straight lines in the master and the reference images and it allows for simultaneous matching and parameter estimation. Affine and 2D similarity functions have been used as the transformation function and the optimum sequences for the parameter estimation based on line segment orientation and various regions within the image have been derived. Using real data sets, the results proved the reliability and feasibility of the proposed approach noting that the new approach works well only if the transformation function is valid.

This paper introduces a new model ‘The Line-Based Transformation Model (LBTM)’ as a transformation function that could incorporate with any of the previous techniques or serve for a new standalone technique. Using the new model,
extracted and matched linear features do not need to be converted to tie points. Instead, line segments on linear features can be used directly in one step without converting the matched features to points to recover the model coefficients. Details of the new proposed technique are discussed in the following section.

2. The Line-Based Transformation Model (LBTM)

The LBTM is initially established for high-resolution satellite image rectification to circumvent the complexity of the time-dependent mathematical models and to simplify the relationship between 2D image and 3D object spaces (see the development of the model and related subject in Shaker 2004a,b). The underlying principle of the new model is that unit vector components of line segments on linear features can represent the relationship between image and object spaces. Based on that, the point coordinates in the representation of the ordinary eight-parameter affine model are replaced by the line unit vector components of a straight-line segment on the linear features. This relationship has been proved mathematically and experimentally by comparing the values of the coefficients calculated by the LBTM form and the ordinary point-based form.

Generally, the LBTM is used to calculate the model coefficients by the aid of linear features. Then the recovered coefficients of the LBTM are substituted in the corresponding point-based form to transform the whole image. Any two points along a line segment could be measured in image and object spaces to calculate the line unit vector components. The two measured points on the line segments in image and object spaces are not required to be conjugate points, but the line segments they lie on are required to be segments of conjugate lines.

In this paper, we introduce the same concept to present the relationship between master and reference images in order to recover the model coefficients. In this case, the LBTM will be used to present the relationship between the 2D master and reference images. Figure 1 shows the procedure of the process of image-to-image registration.

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**Figure 1.** Procedures of the image-to-image registration process.
registration. Two different forms of the LBTM are introduced, 2D affine LBTM and 2D conformal LBTM. The two forms have the same structure as 2D affine and 2D conformal point-based models. Adopting these structures allowed the use of the calculated model coefficients in the ordinary point-based model forms and the direct comparison between the results from the developed LBTM and the existing models. The two forms of the model are as follows:

Two-dimensional affine LBTM:

\[ a_x = C_1 A_X + C_2 A_Y + C_3 \]  
\[ a_y = C_4 A_X + C_5 A_Y + C_6 \]

where \((a_x, a_y)\) are the unit vector components of a line segment in the master image coordinate system, \((A_X, A_Y)\) are the unit vector components of a corresponding line segment in the reference image coordinate system, and \(C_1,\ldots,C_6\) are the model coefficients.

The unit vector components in both master and reference image coordinate system can be calculated from any two points on the line segment as follows:

\[ a_x = \frac{x_2 - x_1}{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}}, \text{ and } a_y = \frac{y_2 - y_1}{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}} \]

\[ A_X = \frac{(X_2 - X_1)}{\sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2}}, \text{ and } A_Y = \frac{(Y_2 - Y_1)}{\sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2}} \]

where \((x_1, y_1), (x_2, y_2)\) are coordinates of any two points on the line segment in the master image coordinate system, and \((X_1, Y_1), (X_2, Y_2)\) are coordinates of any other two points on the corresponding line segment in the reference image coordinate system.

Two-dimensional conformal LBTM:

\[ a_x = C_1 A_X - C_2 A_Y + C_3 \]
\[ a_y = C_2 A_X + C_1 A_Y + C_4 \]

where \((a_x, a_y)\) and \((A_X, A_Y)\) are as defined above, and \(C_1,\ldots,C_4\) are the model coefficients.

It is important to mention that the two points defining the unit vector of the line segment in the master and the reference images are not conjugate points but the line segments they lie on are conjugate lines. Moreover, the coordinate system of the master and the reference images could be any Cartesian coordinate system (local or geo-referenced coordinate system). In this paper, we will refer to the line segments implemented in the LBTM to recover the model coefficients by the Ground Control Lines (GCLs). A unique solution for the coefficients of the new model could be calculated by using three and two GCLs for 2D affine and conformal LBTM, respectively. If the number of observations available (number of GCLs) is more than the minimum amount, then a least squares adjustment is used.

As mentioned above, the forms presented for the LBTM are similar to the ordinary forms of the point-based models, with the only difference being the use of line unit vector components instead of point coordinates in order to calculate the
Comparing the coefficients recovered from the LBTM using GCLs and coefficients of the corresponding point-based models using point coordinates shows complete matching between coefficients related to scale and rotation (coefficients $C_1$, $C_2$, $C_4$, $C_5$ in the 2D affine LBTM form and $C_1$, $C_2$ in the 2D conformal LBTM form) and big difference in values of the coefficients related to the translation (coefficients $C_3$, $C_6$ in the 2D affine LBTM form and $C_3$, $C_4$ in the 2D conformal LBTM form). This is because the unit vector is not a unique representation of a straight line as it can represent the line in question and an infinite number of parallel lines.

This problem was addressed in Shaker (2004a,b), and is solved by using a single point to recalculate the translation coefficients. Based on that, the coefficients related to scale and rotation are defined by using GCLs, and the remaining two translation coefficients are recovered by using a single point. After recovering the model coefficients, the ordinary point-based form of the model is used to transform the whole image. The following section presents experimental tests using several real datasets from two different satellites to validate the model efficiency.

3. Experimental evaluation of the LBTM

3.1 Data sets

Both synthetic and real data sets have been used to check the validity and applicability of the new model for image-to-image registration. Here, we refer only to the experimental work using real data sets from two different satellites, IKONOS and QuickBird, since the results of the synthetic data were presented in another publication (Shaker 2004a). The data sets include three IKONOS images for Hong Kong (Hong Kong, China), Melbourne city (Australia), and Zagazeg city (Egypt), and one QuickBird image for Fayoum province (Egypt). A number of ground points, which are used later as checkpoints to verify the results of the new model, have been observed for each dataset by the fast static GPS technique. Most of the points observed are road intersections, intersections between roads and canals or well-known features. The GPS coordinates of each point were determined and corrected by post processing software. Coordinates from GPS were provided in WGS84 Datum and UTM projection. The accuracy of the point observed by GPS is less than 5 cm in $X$ and $Y$ directions. The accuracy of the identification of the points on the image is about half pixel. Details of the characteristics of each dataset are presented in table 1.

Ideally, the performance of the LBTM should be tested by using different images taken from different sensors to cover the general case of image-to-image registration. However, such data sets are not available, and therefore, data sets have been arranged as follows. Each data set consists of master and reference images. The master image is the image delivered by the satellite vendor and the reference image is the master image rectified using a polynomial function after removing the relief displacement, if any, by projecting the ground coordinates to a compensation plane. The only exception is for the Melbourne data set when we did not have an access to the image and we worked only with the coordinates of the observed points. The test was used in this way mainly because of the lack of the data. However, this case is similar to a real case when different images captured in different epochs of time from the same sensor are registered to one geo-rectified image, for instance for monitoring purposes.
As was presented in Shaker and Shi (2003) and using the same data sets described for Hong Kong, Zagazeg and Fayoum, the study showed that polynomial models can be effectively used for image rectification after taking into consideration different factors that may affect the results such as the satellite angle of view and type of terrain. The three different cases have been investigated to study the effect of the previous factors. The results showed that ground coordinates should be projected to a compensation plane in case of working with off nadir images taken for undulated terrain (case of Hong Kong data set). However, the ground coordinates can be used directly without being projected to a compensation plane in case of using off-nadir images covering flat terrain (case of Zagazeg data set) or in case of working with nadir images covering undulated terrain (case of Fayoum data set).

Moreover, Shaker and Shi (2003) found that different orders of polynomials could be used but second-order polynomials was found sufficient for accurate image rectification after abridging the relief displacement problems. The main achievement from using second order polynomials is that it does not need a large number of GCPs like higher orders. In general, accuracy of about 1 m could be achieved using a moderate number of GCPs (from 6 to 12 GCPs) and no significant improvement in the total RMS errors was recorded when increasing the number of the GCPs more than that. The study also concludes that the most important factor in 2D rectification is the quality of the GCPs rather than quantity. More details about the accuracy level of the reference images can be found in Shi and Shaker (2003), Shaker and Shi (2003), Shaker et al. (2005), Hanley and Fraser (2001) and Fraser et al. (2002).

A number of line segments on real linear features have been digitized on the master and the reference images to be used as GCLs for the recovery of the coefficients of the LBTM. Figure 2 shows the distribution of the line segments of the GCLs and the checkpoints for all data sets. Figure 3 presents the dislocation between two conjugate line segments on the master image and the real location on the reference image (in this case, the master and the reference images are presented in the same coordinate system). Coordinates of any two points along each line segment of the GCLs on the master and the reference images are determined and the

<table>
<thead>
<tr>
<th>Specification</th>
<th>Hong Kong</th>
<th>Melbourne</th>
<th>Zagazeg</th>
<th>Fayoum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite Mode</td>
<td>IKONOS</td>
<td>IKONOS</td>
<td>IKONOS</td>
<td>QuickBird</td>
</tr>
<tr>
<td>Coverage area (km²)</td>
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<td>7.0 × 7.0</td>
<td>11.16 × 11.09</td>
<td>17.07 × 18.25</td>
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<td>N/A</td>
<td>0.88</td>
<td>0.61</td>
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<tr>
<td>Elevation range (m)</td>
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<td>50</td>
<td>10</td>
<td>120</td>
</tr>
<tr>
<td>Coordinate system: Master image</td>
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<td>Local (pixel-line)</td>
<td>WGS 84 UTM</td>
<td>WGS 84 UTM</td>
</tr>
<tr>
<td>Reference image</td>
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<td>WGS 84 UTM</td>
<td>WGS 84 UTM</td>
<td>WGS 84 UTM</td>
</tr>
<tr>
<td>Number of GCLs</td>
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<td>12</td>
<td>40</td>
<td>22</td>
</tr>
<tr>
<td>Number of checkpoints</td>
<td>38</td>
<td>48</td>
<td>13</td>
<td>28</td>
</tr>
</tbody>
</table>
unit vector components are calculated. Table 1 shows the number of the GCLs digitized for each data set.

4. Results and analysis

As introduced above, each data set comprises a master image that needs to be transformed to the reference image. The coordinate system for the master image of different data sets is varied from local image coordinate system (for Zagazeg and Melbourne images) to WGS84 UTM coordinate system (for Hong Kong and Fayoum images), as table 1 shows. In all cases, the procedure of the registration process using both 2D affine and conformal LBTM followed the following steps: (a) digitizing the GCLs in the master and the reference images, (b) calculating the unit vector components of the GCLs, (c) determining the coefficients of the LBTM using the GCLs, (d) correcting the calculated translation coefficients by the aid of one
point, and finally, (e) substituting the coefficients calculated from the LBTM forms to the corresponding point-based forms to register the whole image. Tests have been conducted using the real data sets and results are summarized and presented in figure 4 in terms of RMS errors of the independent checkpoints in the $X$ and $Y$ directions.

From the results obtained, it is obvious that the new technique worked well in all of the experiments. In most of the cases, the investigation shows that applying different configurations of the control straight lines indicates that the inclination angle (the angle in the $XY$ plane) of the GCLs does not significantly affect the accuracy of the results whereas the distribution of the GCLs on the area covered by the image may affect the results. This is similar to the case when polynomial models and GCPs are used for image registration. In that case, the quality of the results of the registration process is based not only on the polynomial order, image angle of view, and number of GCPs but also on the distribution of the GCPs on the image. Therefore, the results presented in figure 4 are based on well-distributed GCLs.

The investigation also shows that there are no considerable differences in the overall accuracy of the results obtained by applying the 2D affine LBTM and by applying the 2D conformal LBTM. However, the results obtained using the 2D conformal LBTM are sometimes more consistent than the results from applying the 2D affine LBTM.

Based on several studies which have been conducted to compare the manner the affine and the conformal transformation models handle errors, especially for the interior orientation process in photogrammetry (see Fryer 1993, Fraser 1982), it has been found that the affine transformation distributes any observation error consistently amongst all other observations and therefore the apparent size of any

Figure 3. Dislocation of linear features on the master image. The solid lines show two line segments on linear features in the Hong Kong master image, and the dashed line shows the correct location of the corresponding line segments digitized and overlaid onto the master image from the reference image.
observation error is minimized. However, they found that the relative shape and the geometry of the image are distorted after the transformation process. On the other hand, conformal transformation redistributes any observation error in a less complicated way and thus observations may have larger residuals but conformal transformation reserve the relative shape and the image geometry better than in case of using the affine transformation.

Back to the use of the LBTM and based on the previous discussion, errors of the GCLs observed in both master and the reference images are handled in the same way, resulting in better registration accuracy.
manner as in case of using the ordinary affine and conformal transformation models. Using the form of the 2D affine LBTM, the observation errors are equally distributed in all observations and the residuals of the observations is minimized. In this case, better results from the transformation process could be obtained but only in case of having systematic errors, which is a consistent error on the image and the redistribution of the error by using the affine transform will not significantly affect the results. However, in case of any random errors due to misidentification of one or more of the observations (in this case the GCLs), the 2D affine LBTM will distribute the random error on all other observations and the final results will be affected. As a result, the relative shape and the image geometry will be distorted and the overall accuracy will be declined.

A closer look at figure 4 indicates that increasing the number of GCLs seems to improve the accuracy of the results in most of the cases by using the 2D affine LBTM. However, a key feature established from these results is the accuracy of the GCL itself. The higher the accuracy of the GCL is, the better the results that can be achieved. This is obvious from the results shown in figure 4(a) when there is a disturbance in the accuracy of the results in some cases due to the accuracy of the GCLs. One example from the figure can be seen when increasing the number of the GCLs from 24 to 28, the accuracy of the results decreases. Further investigation on the quality of the GCLs digitized on the image shows that the GCLs number 25, 26 and 28 are not digitized accurately because they are located in very shadowy areas due to very high buildings or some hills surrounding them. Consequently, the results achieved by using the 2D affine LBTM are significantly affected.

Conversely, applying the conformal form to the same dataset gives more consistent results because the results were not affected by the random errors as in the previous case. As introduced above, the random errors were not distributed to the other observations in the same manner like in the affine transformation and thus the relative shape and geometry of the image are reserved after the transformation process. Generally, the previous results should not be constructed as indicating that the conformal form is always better than the affine form of the LBTM but the results indicate that conformal LBTM form could give better results if there are some random errors in the observations of the GCLs. However, the affine form could present better results if only systematic errors existed. This is obvious from the results obtained from the Fayoum QuickBird images when only systematic errors are exist and random errors are not recorded.

Generally, the investigation shows that the accuracy of the results was not changed significantly when the number of the GCLs exceeds a certain quantity. These numbers were found to be ranged between 8 and 16 GCLs. It is worth mentioning that this is the case only when GCLs having the same weight of accuracy are used (case of no random errors in the observations are recorded). The results also indicate that the accuracy of the registration of nadir or near-to-nadir images (such as Melbourne and Fayoum images) is found to be slightly better than the accuracy of the registration of off-nadir images (such as Hong Kong and Zagazeg images). This could be because of the distortion in the image due to relief displacement or due to inaccurate identification of the GCLs which could have occurred because of the sensor inclination angle of view and shadows. In all cases, an accuracy of less than 2 m can be achieved using a moderate number of GCLs and the LBTM. These results are very encouraging and comparable to those obtained from using GCPs, keeping in mind that the reference image has already an initial
error of about 1 m from the pre-rectification process as was explained in the Data sets section.

5. Conclusions

This paper presents the use of the new LBTM for image-to-image registration. The new model introduces the relationship between master and reference images using unit vector components of line segments of straight lines on linear features. The line segments may not be conjugate segments but the straight lines they lie on are conjugate lines. Unit vector representation, which can be obtained from any two points along straight-line segments, was chosen because vectors are always available and can be easily defined and extracted from images. The LBTM is presented in this paper in two forms: (a) 2D affine LBTM and (b) 2D conformal LBTM. The developed model is used to calculate the model coefficients by the aid of linear features. Then the recovered coefficients of the LBTM are substituted in the corresponding point-based form to register the whole image. The model is simple because it is linear in the unknowns to be determined and does not require any initial approximation values.

Several experiments have been conducted using real datasets and the results show that both forms of the LBTM are applicable for image-to-image registration of high-resolution satellite imagery. In particular, the results reveal that an accuracy of better than two pixels can be achieved using a moderate number of GCLs and the LBTM. These results were for the data sets presented under the conditions explained in this paper. It is important to mention that the form of the LBTM presented in this paper does not accommodate the effect from relief displacements due to the variations in terrain elevations and sensor angle of view. Also the performance of the model can be further assessed by using completely independent overlapping imagery. It is expected that the LBTM presented in this paper and its other forms are likely to gain the interest of the user community of high-resolution satellite imagery, after completing the assessment of the model, because it could be used for several applications such as map updating, change detection, data fusion, and GIS applications.

5.1 Future work

In future studies, the general case of using different images from different sensors will be investigated for image-to-image registration using the LBTM. The effects of the variations of the terrain elevations of the area covered by the images, and the sensor inclination angle of view on the performance of the model will also be investigated. Moreover, the use of different forms of the LBTM will be presented to cope with the shortcomings from any of the above-mentioned effects.

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