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A generic framework for image rectification using multiple types of feature

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ABSTRACT

In photogrammetry, the traditional image matching and precise rectification is mainly based on point features, which are simple, intuitional and accurate. In many cases, however, it is difficult to acquire accurate ground control points in the areas where cross points and corners are not available, thus the point-based precise rectification is unfeasible. On the other hand, features such as straight lines, free-form curves and areal regions are usually more stable than point-based features and can be utilized to cope with the problem of missing points and to register image accurately. In this paper, a generic framework for image precise rectification using multiple features, including points, straight line segments, free-form curves and areal regions is proposed. Firstly, a generic framework for image rectification using multiple features is established based on the generalized distance, which differs for different types of features. Secondly, a robust and smooth Hausdorff distance is proposed for curve-based and area-based geometric correction. The continuity and derivability of the novel Hausdorff distance makes it possible to minimize the distances via gradient descent approaches. Thirdly, the generalized distance is specified by the existing point-based and straight line-based distances and the suggested curve-based and area-based distance. Finally, uniform error equations are integrated into the geometric correction models based on multiple features. The experimental results show that the generic framework is reliable for image rectification, and can be applied in multi-source images (SAR and optical image).

1. Introduction

In traditional photogrammetric operations, image precise rectification is performed through a point-based approach, where evenly distributed ground control points (GCPs) are used to estimate the parameters of the imaging model (e.g. exterior orientation parameters of rigorous sensor model). Although point-based image rectification is simple, intuitional, accurate and fast, it is not always the best choice to use point-based approaches when evenly distributed GCPs are unavailable. For instance, point-based registration, which is generally built on area-based cross-correlation, usually requires spatial resampling when the resolutions of the reference image and the source image are different (Behling et al., 2014; Lemoine and Giovalli, 2013; Chen et al., 2013). Additionally, it is difficult to acquire accurate GCPs when cross points and corners are not distinguishable, e.g. in desert district or in SAR image, and a single pixel may be unstable in multi-sensor and/or multi-temporal remotely sensed images, which makes it impossible to obtain the corresponding points automatically. Furthermore, since topographic maps are usually the source of controls for rectification of remotely sensed images, points, such as road intersections, which are easily identifiable on maps are commonly used. Problems in using these points include insufficiency of points, poorly defined or inadequately distributed intersections (Masry, 1981; Ajayi, 1993). Nevertheless, many other features, including straight lines, free-form curves and areal regions, can be applied to cope with the misidentification problem of points. Compared to points, other features can be easier to obtain since man-made objects include a lot of linear curves especially straight lines. Also natural objects like river bank lines and coast lines as well as vegetation boarders offer good possibility to extract diverse features (Heikkinen, 2002).

Among these features, straight line has been extensively discussed for years, and many straight-line-based approaches are suggested (Liu et al., 1990; Schenk, 2004; Shaker, 2004; Zhang et al., 2008; Teo, 2013), including some automatic matching approaches (Habib et al., 2003a; Long et al., 2014; Ok et al.,

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2012). The reports about areal regions and areal polygons, however, are much fewer. Dowman and Dare (2000) and Dare and Dowman (2001) introduced an automatic approach of feature-based registration, which yields a large set of tie points distributed across the master and slave images. However, the rectification is directly performed using the tie points, and the accuracy is limited (the RMS residuals of checkpoints in a full scene are more than 10 pixels). Ji et al. (2000) proposed a robust linear least-squares estimation of camera exterior orientation using multiple geometric features (points, lines, and ellipses), and Zhang et al. (2011) proposed a method of relative orientation based on multi-features (points, straight lines, and circular curves), but the irregular shapes were not included. Only recently, areal polygon is considered (Long and Jiao, 2012).

For a long time, straight line and free-form curve are collectively referred to as “linear features”, and they can be used in various photogrammetric operations, such as: space intersection, space resection, and triangulation (Mulawa and Mikhail, 1988). Line Photogrammetry (Zielinski, 1992; Tommaselli and Tozzi, 1996; Bartoli and Sturm, 2005; Van Den Heuvel, 2001; Tommaselli, 2012) and Generalized Point Photogrammetry (Zhang and Zhang, 2005; Zhang et al., 2008) have been developed by establishing the photogrammetric observation condition equations of the linear features. In general, most of the existing approaches are based on the concept of fitting the linear features with analytical equations. Zhang et al. (2008) mentioned that for exterior orientation, the space curves could be arbitrary free form linear features as long as they can be represented by a series of connected points, and the disparity between the observed image feature and the projected space feature would getting smaller and smaller during iterations, but the iteration details of point series were not provided. Consequently, in order to successfully apply feature based measuring methods the choice of right feature model (line Habib et al., 2003b, b-spline Gruen and Li, 1997, cubic splines Lee and Yu, 2009, etc.) is crucial. If a wrong model is chosen, the image observations on selected feature model can be fit well, but the object may not be precisely presented, which may lead to ambiguity in object reconstruction (Heikkinen, 2002).

The contribution of this paper includes two aspects: (1) a robust and smooth Hausdorff distance is developed to measure the distance between free-form features; (2) a generic framework for image rectification is established, and together with the conventional point based distance, the existing straight line based distance and the proposed free-form feature based distance, different types of features can be applied to rectify the remotely sensed image precisely. Specifically, all kinds of control features will be integrated into a generic feature based imaging model, where the free-form curve and areal region are represented as point sets instead of analytical equations. To evaluate the distance between features, the Hausdorff distance (Huttenlocher et al., 1993) is introduced. However, the original Hausdorff distance is not differentiable as its function involves several “max” or “min” operators. Also, it is not robust to outliers because the outliers may significantly affect the distance due to the operator of “max” (Dubuisson and Jain, 1994). Therefore, a robust and smooth Hausdorff distance (RS-HD) is proposed to involve the distance between features into the process of optimizing imaging model.

2. Generic framework for image rectification

2.1. Mathematical notation

In this paper, two conjugate features from the image space and object space are considered. The features are represented as point sets, and the following notations are used in this paper:

- $S_A \subseteq \mathbf{R}^2,\ S_B \subseteq \mathbf{R}^3$—the image space and object space,
- $A \subset S_A,\ B \subset S_B$—a feature in image space and a feature in object space,
- $N_A,\ N_B$—number of points of image feature and object feature,
- $f(\cdot,\mathbf{t}) : S_B \to S_A$—projection of a point from the object space to the image space, where $\mathbf{t}$ is the set of parameters of the transformation,
- $B_\mathbf{t}$—a feature in image space projected from the object feature B point-wisely under a transformation of $f(\cdot,\mathbf{t})$,
- $\|a,b\|$—the Euclidean norm of point a and point b,
- $h_{rs}(A,B_\mathbf{t})$—the directed distance from feature A to feature $B_\mathbf{t}$,
- $d(a,B_\mathbf{t})$—the distance from point a to feature $B_\mathbf{t}$,
- $\rho(A,B_\mathbf{t})$—the generalized distance from feature A to feature $B_\mathbf{t}$, which can be either a scalar or a vector.

2.2. Point-based imaging model

The classic imaging model is used to create the relationship between the three-dimensional spatial coordinate of ground point and plane coordinates of the corresponding image point, and in general, the generic model can be expressed as formula (1):

$$\begin{cases} f_x(x,y,X,Y,Z,\mathbf{t}) = 0 \\ f_y(x,y,X,Y,Z,\mathbf{t}) = 0 \end{cases} \tag{1}$$

where $\mathbf{t} = (t_1,t_2,\ldots,t_n)^\top$ denotes the n parameters of imaging model of the sensor, (x,y) denotes the coordinates of GCPs in image plane, (X,Y,Z) denotes the coordinates of GCPs in object space.

At present, the commonly used imaging models include rigorous sensor model, affine model, polynomial model, Rational Function Model (RFM), etc. All these models can be expressed as formula (1), and the method proposed in this paper can be used for all kinds of imaging models. The following Section 2.3 describes the process of establishing the error equations using diverse Ground Control Features (GCFs).

2.3. Feature-based imaging model

A GCF is consisted of a ground feature B and an image feature A which are conjugate. The ground features are usually collected from the reference image (orthorectified image) with the help of DEM data. The projection feature $B_\mathbf{t}$ of ground feature B can be calculated via formula (1) by transforming all points in B to image space. Evidently, if the imaging model and the terrain data are accurate enough, $B_\mathbf{t}$ and A should coincide with each other. Therefore the following constraint between A and $B_\mathbf{t}$ can be assumed:

$$\rho(A,B_\mathbf{t}) = \mathbf{0} \tag{2}$$

where $\rho(A,B_\mathbf{t})$ is the generalized distance or disparity between A and $B_\mathbf{t}$.

Then error equations of a GCF can be established by linearizing the formula (3):

$$-\mathbf{v} = \frac{\partial\rho(A,B_\mathbf{t})}{\partial\mathbf{t}}\Delta\mathbf{t} - \mathbf{l} \tag{3}$$

where $\mathbf{v}$ is a random error vector, $\mathbf{l} = \rho(A,B_{\mathbf{t}_0})$, and $\mathbf{t}_0$ is the initial value of $\mathbf{t}$.

Formula (3) describes the generic error equations of different features, and the generalized distance $\rho(\cdot,\cdot)$ has different forms, which is discussed in Section 4. In order to evaluate the distance of free-form curves and areal regions, Hausdorff distance is introduced in Section 3, firstly.