TOWARDS A NEW PARADIGM FOR REGISTRATION OF SAR IMAGES USING LINEAR FEATURES

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ABSTRACT:

This paper summarizes a preliminary progress made in our ongoing R&D project concerned with developing a new paradigm for orientation and registration of SAR images. The basic idea is to replace traditional orientation procedures that use only point features with methods accommodating higher level features in general, and one-dimensional features in particular within the employed optimization frameworks of SAR-imagery orientation. Our major strands in this paper are first, to motivate the use of Feature-Based Photogrammetry (FBP) methods particularly as they pertain to support autonomous orientation and registration of SAR images and secondly to present a mathematically and stochastically rigorous adjustment model to accommodate such features explicitly. While this project is just at its very preliminary stages, the new ideas it brings will definitely open the door for FBP techniques, originally developed for frame imagery, to evolve and have a great impact on other remote sensing technologies.

1. INTRODUCTION

Feature-Based Photogrammetry (FBP) has been a tremendously active field of research for almost two decades. It differs from (traditional) analytical photogrammetry in the types of primitives employed in a variety of its fundamental tasks. While in traditional photogrammetry zero-dimensional entities, i.e., points are exclusively used as a driving power in its various orientation and exploitation procedures – in feature-based photogrammetry as the name suggests linear, or rather one-dimensional features often corresponding to elongated man-made features in the object space are employed. Of course, that means that no prior correspondence between distinct point in object space and its projection in the image is required and the entire linear feature (with arbitrary geometry) is accommodated in an appropriate mathematical model. Moreover, such a correspondence is simply obtained as a trivial by-product of the employed feature-based triangulation.

Over the years many researchers have argued in favor of accommodating linear features instead of points for different photogrammetric tasks (Kubic, 1988; Mikhail, 1993; Forstner, 2000, Zalmanson, 2000; Habib et al, 2001; Schenk, 2004). With their vision aimed at making the photogrammetric processes more accurate, robust and as autonomous as possible, their central arguments were based on the observation that in autonomous environment one-dimensional features are more easily and reliably detected and matched than points. In addition, typical aerial scenes contain many linear features (e.g., roads, buildings, creeks, etc.) which are also most likely to appear in some readily available geographic information system that can be used to provide control information for image orientation. Also, as traditional point-to-point correspondences between image and object features are not required, virtually as many points as necessary (on respective linear features) can be used. That increases the redundancy budget of the system and ultimately leads to increased robustness and precision.

It is therefore very surprising that such a widespread and promising research filed with virtually unlimited practical applications had been so far very much limited to frame geometries and has not been extended to accommodate orientation and analysis procedures of other remote-sensing sensors with different geometries. In fact, only few publications (e.g. Lee et al, 2000), have attempted to utilize FBP methods to address orientation problems of push-broom sensors and essentially none (to our best knowledge) have tried to carry-out similar ideas on Synthetic Aperture Radar (SAR) sensors.

In an attempt to fill the aforementioned gap this paper first aims at motivating the employment of FBP techniques specifically as they pertain to registration/orientation of SAR imagery. We then follow by presenting a general framework for the recovery of the orientation of SAR sensors combining any prior information on the sensor trajectory along with a mathematically rigorous incorporation of 3-D free-form curves. The proposed model does not address any existing imaging system specifically, but rather, provides a generic framework to solve the orientation problem for a general SAR sensor.

The remainder of this paper consists of four sections and is structured as follows. After briefly describing the physical principles and geometry of a generic SAR sensor section 2 proceeds with formally stating the problem to be addressed and reviews the current state of the art on SAR registration. Section 3 and 4, then present the proposed general framework for SAR parameters determination using linear features represented either analytically or in free-form. Finally, in section 5 the status of an ongoing research project on the subject is presented and future work is outlined.

2. SAR OVERVIEW

Synthetic Aperture Radar (SAR) is a rapidly emerging technology with a central role in a wide range of civilian and military applications. Interferometry (IFSAR), Differential Interferometry (DIFSAR) and Stereo SAR are the three leading SAR-based techniques extensively employed in topographic mapping, targeting, deformation analysis, geological and metrological exploration and other geospatial fields. Similarly to optical sensors, a prerequisite for generating accurate geospatial products from SAR imagery is accurate SAR payload orientation. For optical imagery this entails determining sensor position and attitude, here, an accurate knowledge of sensor position and velocity is required. Traditional methods of obtaining position and velocity of SAR sensors either entirely rely on the available on-board navigation telemetry or aim to improve the accuracy of such telemetry using ground control points (GCPs) manually identified on SAR images (Curlander, 1982; Mohr et al, 2001; Goncalves, 2002). Unfortunately, quite in contrast to a relative simplicity of manual identification of control points in optical imagery, such a task is far from being simple for SAR images, due to their inherent "speckled" nature. Moreover, that difficulty is considerably increased when autonomous extraction and matching procedures are sought. A promising direction to address the task at hand is to modify the dimension of the primitives with which the registration is carried out. Instead of using zero-dimensional GCPs, we may use one-dimensional linear features, often corresponding to elongated man-made objects (e.g., roads, rail-roads, hydrologic features, etc,), that have a distinct appearance in SAR images. What makes the returned EM signal from such features rather distinct is the fact that these features are usually (topographically) smoother than their immediate environment and their dielectric properties are also quite different. In fact, the problem of extracting such features both manually and even automatically has been successfully addressed in the literature (e.g. Li et al, 1995). However, so far, even when linear features have been successfully detected and matched with their counterparts from some GIS network, the subsequent orientation procedures have remained point-based. Also, as we'll be motivated in the following feature-based orientation procedures may be helpful It is therefore this particular gap that the project reported herein is trying to close.

Before presenting our general framework that deals with orientation of SAR images with linear features, we briefly summarize, following (Mikhail et al., 2001) the geometry model of a generic SAR sensor and make explicit a few central arguments addressed in the sequel of the paper.

Each pixel in a preprocessed SAR image is associated with two measurements that are made for a given scatterer, being its range and its Doppler frequency shift. The range is determined by the amount of time it takes for the EM pulse to make a round-trip between the sensor and the scatterer. The Doppler parameter is established from the well-known physical phenomenon entitled the "Doppler Effect", according to which frequency shift occurs when two objects are moving towards each other. In three-dimensional space, the Doppler parameter constraints the scatterer to reside on the cone with an apex at the sensor position, its axis coincident with SAR velocity vector and with cone angle being equal to the angle between the range vector (to the scatterer) and the SAR velocity vector as shown in Figure 1.

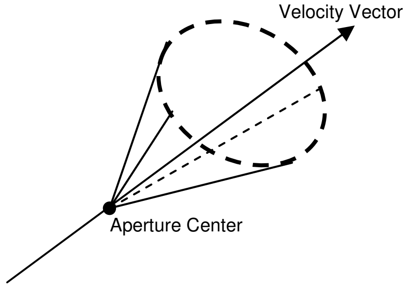

Figure 1: Doppler cone condition.
(Adopted from Mikhail et al. (2001))

Formally, the two SAR measurements are:

$$f_D = \frac{2}{\lambda} \frac{\dot{\vec{S}} \cdot (\vec{P} - \vec{S})}{\left|\vec{P} - \vec{S}\right|} \qquad (1)$$
$$R = \left|\vec{P} - \vec{S}\right|$$

where:

f_D, R are the Doppler shift and range measurements respectively, $\vec{s}, \dot{\vec{s}}$ are the 3-D position and velocity of the sensor, λ is the radar wave-length and $\vec{P}$ corresponds to the 3-D coordinates of the scatterer position on the ground.

The problem of SAR orientation is thus, to accurately determine the sensor trajectory $\vec{s}, \dot{\vec{s}}$ using SAR observables and some ground control. Traditionally, that is done by applying a simple correction (in most cases polynomial) model to the trajectory state vector and using a set of ground control points to estimate the coefficients of the correction polynomial. However, apart from the fact that these techniques required a well-defined set of control points which, as has been stressed earlier, cannot be easily and reliably detected (even manually) there is another problem associated with the rather simplistic solution of the orientation problem. Qualitatively speaking, the traditionally applied "correction" models only account for systematic errors in the sensor trajectory. In real scenarios, however, especially, for highly maneuvering airborne SAR systems, undergoing rough platform perturbations and instabilities, that simplistic trajectory modeling may not be adequate. Here, faithfully modeling both the systematic as well as random effects in the trajectory may be necessary. One way of doing it is to take advantage of highly accurate on-board positioning systems (e.g., dual frequency GPS receivers with high sampling rates) which would directly yield an accurate trajectory. Another way, of course, is to use a large and very densely distributed set of control points. But in the absence of such positioning/navigations systems and practical difficulties associated with collecting sets of ground control points with the above mentioned characteristics, other indirect methods employing ground information have to be devised.

It is therefore the purpose of this paper to present a mathematically and statistically rigorous model for SAR geo-referencing using general linear-features in objects space. In the next two sections we will show that the proposed model indeed provides the solution for the major two difficulties associated with point-based-methods mentioned above.

3. ORIENTAION USING PARAMETRIC CURVES

In this section we derive a rigorous mathematical model for determining the orientation (trajectory) parameters of a SAR image from 3-D analytical curves represented parametrically. In what follows we will assume that our control information is given in the form of a class of 3-D curves, called *regular curves*. A regular curve is defined as the locus of points traced out by the end point of a vector $\Gamma(t)=\begin{bmatrix}X(t) & Y(t) & Z(t)\end{bmatrix}^T$ as the curve parameter $t \in \Re$ ranges from a to b. Further, $\Gamma(t)$ must have continuous second derivatives and its first derivatives must not vanish simultaneously anywhere in the interval $a \le t \le b$. We now modify (1) to express that a measured pixel on the SAR image corresponds to $\Gamma(t)$ as follows:

$$f_D = \frac{2}{\lambda}\frac{\dot{\vec{S}}\cdot(\vec{P}(t)-\vec{S})}{\left|\vec{P}(t)-\vec{S}\right|} \qquad (2)$$
$$R=\left|\vec{P}(t)-\vec{S}\right|$$

As stressed earlier, at this stage we are just interested to support a generic auxiliary orientation mechanism. Thereby, we model the dynamic trajectory parameters as some implicit vector-valued process of stochastic onboard measurements β (e.g., GPS, etc.) and non-random factors ξ (e.g., systematic calibration parameters, etc.). We now rewrite (2) to result with the following pair of condition equations written for each pixel on the image that corresponds to $\Gamma(t)$:

$$M=\begin{cases} f_d(Trj(\beta,\xi), f_d, t)=0 \\ R(Trj(\beta,\xi), R, t)=0 \end{cases} \qquad (3)$$

In M two groups of quantities are identified. The first consists of elements that are "observed". These include SAR measurements f_D, R and auxiliary (trajectory) measurements β, collectively denoted by χ, hereafter. The second group consists of non-random factors including those originating from the auxiliary mechanism, i.e., ξ, and **<u>the new parameter t</u>**, associated with $\Gamma(t)$. What's interesting is that this, apparently naive introduction of the curve parameter t, allowing free motion along the tangent direction $\Gamma'(t)=\begin{bmatrix}X'(t) & Y'(t) & Z'(t)\end{bmatrix}^T$ of $\Gamma(t)$ in object space, is in essence a central foundation of our feature-based orientation solution.

To arrive at the set of linear equations, (3) must be linearized. Linearization requires initial values ξ_0 for the non-random parameters ξ as well as an estimate t_0 for the curve parameter t. The simplest way to estimate t_0 is to find the closest point on $\Gamma(t)$ to the circle of intersection of the range sphere and the Doppler cone (Figure 2). The computation of the closest point and its associated parameter t_0 requires, in general, an iterative minimization scheme, such as Newton method.

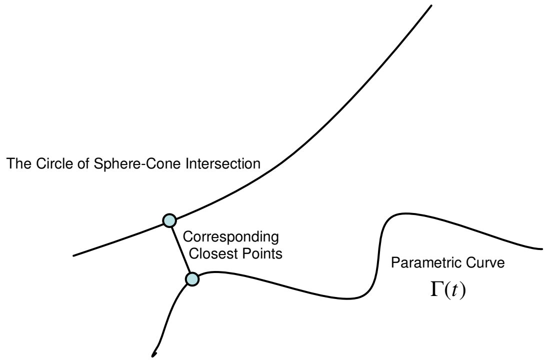

Figure 2: Finding the closest point.

With the initial estimates, system (3) is linearized to yield the following Gauss-Helmert model:

$$\begin{aligned} f_d^0 + A_x^1 d\xi + a_x^2 ds + B_x e = 0 \\ R^0 + A_y^1 d\xi + a_y^2 ds + B_y e = 0 \end{aligned} \qquad (4)$$

With f_d^0, R^0 we denote the evaluation of f_D, R at the measurement vector χ and the initial estimates of the parameters. The partial derivatives of f_D, R with respect to the parameter vector ξ are contained in A_x^1, A_y^1, and those with respect to the measurement vector χ in B_x, B_y, respectively. a_x^2 and a_y^2 are the partial derivatives of f_D, R with respect to the curve parameter s, requiring a continuous first derivative of $\Gamma(s)$. Finally, $d\xi, ds,$ and de are the increments to the parameters ξ, and t, and the "measurements" error vector e, respectively.

For N pairs of image measurements, system (4) is generalized to:

$$M^0 + A_1 d\xi + A_2 dS + Be = 0 \qquad (3)$$

with

$$M^0=\begin{bmatrix}(f_d^0)_1\\(R^0)_1\\\vdots\\(f_d^0)_N\\(R^0)_N\end{bmatrix},\quad A_1=\begin{bmatrix}(A_x^1)_1\\(A_y^1)_1\\\vdots\\(A_x^1)_N\\(A_y^1)_N\end{bmatrix},\quad A_2=\begin{bmatrix}(a_x^2)_1 & 0 & 0\\(a_y^2)_1 & 0 & 0\\0 & \ddots & 0\\0 & 0 & (a_x^2)_N\\0 & 0 & (a_y^2)_N\end{bmatrix}, \qquad (5)$$

$$B=\begin{bmatrix}(B_x)_1\\(B_y)_1\\\vdots\\(B_x)_N\\(B_y)_N\end{bmatrix},\quad dS=\begin{bmatrix}ds_1\\\vdots\\ds_N\end{bmatrix}$$

and with a combined error vector containing both SAR observation errors and auxiliary trajectory errors as follows:

$$e = \begin{bmatrix} d\beta \\ (df_d)_1 \\ (dR)_1 \\ \vdots \\ (df_d)_N \\ (dR)_N \end{bmatrix}$$

The least-squares solution of system (5), minimizing $e^T \Sigma_e^{-1} e$, is given by

$$\begin{bmatrix} d\hat{\xi} \\ d\hat{S} \end{bmatrix} = -\left(A^T (B\Sigma_e B^T)^{-1} A\right)^{-1} A^T (B\Sigma_e B^T)^{-1} M^0 \qquad (6)$$

$$with \quad A = \begin{bmatrix} A_1 & A_2 \end{bmatrix}$$

and

$$\tilde{e} = -\Sigma_e B (B\Sigma_e B^T)^{-1} (M^0 + A\begin{bmatrix} d\hat{\xi} & d\hat{S} \end{bmatrix}^T) \qquad (7)$$

Since the original system (3) is not linear, the solution (6) requires an iterative approach ultimately yielding the best (in the least-squares sense) estimates for the orientation parameters.

As shown, it rigorously combines prior information (from any positioning system, e.g., GPS/INS) and geometric relations between parametric curves in object space and their realization in SAR image.

4. GENERALIZATION TO FREE-FORM CURVES

In this section we formalize the orientation determination problem when some elongated objects, represented as free-form curves are known in object space and can be extracted in the image. A 3D free-form curve Γ_f, is represented by a sequence of vertices $V = \{V_i\}$. The set of vertices V induces an ordered set of line segments $L = \{\vec{l}_i\}$ where segment $\{\vec{l}_i\}$ connects the two vertices $\{V_i\}$ and $\{V_{i+1}\}$ (Figure 3).

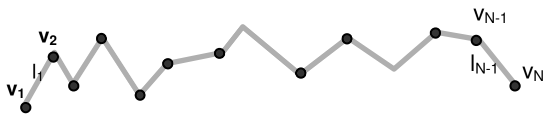

Figure 3: Representation of a 3-D free-form curve.

Let $\Omega = \bigcup_{r=1}^{R} \Psi_r$ ($\Psi_r \bigcap \Psi_s = \emptyset$) be a partial projection of Γ_f, represented by a disjoint set of W components $\{\Psi_W\}$, each comprising a connected set of n_W 2-D pixels in SAR image with $1 \le j \le n_W$. As before, we assume that there is no point-to-point correspondence between features in object space and their (partial) projections in SAR image.

Then, the problem is to come up with the parameters that would describe the relationships between object and image features in the best (in least-squares sense) way.

First, we select a subset $\Lambda \subset \Omega$ of image pixels that belong to the projected control feature. Subsequently, given V and Λ, together with approximated auxiliary trajectory, we follow a similar procedure employed for parametric curves, but now using piecewise linear features in object space. Hence, in each iteration a temporary association between every pixel in Λ and some line segment $\{l_i\}$ with a corresponding segment parameter t, is established. Note, that the correspondence between a given pixel location and its associated line segment is dynamic, and may change from iteration to iteration.

The proposed orientation method with free-form curves is based on the parametric formalism introduced in the previous section. There are some important differences, however. As has been already mentioned the parametric model has been developed for space curves having first order continuous derivatives. Clearly, this is not the case for free-form curves with singularities at the vertices of Γ_f. At these singular locations none of the equations of system (5) that require object space derivatives can be formed. Hence, it is important to discuss how to address these singular cases when encountered. A simple way to circumvent this problem is not to estimate the curve parameter t at the vertices. In this case, the closest point on the corresponding line segment will be kept fixed, that is, the degree of freedom to move along the otherwise unique tangent direction is removed. This solution is plausible in situations where the object space curve consists of relatively long segments, thus reducing the chance for the closest point to coincide with a vertex. For the opposite case, with many short vertices it is recommended to approximate the set of vertices in the neighborhood of the closest point by an analytical curve, e.g. cubic spline, to eliminate singularities. This strategy will allow us to employ the parametric model developed in the previous section without any change.

5. SUMMARY AND FUTURE WORK

This paper has reported several preliminary results from an ongoing R&D research project on registration of airborne and space-borne SAR images employing feature-based photogrammetry techniques. In particular, ERS-2 and RADARSAT space sensors along with some airborne SAR systems will be studied in the near future. For each particular sensor, the proposed mathematical model will be examined with respect to the quantity of linear features available, their shape as well as their distribution (spatial configuration) within the SAR image.

Apart from being an elegant solution to the problem of accurately identifying control feature in SAR images, our proposed stochastic model should yield more accurate estimates for instantaneous position and velocity vectors, being a crucial factor particularly for SAR air-borne platforms often being subject to unstable atmospheric conditions yielding non-smooth variations in their navigation parameters. Obtaining the same performance with traditional methods would either require using highly accurate on-board positioning and navigation equipment or alternatively an extremely dense distribution of GCPs across the entire image - practically impossible requirement for typical SAR mages.

While by no means, the work done so far and reported herein may be considered complete, this paper has provided the motivation for employing FBP techniques for orienting and subsequently registering SAR imagery and by doing that has paved the way for a new paradigm in SAR processing.

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