A GENERAL APPROACH TO GEOMETRIC MODELLING IN PHOTOGRAMMETRY AND REMOTE SENSING

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Summary

This paper presents a universal approach to geometric modelling in photogrammetry and remote sensing and introduces the development of a support tool for image exploitation tasks based on this approach.

Modern photogrammetry and remote sensing is a continuously evolving field. The geometric calibration and orientation of sensors required to georeference the information has always been a major issue for all types of sensors for Earth Observation. The introduction of airborne and spaceborne high resolution digital cameras posed new challenges to image registration precision. In addition, future missions, sensor types and platforms might present totally different geometries and image registration problems: for example, LIDAR, SAR, high resolution optical scanners on unmanned air vehicles (UAV), or even space missions delivering extraterrestrial remote sensing data without the possibility to obtain ground reference. General tools for the geometric modelling of such sensors are not currently available, making it more difficult for a scientist or engineer to simulate or develop the corresponding missions or sensor models.

A universal geometry modelling approach with standardized modelling concepts designed to support interoperability would help to overcome present and future problems in this field. A consortium consisting of the remote sensing group of INDRA Espacio (Spain), the researchers at the Institute of Geomatics (Spain), and the Earth Observation Directorate of the European Space Agency (ESA) decided to attack the issue through modelling concepts that go beyond current technology. The geometric modelling approach is being formalized and a new software tool, the Universal Geometry Engine (UGE), that implements the suggested concepts, is being designed. The system is based on the rigorous modelling of sensor acquisition geometry, operates by generation of observations and subsequent adjustment of the models, and is built on solid geodetic, cartographic and remote sensing grounds. The general requirements to the software are continued support of existing workflows and information exploitation procedures and real extensibility and portability in order to guarantee easy adaptation to other missions, platforms or sensors, whether current or exotic.

1. On geometric modelling in remote sensing

Earth Observation (EO) satellites collect daily reams and reams of data about the surface of the Earth; this is what in EO science is classified as the "acquisition phase". Then, apart from some special cases, to make sensible use of these data ("interpretation phase") it is in general necessary to place the information in a form and reference system that is suitable for the job; this is the "normalization phase", and an important part of it is the linking of the information to the position on the Earth surface to which the data refer, more specifically referred to as georeferencing. The precision with which the relationship must be established is linked with the spatial resolution of the sensors; so, while this problem existed since the beginning of EO satellites, it is exacerbated by the continuing increase of the resolution achieved by modern EO sensors.

The data, as collected by the sensors, are arranged in what is called the "image space" (with an obvious reference to photographs), the structure and properties of which is determined by the type and characteristics of the sensor; in general terms, the problem is that of relating the image space to the 3D "object space" from where the data were collected. Since position on the surface of the Earth is measured with respect to geodetic reference frames, the problem takes the form of defining a relationship between the image space and a reference frame.

Taking as example images, the most common type of EO product, and the one for which the problem of georeferencing is most acute, the approach that is normally taken to establish the relationship between the image and one geodetic reference frame involves several steps. First, starting from the estimated (in the sense that it is derived from orbit data) position of the satellite, perspective and atmospheric distortions are removed, and geodetic coordinates are computed for image corners; the image is at this point said to be "georeferenced". Secondly, an elevation model of the surface is fitted to the image using image coordinates and/or ground control points to remove the distortions caused by the relief; after this step, the image is said to be "orthorectified". Finally, the image is carefully graphically (slightly) distorted to ensure that the ground control points fall at their "real" positions. This final correction generally is completely independent of the sensor geometry and orientation, and is based on quite general mathematical procedures, such as affine transformations. It has to be noted that, while the term "distortion" is used liberally in the preceding text and in common practice, in fact most of the corrections that are applied to the image are direct consequences of the intrinsic characteristics of the sensor; they do not have any of the derogative characteristics that the term implies, and could be predicted and compensated with an accurate model of the sensor.

The "model", or "geometric model" of the sensor, as used in this context, is a mathematical relationship that connects the 2D image space (defined by two coordinates e.g. coordinates of points in a digital image instrumental reference frame, for instance lines and columns of a digital image, or the slant range and azimuth coordinates of a SAR image), and the 3D object space, which can be defined e.g. by a geodetic reference frame in which the captured scene is to be represented. With such a relationship it is usually possible to derive the image space from the object space (compute the image coordinates of a given target on the ground) or the object space from the image space (locate in geographic coordinates objects identified in the image). The models are used to mathematically describe the geometrical phenomena associated with remote sensing sensors. In the context of geometric modelling, a model represents the functional and stochastic relationship between measured data (= the observations of the model, e.g. orbit and ground control), constant data (instrument properties) and unknown data (the parameters of the model).

The advantage of using accurate sensor models - as opposed to correction of geometric distortions of the images - are many: the transformations are applied uniformly, they are mathematically well defined, error estimation can be treated properly, consistency among different sensor types is much more easily ensured, and so on. Unfortunately, while many commercial packages used in the EO domain include also accurate sensor models for many existing satellites, they are not well suited to model new sensors, or to offer the means to researches to integrate their own models. Therefore, developers of new systems often need to implement their own modeling tools.

A more subtle advantage of the model is that of permitting to treat the images taken by the sensor as "measurements", in the sense that with an accurate model it is possible to transform the spatial relationships among features of the image in the distances and angles among the objects that those features represent. It becomes then possible to adopt the same tools and techniques used for geodetic and photogrammetric network adjustment to remote sensing. This automatically opens a whole new range of possibilities: optimal - in the least squares sense - estimation of the network and of the sensor model parameters, possibility to calibrate simultaneously more than one sensor, consistent georeferencing of heterogeneous sensors, and finally - and most importantly - the opportunity of treating all the sensors in a uniform way.

What is required, then, to support the more systematic use of sensor models in remote sensing is an environment where models can be created and used easily, and where all the traditional geodetic network adjustment tasks are carried out independently of the sensor type; and this is precisely what the development that is described by this paper aims to do.

2. A general approach to geometric modelling

2.1. Motivation

Generally speaking, remote sensing applications based on low resolution imagery (i.e. data with a pixel footprint measured in Km's) have paid little attention to geometric sensor modelling. The same (with some exceptions) occurs in those thematic applications based on medium resolution imagery (i.e. 80-100 m pixel footprint). On the contrary, geometric modelling has always played a major role in all remote sensing applications that exploit the metric and geometric properties of the images. The applications of the latter type include, among others:

- Standard cartographic production based on airborne photogrammetric systems.
- Mapping applications, i.e. extraction of cartographic features for medium (up to 1:25000) to small scale maps (e.g. 1:500000), based on medium-resolution satellite optical imagery (eg Landsat, SPOT, IRS)
- Mapping applications based on high-resolution remote sensing satellites, like Ikonos, QuickBird, and Orbview-3, with 1 m spatial resolution for panchromatic imagery. These applications require the most advanced geometric modelling techniques.
- DEM generation based on SAR data, whether by radargrammetry or SAR interferometry techniques. The sensor geometry plays a key role in one of the most remarkable SAR applications: the measurement of

centimeter scale movements of radar targets (earth crust, buildings, radar reflectors...) by the so-called SAR differential interferometry technique.

A further, special category of sensors groups those used for observations of extra terrestrial bodies: in these cases "ground truth" is especially difficult to establish, and a rigorous sensor model is the only means to obtain reliable data.

All of these applications require accurate transformations from image space to object space and viceversa, and this is precisely what the sensor model makes possible. As already stated the sensor model expresses the mathematical relationship between the (often) 2D image space and the (always) 3D object space. Rigorous models are based on a mathematical description of the operation of the sensor: for example, the model of a frame camera is based on the collinearity equations. There are, however, several operational remote sensing applications that cannot be modelled by physical and geometric models; in these cases the so-called empirical models provide an adequate solution in many a practical context. Among the most commonly adopted empirical models there are the 2D and 3D polynomial functions; the 3D rational functions, which play a fundamental role for instance with the high-resolution optical imagery; and the Direct Linear Transform.

While the motivations for the use of (rigorous) models are strong, as a general rule commercial EO tools do not support specific, tailored modelling in respect of new sensors or sensor types; they often do include models of the most common sensors, but do not furnish the means to incorporate user-designed models. Innovative sensors, or novel exploitation methods (eg multisensor fusion) have to be modelled "from scratch"; this is for example the case for new types of photogrammetric quasi line scanners currently under development, or for the Leica ADS40, where a specially designed orientation manager had to be implemented, which exclusively treats the data of this sensor. The commercialization and value adding for new sensors is a difficult and expensive task.

The idea at the base of the implementation of a software tool capable to fill this "gap" is to extend the methodology of geodetic/photogrammetric networks (and its underlying mathematical and statistical theories) to remote sensing (thus incorporating the power of optimal least-squares parameter estimation and hypothesis testing). Therefore, the tool must encapsulate the algorithm for the network adjustment behind an interface that allows a wide variety of sensor models to be used. More generally, such a tool should provide a solution to the common tasks in instrument modelling and parameter estimation, in order to provide an environment where new sensor models can easily be "plugged in" and the data they collect exploited, (ideally) without any specialized processing or re-implementation of common tasks.

2.2. Modeling concepts

The classical way to do modelling for sensor orientation and calibration is well established. Once the mathematical –functional and stochastic– model of the imaging process is known, all that has to be done is to estimate the model parameters from measurements on the images. Most times these measurements –the so called photogrammetric observations, or image coordinates or pixel coordinates– are not sufficient to determine the model parameters because of rank deficiencies (related to object reference frames) or because of unfavourable error propagation (related to the network geometry weaknesses). Therefore, it is necessary to add control information, usually ground control or trajectory control.

From a mathematical point of view, all that needs to be done is creating a, more or less big, more or less homogeneous, estimation problem from a number of equations of the type

$$f(t, \ell + v, x, i, u) = 0$$

where f is the functional model, t is a time reference in case of time dependent static problems, ℓ are the measurements, v are the residuals to the measurements, x are the parameters of interest and i, u are instrument calibration constants and other model auxiliary constants respectively. The stochastic model is described by the covariance matrix of the observations $C(\ell, \ell)$ or, equivalently of the residuals $C(v, v)$.

The above formulation leads to the well known non-linear, implicit least-squares parameter estimation problem where the optimal set of parameters x bring $v^T C(\ell, \ell)^{-1} v$ to a minimum.

If the formula above is seen as a "functional template," then a software system based on this template can be open to the estimation of parameters for any type of modelling as long as the functional model equations fit the template. Taking advantage of this "functional template" is a matter of formalization and organisation.

The proposed thematic scope for such an implementation is that of Earth Observation geometric sensor modelling plus ancillary general modelling to support it. One key aspect of the approach is the use of object-oriented technology. This can be regarded as an enabling technology for the generic modelling concept. Thus, the functional model templates translate, in terms of software implementation, into an abstract root model class that defines a standard interface. Furthermore, this inheritance approach can be cascaded to physical models like radiometric correction functions or can be reused for atmospheric refraction compensation functions.

The statement “ancillary general modelling” has a very precise meaning: a system with general geometric modelling capacities shall accept observation equations whose parameters do not necessarily include a sensor. This means that any other problem related to the sensor and its geometry (geodetic problems, reference and coordinate system transformation, radiometric aspects, etc) may be treated in the same way and may therefore easily be included within the same framework. Radiometric modelling may be used as an explanatory example. A typical problem when producing land continuous, seamless, orthophoto coverages is that of geometric and radiometric inconsistencies. In many systems lacking the proposed generality and extensibility aspects, radiometric inconsistencies are not tackled with a consistent methodology and are solved – rather, mitigated – in the object space and not in the image space. It is proposed that such a correction should be done by a proper modelling of the radiance which results in the capability of correcting the associated radiance of each pixel of the image, that means in the image space. In this context, it comes very naturally to add, for instance, a radiometric calibration function that corrects the intensity of a pixel as a function of the pixel coordinates.

The necessity for the general model for a general geometric modelling approach can be illustrated through the example of refraction modelling. Past computer limitations and past mental inertia dictate that atmospheric refraction be handled as a pre-processing correction together with some strong assumptions and/or restrictions on the sensor orientation. The corrections were based on standard and simplified atmospheric models (see for instance [Schenk, T., 1999]). However, such limitations do no longer exist, while modern high-resolution sensors or high precision applications do require a more accurate modelling of this effect. An atmospheric refraction model is part of a sensor geometrical model. Like for any other phenomena, refraction modelling can be done at various levels of sophistication, starting from simple models based on global, approximating parameters (no seasonal dependency, no geographical dependency out of height) for particular situations (nadir looking images) to end with more complex models taking into account the time of acquisition and the sensor to object relative position. Refraction models should be reused from one sensor to another, very much as rotation matrix parameterization or any other common repetitive mathematical pattern should be. Therefore, starting with very simple, basic models they can be refined and embedded into the sensor model. At that point, they become part of the sensor model like any other formula or expression it includes and they can be further used in the application modules in a transparent way. The advantage of the proposed approach over the usual, approximate approach goes beyond physical correctness. New sensor models can be added more easily without necessarily having to model refraction for each sensor. Furthermore, pre-processing and post-processing corrections are error prone. Somehow the system has to keep track of whether the “correction” has been applied or not. Mistakes derived from this off-line corrections are frequent. Many times, in photogrammetric bundle adjustment software packages, the refraction effect is approached as one more correction to image coordinates; by attacking instead the refraction as a modelling issue, the importance and impact of the errors introduced may be decreased.

2.3. Sensor models

Geometric modelling can be regarded as an intermediate step between image acquisition and image exploitation. A general approach has to answer the question “which sensor models shall be supported?” Clearly, the orientation and calibration parameter determination of at least the known types of active and passive sensors for Earth observation should be supported. An implementation of the approach would need to be truly extensible, that means adding sensor models should be possible through modifications on configuration level only. In other words, it has to be ensured that the sensor models can be loaded into a software application as plug-and-play components. This may be carried out within a specific geometry engine, in extensible commercial software packages or, possibly, by including the model as part of the header record of images for distribution: the header would thus include the sensor model and its parameters. In the latter case, upon reception of an image, the user would extract a, say, DLL from the data itself and load the DLL into the application module, thus enabling it to deal with that particular type of image and/or with that particular image. In this case, the DLL would act like a black box that contains the model and allows working with it without giving information on the particular mathematical model. Additionally it may contain code that would restrict the use of the model to one particular image. This would be, as well, an efficient way to protect intellectual property and, at the same time, to deliver rigorous image formation models.

2.4. The Network

A network is a set of parameters and a set of relations between them. A relation is an observation and a mathematical model. Thus, two parameters in a network are related if there is an observation whose mathematical model includes, at least, the two parameters. The parameters are the unknowns of the problem. The observations are the data of the problem.

As described previously, unknown parameters and their covariance matrices as well as the observations' residuals and their covariance matrices may be estimated (in the least squares sense) from a non-linear implicit model by iterative linearization of $f(t, \ell + v, x, i, u) = 0$ with respect to ℓ and to x at some initial approximation for x. [Koch,K-R.,1988].

For the presented approach it is proposed to create not only a numerical model of the network but the network itself. This can be achieved by applying discrete mathematical techniques (on graphs and hyper graphs) and by using well known data structures. The network object contains all the information related to the specific geometric problem.

The advantage of such a network object is that:

- its structure can be reviewed easily through customized representations of the network,
- it can directly be accessed and modified through an user interface, and
- it can be exported.

Once the network structure is created, advantage is taken of it to perform a structural analysis of the network, such as connectivity analysis. Network connectivity analysis refers to the analysis of statistics related to the nodes and edges of the network associated graph [Colomina,I.,1993]. The graph of the network contains a node for each network unknown group. Two nodes are related by a graph edge if there is an observation that, at least, involves the two parameter. For instance, one might detect mistakes in parameter coding by looking at the network graph vertex connectivity histogram.

Thus, the direct accessibility of the network has great advantages for model developers, scientists and engineers in charge of mission design, sensor design validation and simulations. To such users, which can be found in the places where innovative modern remote sensing research and development is being carried out, an implementation of the proposed approach may provide a powerful tool.

3. Conclusions

Currently, the design of a software tool that supports the treatment of geometric modelling problems for remote sensing adopting the unified approach described above is being carried out in the frame of the UGEI project (reference earth.esa.int/rtd). A complete geometry engine will be available and usable for solving geometric problems for all types of sensors; any sensor will be accommodated easily as long as the general model template and interface are respected. The outcome will be the more efficient development of solutions for new sensors; using a general modelling approach, duplication of the development of tasks common to geometry tools will be avoided.

More generally, the approach driving the UGEI development allows the whole geometrical modelling issue to be abstracted, as it is based on fundamental mathematical modelling techniques, which are not bound or limited to any specific scenario.

On a longer term perspective, UGEI might contribute to support new standards for geometric modelling, the recommendations for which are being studied by organizations like the European Spatial Data Research. The EuroSDR project "InterOCI - Interoperability for Orientation and Calibration data of Photogrammetric Images" for example is conducting a study on the existing mathematical models and approaches, which would aid in the formulation of an interoperability standard.

4. References

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