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Aerial multi-camera systems: Accuracy and block triangulation issues

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ABSTRACT

Oblique photography has reached its maturity and has now been adopted for several applications. The number and variety of multi-camera oblique platforms available on the market is continuously growing. So far, few attempts have been made to study the influence of the additional cameras on the behaviour of the image block and comprehensive revisions to existing flight patterns are yet to be formulated. This paper looks into the precision and accuracy of 3D points triangulated from diverse multi-camera oblique platforms. Its coverage is divided into simulated and real case studies. Within the simulations, different imaging platform parameters and flight patterns are varied, reflecting both current market offerings and common flight practices. Attention is paid to the aspect of completeness in terms of dense matching algorithms and 3D city modelling – the most promising application of such systems. The experimental part demonstrates the behaviour of two oblique imaging platforms in real-world conditions. A number of Ground Control Point (GCP) configurations are adopted in order to point out the sensitivity of tested imaging networks and arising block deformations. To stress the contribution of slanted views, all scenarios are compared against a scenario in which exclusively nadir images are used for evaluation.

1. Introduction

Oblique aerial images, alone or in combination with vertical aerial images, have always been seen as a very attractive data source thanks to their intuitive nature. Documented use of oblique imagery dates back to the nineteenth century. Gaspard Félix Tournachon acquired the first aerial photograph in 1858 by raising a balloon over the village of Petit Bicêtre in France (Colwell, 1997). Two years later, the oldest surviving oblique aerial image was taken by J.W. Black and S. King in Boston, USA, from a balloon. In 1887 a balloon again was employed by a German forester to acquire aerial photos over forests in order to identify and measure stands of trees (Colwell, 1997). The same year also saw the birth of aerial photography from a kite, thanks to a British meteorologist, E.D. Archibald (Colwell, 1997). At about the same time in France, the Tissandier brothers conducted other experiments of kite and balloon aerial photography. Thereafter this practice of acquiring images from kites moved across the Atlantic and advanced rapidly. In 1906 G.R. Lawrence, using between nine and seventeen large kites to lift a huge camera, took some oblique aerial photographs of San Francisco (USA) after an enormous earthquake in the area. Thanks to the rapid progress in military photography from airplanes, kites were then abandoned in favour of powered flight, which gained importance for military reconnaissance during World War I. Simultaneously, single and multiple lens cameras were produced for oblique-only or combined configurations in the UK, Germany, France, Italy, Switzerland and USA (Manual of Photogrammetry, 1952). In the 1930s for instance, the U.S. Geological Survey and the U.S. Army used a Fairchild T-3A five-lens film camera for mapping, surveillance and reconnaissance purposes. Finally, during World War II, oblique aerial photography was employed for reconnaissance purposes before and after bombing missions (Nocerino et al., 2012), thus further stimulating the rapid development of new cameras, lenses, films and camera mounting systems (Aber et al., 2010).

The concept of fitting several imaging sensors into a unique camera housing re-emerged for civil applications with the introduction of digital imaging technology (Petrie, 2010). However, the true revival of oblique imaging systems for geospatial applications occurred in 2000 when Pictometry International introduced their five-lens camera system that incorporated vertical and slant views (Patent Ser. No. 60/425,275, filed November 8, 2002). Pictometry imagery has also, more recently, been disseminated through the Bird's Eye view function of current Bing Maps. Over the past decade, the geospatial industry has enthusiastically taken up oblique imaging technology. New businesses have been born

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(e.g. Icaros, Simplex Mapping Ltd., VisionMap) and a growing number of existing companies (e.g. IGI, Leica/Hexagon, Track'Air/MIDAS, Vexcel/Microsoft, BSF Swissphoto) now include oblique camera systems in their portfolios. As competition has grown, the market has evolved and expanded its offerings. To date, most prominent cities in the world have been covered with georeferenced oblique images and these datasets are usually updated every few years to ensure that they are current. This also gives rise to valuable multi-temporal databases of image data (Karbo and Simmons, 2007).

Today, the oblique camera systems are available in a variety of configurations, the differences between designs being mainly in the imaging sensors (number, arrangement, format and sensitivity) and the mode of acquisition, which include:

– *maltese-cross systems* comprising five different imaging sensors, one pointing vertically and the other four pointing symmetrically in the four cardinal directions. Camera formats range from small to large depending upon the intended applications, and the tilt angles normally lie between 30° and 45°. These oblique camera systems are suitable for large areas mapping of 3D city modelling.
– *fan systems*, which mainly come as twin cameras, with the sensors positioned linearly along- or across- track, making them very suitable for corridor mapping. A quite innovative fan solution is offered by VisionMap with the A3 Edge sensor, a stepping frame system that captures up to 64 images per sweep, corresponding to a field of view of 109°.

Most of today's oblique camera systems acquire RGB images, though acquisitions in the NIR band are becoming standard in the newer commercial systems.

On the application side, the actual interest in oblique photography for mapping purposes is due to its primary quality: the imaging of entire building façades and, normally, their footprints as well. Possible applications based on oblique aerial views are multiple: dense point cloud extraction for 3D city modelling (Wang et al., 2008; Fritsch et al., 2012), monitoring situations during mass events and environmental accidents (Kurz et al., 2007; Grenzdörffer et al., 2008; Petrie, 2008), building detection and reconstruction (Nex et al., 2013), urban area classification (Gerke and Xiao, 2013), identification of structural damage to buildings (Nyaruhuma et al., 2012), updating of road databases (Mishra et al., 2008) and administration services (Lemmens et al., 2008). From a practical point of view, the extracted geometric information should be complete, reliable, generated with minimal interaction, all while keeping the survey cost at the optimal level. However, although the abundance and practical utility of this oblique image data is clear, both dealing with the resulting very large datasets and automated processing remain a challenge. This is primarily because complex image configurations are imposed by the oblique image acquisitions and because of shortcomings in on-board direct orientation sensors that do not satisfy the strict requirements of geomatics applications.

The prospect of information extraction from oblique imagery has also given impetus to scientific initiatives (e.g. EuroSDR Benchmark on Image Matching; ISPRS Scientific Initiatives) aimed at evaluating the current status of available tools and at boosting further research into automated orientation (Wiedemann and More, 2012; Rupnik et al., 2013), dense image matching (Gerke, 2009; Rupnik et al., 2014), object detection and 3D reconstruction (Xiao et al., 2012). These efforts target developers and users in delivering comparative performance analyses on the provided datasets, in particular for dense matching and 3D reconstruction (Cavegn et al., 2014). However, in spite of new data processing developments and comprehensive evaluation of block triangulation results, what has been largely overlooked until now is any revision of traditionally adopted flight patterns. Open questions include: (i) How do different overlap scenarios influence the precision of computed object points? (ii) What is the right balance between aerial survey precision and productivity? (iii) How should a flight be planned in terms of overlap and camera configuration parameters (e.g. tilt) to achieve most complete results? (iv) What, after all, is the influence of the oblique views on the image block triangulation from the point of view of obtainable accuracy?

In the following sections of the paper, the authors address the above problems related to oblique multi-camera systems in terms of image triangulation (self-calibration is not the primary scope of the paper). Section 2 reports on existing flight planning routines and simulation studies of various block configurations. The influences of varying sensor size, tilt angle and overlap (in nadir and oblique cameras) are considered regarding the obtainable accuracy, with attention being given to the issue of completeness of point cloud retrieval in urban environments. Section 3 briefly describes the image orientation task related to oblique imagery. Lastly, Section 4 reports the results of two real-case studies. The behaviour of image blocks is evaluated for different Ground Control Point (GCP) configurations, different image overlaps, and GNSS assisted image triangulation.

2. Flight planning – simulated case studies

Flight planning refers to the initial determination of flight geometry, given the area of interest and the required end-product, and thus the desired accuracy. In the case of traditional nadir imagery, the parameters that are optimized are the flying height, the camera with its optics and the overlap pattern. Depending upon the type of photogrammetric application, adopted lenses can vary from wide to narrow angles. As a general rule, long focal lengths are used when large height variations are present (cities, mountainous areas), whereas short focal lengths are preferred in rural areas, for overview flights or when better height accuracy is targeted. Extensive studies on optimization of flight pattern scenarios were carried out during the second half of the 20th century (Förstner, 1985; Ackermann, 1992; Kraus, 1997, 2007). At that time, digital photogrammetry was still an unrealised concept and manual stereoscopic observations were commonplace. Hence, the attention remained around vertical imaging while combined vertical and oblique photography was conceived merely for pictorial representation. The prevailing rule-of-thumb suggested that flying scenarios with 60% forward overlap would ensure a 3-fold coverage for points down each side of the image, providing for strip formation. Furthermore this also afforded good stereoscopic viewing with a good base length for 3D measurement. At the same time, the 20–40% side overlap provided a sufficiently strong geometry to tie the neighbouring strips of photography together. Reduced processing times and compilation costs were a top priority; therefore the fewer images covering the area of interest the better the economy of a project.

The costs of mapping with photogrammetry started to significantly reduce as the technology matured and the digital era was embarked upon. This brought about automated image measurement, which raised the compilation efficiency and reduced human operator interaction. Automation gave rise to a new tendency to fly denser patterns, in particular in the in-flight direction. Also, thinking in terms of single stereo models gave way to thinking in terms of multi-image bundles of rays (McGlone, 2004; Aber et al., 2010).

Within this context of "digital evolution", oblique multi-camera systems started again to be developed and employed for different application fields and market niches. They began to be thought as instruments for cartographic mapping, rather than only for