Archives of Photogrammetry, Cartography and Remote Sensing, vol. 31, pp. 21-28
ISSN 2083-2214, eISSN 2391-9477
DOI: http://doi.org/10.2478/apcrs-2019-0002

REVIEW ARTICLE

AIRBORNE OBLIQUE IMAGING: TOWARDS THE HYBRID ERA

Isabella Toschi

3DOM - 3D Optical Metrology Unit, FBK - Bruno Kessler Foundation, Trento, Italy

KEY WORDS: oblique images, LiDAR, sensor, fusion, orientation, matching

ABSTRACT: If the use of oblique aerial camera systems is steadily growing for 3D capture of urban areas, their combination with a LiDAR unit seems to have all the potential to lead the airborne mapping sector a step forward. To fully exploit the complementary sensor behaviour, a new perspective should be adopted that looks beyond the traditional data processing chains and extends them towards an hybrid data processing concept. Assisted tie point matching, integrated sensor orientation and augmented 3D reconstruction are the keystones of a rigorous hybrid workflow for hybrid sensors. They should all rely on a deep understanding of the different properties of active and passive 3D imaging, and of the uncertainty components in their measurements. The paper will focus on the most recent answers to these issues, that open new opportunities for boosting the quality of the geospatial products w.r.t completeness, geometric quality, object detection and processing efficiency

1. INTRODUCTION

Over the past two decades the airborne market for area-wide data acquisition has enthusiastically taken up oblique imaging technology: almost all existing companies in the geospatial sector now include multi-head oblique camera units in their portfolios and in a variety of configurations (Lemmens, 2014; Remondino and Gerke, 2015). The differences among their designs mainly concern the embedded imaging sensors (e.g. number, arrangement, format and spectral sensitivity) and their modes for image acquisition (e.g. Maltese cross, fan and block configurations). Actually, the idea of taking oblique images, i.e. such that the orientation of the optical axis deviates from the nadir direction, is nothing new –their use for military survey has been documented for over a century. More generally, oblique imaging has always been seen as a very attractive information source, and the reason for this is quite obvious, given the intuitive nature and the enhanced prospect of knowledge extraction typical of a slanted view geometry. Indeed oblique images, unlike traditional nadir-looking ones, display building facades and other urban vertical objects, thus making it possible to potentially reconstruct them (Haala et al., 2015; Toschi et al., 2017). Furthermore, with recent advances in dense surface generation from imagery, the geometric processing incl. high density image matching, filtering and meshing, can now be performed in "true" 3D space, thus fully exploiting the vantage viewpoint offered by oblique image acquisitions (Haala and Rothermel, 2015). However, this all comes at a cost, i.e. extending the traditional photogrammetric approaches to cope with unprecedented challenges in airborne applications, such as: large variations in image scale and illumination, multiple occlusions, an increased disparity search space and higher variances of observations quality across depth maps.

In this perspective, a concurrent acquisition of LiDAR (light detection and ranging) and (oblique) imagery data and the exploitation of the complementary sensor behavior, is likely to be the game changer for the airborne mapping sector. Apparently, the market is ready to support this trend towards a hybrid mapping concept, and in the near future most of the airborne data collection will be performed by a combination of active and passive sensors. Indeed, exploiting the advantages of both data sources may allow to cope with sensor-specific issues, thus potentially improving the quality of the final geospatial products. Furthermore, considering the flying restrictions and regulations, collecting all relevant data when already flying is also an efficient and cost-effective solution. Therefore, if almost all new generations of airborne LiDAR systems integrate in the same platform a LiDAR unit and a passive imaging unit (Mandlburger, 2019; Toschi et al., 2019), the last few years have seen the advent on the market of the first examples of hybrid mapping solutions integrating oblique imaging and LiDAR sensor into one system. Among the others, the two most popular commercial examples of such new hybrid paradigm are:

- the Leica CityMapper hybrid airborne sensor, combining a Hyperion LIDAR unit and a five-camera system (one nadir and four oblique looking camera heads),
- the IGI LiteMapper series, integrating different topographic and bathymetric LiDAR sensors with up to five camera heads (nadir and oblique).

2. HYBRID WORKFLOW FOR HYBRID SENSORS

As far as the data processing is concerned, the real challenge here is to extend the traditional processing chains for LiDAR and airborne photogrammetry towards a combined hybrid workflow. Indeed, there is clearly the need for an integrated (automatic) processing of the concurrently acquired ranging and imaging data, in order to improve their co-registration and exploit the full potential of both data sources. For this, it is paramount to (i) develop a deep understanding of the sensor-specific properties and related uncertainty sources, and (ii) consider the collected data as a hybrid dataset, and not as separate LiDAR and oblique imagery data. The final aim goes far beyond the merely enriching of the monochromatic laser echoes with RGB information, or rather the possibility to generate true-orthophotos in one go. Indeed, the new hybrid processing workflow should be conceived in such a way as to lead the airborne mapping sector a step forward, by integrating, and possibly enhancing, the most recent advances in both LiDAR processing and photogrammetric/computer vision techniques. As demonstrated by the growing body of literature dealing with it (Mandlburger *et al.*, 2017; Toschi *et al.*, 2018; Toschi *et al.*, 2019), this represents an hot research topic for the scientific community, and mainly involves the following aspects: assisted APM (automatic tie point matching), integrated sensor orientation and augmented dense 3D reconstruction.

2.1. Assisted tie point matching

A well-known challenge of APM in oblique acquisition scenarios is to match points across different viewing directions (Gerke *et al.*, 2016; Moe *et al.*, 2016). Compared to standard APM in nadir-only image blocks, issues like occlusions, large perspective distortions and symmetrical ambiguities should be dealt with, when oblique views are included in the block. The standard approach is to transfer keypoints found in the user-selected master images, to all overlapping images by exploiting their input external orientations (EO) and the shape of the terrain. Height buffers are added/subtracted to the terrain elevations in order to account for systematic effects in the EO, DEM accuracy and presence of buildings. Finally, a consistency check based on cross-correlation is applied to merge points transferred from different views and filter out outliers. Although reliable and high performing in case of nadir-only acquisitions, this approach may lead to unbalanced distributions of tie points among the different views, if applied to oblique image blocks. As an example for this, Table 1 lists the percentages of total tie points matched across camera views (NA-Nadir, FW-Forward, BW-Backward, LE-Left, RI-Right). It refers to an oblique dataset acquired with the Leica CityMapper hybrid sensor over the city of Heilbronn (Germany). It includes a total of 3,050 images, and features an average nadir GSD (ground sampling distance) of 12 cm, and along-across overlaps of 80% and 60%, respectively. The hybrid sensor, flight trajectories, control point distribution, and image footprint of one single exposure are showed in Figure 1.

Figure 1. The Heilbronn CityMapper dataset. Left: the Leica hybrid sensor. Centre: the planned flight trajectories (blue lines), image footprints (white polygons) and control points (green triangles). Right: the image footprint of one single exposure (nadir image in red, oblique images in blue).

A more balanced distribution of tie points across camera views is achieved by applying an iterative regularization strategy, including tie points filtering based on geometric and statistical criteria, and automatic points tracking based on the initial EO parameters. Corresponding results are reported in Table 2.

	NA	FW	BW	LE	RI
NA	47.1%	28.7%	28.7%	18.0%	17.2%
FW		45.1%	39.3%	9.4%	8.8%
BW			44.3%	9.5%	8.9%
LE				35.1%	34.4%
RI					36.7%

Table 1. Traditional APM: percentages of tie points across the different camera views.

	NA	FW	BW	LE	RI
NA	47.2%	40.7%	41.2%	40.8%	38.6%
FW		61.3%	58.6%	34.6%	32.5%
BW			60.7%	34.8%	32.6%
LE				58.1%	57.8%
RI					61.4%

Table 2. Improved APM: percentages of tie points across the different camera views.

To further improve the APM in hybrid acquisition scenarios, the concurrently acquired LiDAR data may be exploited to guide the matching from object space. A geometry-constrained point transfer (Figure 2) may indeed use LiDAR-derived height information to provide for a better representation of the scene 3D geometry, including buildings and other ground objects. Besides supporting the transfer of points across different viewing directions, this may have a beneficial effect on the processing time, by limiting the required vertical buffer and, consequently, the search area in the overlapping images.

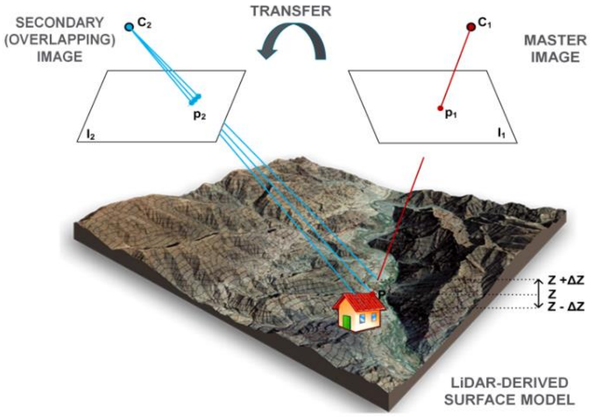

Figure 2. The transfer of keypoints between overlapping images, guided by LiDAR-derived knowledge on object space.

2.2. Integrated sensor orientation

To fully and rigorously exploit the potential of both data sources in one go, it is crucial to (i) reduce the risk of bias between the generated LiDAR and photogrammetric point clouds (i.e. to improve the relative orientation between them), and to (ii) increase the multi-sensor block stability under challenging configurations (e.g. corridor mapping). However, although initially georeferenced with the same refined trajectory, the further adjustments of LiDAR strips (SA) and of the bundle of image rays (BBA) are normally performed separately by traditional software solutions. A first step towards an integrated sensor orientation is e.g. the use of LiDAR-derived 3D points as ground control information (observed unknowns) in the image BBA. As demonstrated in (Toschi *et al*., 2018), this leads to promising results, by supporting the vertical agreement between the LiDAR and DIM clouds while, at the same time, reducing the need for field-surveys ground control points. A further step is to perform a rigorous hybrid adjustment, as the one implemented in the OPALS software by TU Wien, and described by Glira *et al.* (2019). An integrated sensor orientation where image BBA and LiDAR SA are concurrently performed, should rely on searching for reliable homologous features between LiDAR and imagery, e.g. correspondences between LiDAR points, image tie points and (when available) GNSS-measured control points. These correspondences should be only searched for in those areas where both LiDAR and photogrammetry deliver consistent measurements of the Earth surface: a deep understanding of the specific characteristics of both measurement techniques is therefore a fundamental pre-requisite. A further issue is to properly define the role (as unknowns, soft-constraints and hard-constraints) and weight of the many LiDAR-related, camera-related and trajectory-related parameters involved within the integrated adjustment itself.

2.3. Augmented dense 3D reconstruction

If a suitable redundancy and a good geometric configuration of image rays are available, photogrammetric point clouds can today feature a spatial resolution equal to the GSD of the original imagery, and a vertical accuracy below the GSD level. In particular, dense surface generation from imagery is notably strong on details and edges due to the high resolution defined by the pixel ground resolution. Furthermore, the overall dense matching quality improves when oblique images are included in the block: indeed, DIM from multi-view aerial blocks can be an effective solution to overcome the problem of viewpoint restrictions, providing for a more complete and precise information extraction in urban scenarios (Haala and Rothermel, 2015; Remondino *et al*., 2016). However, in the presence of poor texture, such as strong shadows or large white surfaces, or in case of small yards and very narrow streets, DIM reconstruction is limited by its ability to resolve texture, or even partially prevented by stereo-occlusions. If concurrently acquired LiDAR data is available and well co-registered, these issues can be mitigated by the complementary sensor behaviour. Specifically, the main strengths of LiDAR data are its high reliability of height information and multi-target capability, that enables the penetration of vegetation for bare ground acquisition and modelling. To sum up, in aerial applications the DIM point cloud is typically of higher density than the LiDAR data, whereas it features a lower depth precision than the LiDAR points. Therefore, LiDAR data can potentially support the surface generation from imagery, by additional depth measurements for higher precision and completeness.

(a) DIM only (b) DIM only

(c) DIM + LiDAR (d) DIM + LIDAR

Figure 3. Dense 3D reconstruction based on imagery only (a,b) and generated by integrating DIM and LiDAR data based on their precision and density (c,d). Source: Leica CityMapper dataset of Heilbronn processed with the nFrames software SURE.

However, a rigorous and consistent integration of DIM and LiDAR points is quite challenging, given their high variation in spatial resolution and precision. These differences should be considered while fusing the two sources of information. For instance, within the nFrames software SURE the photogrammetric precision values for each individual point are estimated and used during the fusion process. As an example for this, Figure 3 shows two views of the DIM results achieved from imagery only (top), and integrating LiDAR data (bottom). They were generated from the Leica CityMapper dataset of Heilbronn, using the SURE software.

3. CONCLUSIONS

If the use of oblique aerial camera systems is steadily growing for 3D capture of urban areas, their combination with a LiDAR unit seems to have all the potential to lead the airborne (urban) mapping sector a step forward. To fully exploit the complementary sensor behaviour a new perspective should be adopted, that looks beyond the traditional data processing chains and extends them towards a hybrid data processing concept. Assisted tie point matching, integrated sensor orientation and augmented 3D reconstruction are the keystones of a rigorous hybrid workflow for hybrid sensors. They should all rely on a deep understanding of the different properties of active and passive 3D imaging, and of the uncertainty components in their measurements. The first answers to these issues are promising and open new opportunities for boosting the quality of the geospatial products w.r.t completeness, geometric quality, object detection and processing efficiency.

LITERATURE

Gerke, M., &Nyaruhuma, A. (2009). Incorporating scene constraints into the triangulation of airborne oblique images, *ISPRS Int. Archives of Photogram., Remote Sens. & Spatial Inf. Sci.*, 38, 4-7.

Gerke, M., Nex, F., Remondino, F., Jacobsen, K., Kremerd, J., Karel, W., Huf, H., & Ostrowski, W. (2016). Orientation of oblique airborne image sets - Experiences from the ISPRS/EuroSDR benchmark on multi-platform photogrammetry, *ISPRS Int. Photogram., Remote Sens. & Spatial Inf. Sci.,* 41, 185-191.

Glira, P., Pfeifer, N., & Mandlburger, G., (2019). Hybrid orientation of airborne LiDAR point clouds and aerial images., *ISPRS Ann. Photogram., Remote Sens. & Spatial Inf. Sci.*, IV-2/W5, pp. 567-574.

Haala, N., & Rothermel, M. (2015). Image-based 3D data capture in urban scenarios. Proc. Photogrammetric Week 2015, D. Fritsch (Ed.), 119-130.

Haala, N., Rothermel M., & Cavegn, S. (2015). Extracting 3D urban models from oblique aerial images. *Proc.of the 2015 Joint Urban Remote Sensing Event (JURSE)*, pp. 1-4.

Lemmens, M.J.P.M. (2014). Digital oblique aerial cameras: A survey of features and systems. *GIM International*, Apr. 2014, pp. 20-25.

Mandlburger, G. (2019). Recent developments in airborne LiDAR. *GIM International*, Mar./Apr. 2019, 22-27.

Mandlburger, G., Wenzel, K., Spitze, A., Haala N., Glira P., & Pfeifer, N. (2017). Improved topographic models via concurrent airborne LiDAR and dense image matching. *ISPRS Ann. Photogram., Remote Sens. & Spatial Inf. Sci.*, 4, 259-266.

Moe, K., Toschi, I., Poli, D., Lago, F., Schreiner, C., Legat, K., & Remondino, F. (2016). Changing the Production Pipeline - Use of Oblique Aerial Cameras for Mapping Purposes, *ISPRS Int. Archives of Photogram., Remote Sens. & Spatial Inf. Sci.*, 41, 631-637.

OPALS, by TU Wien - https://opals.geo.tuwien.ac.at

Remondino, F., & Gerke, M. (2015). Oblique Aerial Imagery – A Review. *Proc. Photogrammetric Week 2015*, D. Fritsch (Ed.), 75-83.

Remondino, F., Toschi, I., Gerke, M., Nex, F., Holland, D., McGill, A., Talaya Lopez, J., & Magarinos A. (2016). Oblique aerial imagery for NMA - Some best practices. *ISPRS Int. Archives of Photogram., Remote Sens. & Spatial Inf. Sci.*, 41, pp. 639-645.

Rupnik, E., Nex, F., Toschi, I., & Remondino, F. (2015). Aerial multi-camera systems: Accuracy and block triangulation issues. *ISPRS Journal of Photogrammetry and Remote Sensing*, 101, 233–246.

SURE, by nFrames - www.nframes.com

Toschi I., Ramos M. M., Nocerino E., Menna F., Remondino F., Moe K., Poli D., Legat, K., & Fassi F. (2017). Oblique photogrammetry supporting 3D urban reconstruction of complex scenarios. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, 42, 519-526.

Toschi, I., Remondino F., Hauck T., & Wenzel K. (2019). When photogrammetry meets LiDAR: towards the airborne hybrid era. *GIM International*.

Toschi, I., Remondino F., Rothe R., & Klimek K. (2018). Combining airborne oblique and LiDAR sensors: investigation and new perspectives. *ISPRS Int. Archives of Photogram., Remote Sens. & Spatial Inf. Sci.*, 42, 437-444.

Wiedemann A., & More, J. (2012). Orientation strategies for aerial oblique images. *ISPRS Int. Archives of Photogram., Remote Sens. & Spatial Inf. Sci.*, 39, 185-189.

LOTNICZE OBRAZOWANIE UKOŚNE: W KIERUNKU ERY INTEGRACJI SENSORÓW

SŁOWA KLUCZOWE: obrazowanie ukośne, LiDAR, sensor, fuzja, orientacja, dopasowanie obrazów

Streszczenie

Zastosowania ukośnych systemów kamer lotniczych stale rosną szczególnie w przypadku pozyskiwania danych 3D dla obszarów miejskich. Ich połączenie z jednostką skanującą LiDAR ma potencjał, by poprowadzić sektor mapowania z danych lotniczych o krok do przodu. Aby jednak w pełni wykorzystać komplementarne współdziałanie sensorów, należy przyjąć nową perspektywę, która wykracza poza tradycyjne formy opracowania danych i rozszerza je na koncepcję hybrydowego ich przetwarzania. Wspomagane dopasowanie punktów wiążących, zintegrowana orientacja sensorów i rozszerzona rekonstrukcja 3D to kluczowe elementy rygorystycznej hybrydowej metodyki przetwarzania zintegrowanych sensorów fotogrametrycznych. Polegać ona powinna na głębokim zrozumieniu różnych właściwości aktywnego i pasywnego obrazowania 3D oraz założeń niepewności pomiaru internowanych technologii. Tematem przewodnim artykułu są najnowsze odpowiedzi na te przedstawione problemy, które otwierają nowe możliwości poprawy jakości produktów geoprzestrzennych co do kompletności, jakości geometrycznej, wykrywania obiektów i wydajności przetwarzania danych w zintegrowanych systemach obrazowania ukośnego i skanowania laserowego.

Details of author:

Dr Isabella Toschi
e-mail: toschi@fbk.eu

Submitted 29.08.2019
Accepted 13.09.2019