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Review of Methods of Combined Orientation of Photogrammetric and Laser Scanning Data

Abstract

The objective of the paper is to review the state of the art of analytical methods of integration of photogrammetric and laser scanning data which is an important scientific and practical issue. Basing on the conclusions included in previous studies, it can be observed that the analytical integration of photogrammetric and laser scanning data is an interesting area of research, especially in case of absolute orientation of images and point clouds in a sequential or one-stage adjustment process. The results of the state-of-the-art analysis are shown according to four division criteria: method of registration, workflow stage, data capture technology and calculation order. After presenting all aspects of the problem, the author proposes the two-step classification of variants of data analytical integration based on order of orientation calculation and methods of registration.

Keywords: laser scanning, photogrammetry, co-registration, data integration.

1. Introduction

The combination of photogrammetric and laser scanning data is an important research and practical issue. Many authors have discussed several aspects of data integration [1, 2]. The others use another term for integration – fusion [3-5]. The paper is focused on review of methods of analytical integration of photogrammetric and laser scanning data. Both mapping technologies have multiple common features. Airborne and mobile data are captured together with other sensor observations (GPS, INS) for trajectory definition, terrestrial data are captured from one point (like central projection), usually without extra observation like GPS, but the control points network is used. There are certain significant differences, as well. Photogrammetry uses the raster data sampled continuously, but stored discreetly in pixel grid; laser scanning uses a point cloud, which is a result of 3D discreet sampling. Photogrammetry usually captures and processes RGB and, optionally, infrared data. Laser scanning is mostly a geometric method, but almost always it presents its data in an intensity scale and point clouds can be colorized after acquisition [6, 7] compared both technologies and presented the problem more detailed by DTM and DSM generation.

After data acquisition, the absolute orientation is the most important process before the final mapping product generation. Photogrammetric data as imagery has to be adjusted, usually within the photo triangulation process. The LiDAR data as a point cloud have to be adjusted within the registration process. After data adjustment, 3D geometry is usually measured.

Tab. 1. Advantages and disadvantages of aerial imagery and LiDAR for surface reconstruction [8]

	LiDAR	Aerial imagery
Advantages:	High point density*)	Rich in scene information
	High vertical accuracy	High H+V accuracy
	Waveform analysis	Redundant information
Disadvantages:	No scene information	Stereo matching
	Occluded areas	Occluded areas
	Horizontal accuracy?	Degree of automation?
	No inh. redundancy	

*) Methods of dense matching leads today to high resolution points clouds, as well

There are some advantages and disadvantages of applying LiDAR and aerial imagery to surface reconstruction (Tab. 1) [8]. The table is valid with one exception. Photogrammetry also nowadays provides high density point clouds by dense matching methods. In the same paper, the authors present very interesting gradation (or classification) of the invariant for fusing aerial imagery with LiDAR (Tab. 2).

Tab. 2. Advantages and disadvantages of aerial imagery and LiDAR for surface reconstruction [8]

	LiDAR	Aerial imagery
Raw data	3D point cloud	pixels
Feature extraction	patches	2D edges
Processing	grouping	matching
Results	3D edges	3D edges, patches

They start with the most basic features (raw data) – for LiDAR it is a 3D point cloud and for photogrammetry – pixels. The next level is a feature extraction result as patches for LiDAR and 2D edges for photogrammetry. On the next level - processing, grouping is the LiDAR invariant feature and matching is the aerial imagery invariant feature matching. The last level is a level of results. For both methods, the authors declare 3D edges, for aerial imagery they additionally declare also patches. The above discussion is very inspiring for the continuation of a much more profound analysis of the nature and features of photogrammetric and laser scanning data.

The title of this paper is a review of analytical integration methods of photogrammetry and laser scanning data. The problem was signaled in author's PhD thesis [9] and the basic division of the data integration cases was proposed (Fig. 1).

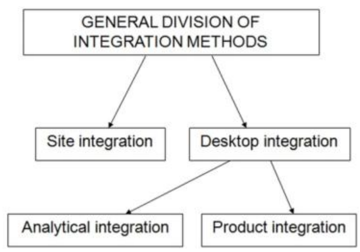

Fig. 1. General division of integration methods according to the stage of workflow [9]

In general, data integration can be divided according to the stage of the workflow into site integration and desktop integration. Site integration is the integration during the data capture process and it depends on the construction of sensors and auxiliary equipment (special tripod, mount of the camera on the scanner, etc.). Desktop integration is the integration during processing: it can appear as analytical integration and as product integration. Analytical integration gives the widest palette of potential variants. The paper discusses different possibilities of the analytical integration at the stage of absolute orientation of the data, but there are other stages of the workflow, where integration can be applied. For instance, it can be executed during the measurement of the point cloud, when finding the position of control points or check points or other reference features, also by the orthorectification process, orthoscan generation, surface, planes and edges searching and other production processes. The site integration can be used as a first step of advanced analytical integration [10]. There is also another category within the desktop integration – product integration applied when one part of the object is done with the use of photogrammetry and another by laser scanning and, afterwards, it is merged into one product.

The area of research presented in this paper overlaps these analytical integration cases at the stage of absolute orientation (in photogrammetric terminology) or/and registration (LiDAR term). It is also referred to as “co-registration” [11, 12].

2. Classification of Methods

The appropriate classification of the methods presenting the entire problem should take into account different criteria. Based on wide publication research of the last 18 years, four criteria were selected for the complete description of all aspects of analytical data integration at the stage of orientation, later named “orientation integration” for comfort. The issue of registration quality of several methods is presented in the book of Rönnholm [13]. Basing on review of methods the following classification criteria of the methods of orientation integration are defined as the most helpful ones: criterion of registration method, criterion of workflow stage, criterion of data capture technology and criterion of calculation order.

2.1. Criterion of registration method

The criterion of registration method is presented in the PhD thesis of A.S.Gneeniss [14]. All the variants of orientation integration can be divided into: feature-based registration, surface-based registration and intensity- and frequency-based registration.

The feature-based registration is the registration of two sets of photogrammetry and laser scanning data, where the geometrical relation is defined by the corresponding 2D and 3D features, like ground control points (GCP) [15, 16], straight lines [17, 18], edges, patches [10], shapes [19], planes [4, 20] and 3D models [21]. The feature of the known position or geometry is used in another data set or these features can be described by an observation equation and the equation can be used for one-step least-square adjustment.

The surface-based registration takes advantage of the relative relation between the surface calculated in the photogrammetric measurement and the point cloud. Postolov et al. [22] described a method of fitting the surfaces calculated from image- and scanner data using least-square adjustment. Gneeniss et al. [23, 24] described a similar method, but they extended it by additional extraction of "reference LiDAR Control Points" and photo triangulation with camera calibration.

The third category is the intensity- and frequency-based registration. These methods utilize additional information captured by scanning. Reflectance images generated from point clouds can be matched using photogrammetric algorithms for registration of TLS [25] or ALS data [26]. For instance, intensity values projected on the surface (such as an artificial image) can be analyzed and can be matched with other imagery [27].

2.2. Criterion of workflow stage

The second division criterion of orientation integration methods is the stage of the workflow. The author of this paper would suggest using such a criterion just for describing the complexity of the problem in a better way. The criterion relies on the level of data processing. According to the review of publications, there are three stages of data processing, where data can be used for analytical integration: calibration, orientation/registration/ georeferencing and final product generation. There is one more possibility with mixed data being at different stages of the workflow.

Integration is executed together with the sensor calibration process. The data is integrated and the calibration of the sensors proceeds in order to enhance the accuracy of data. For instance, Habib et al. [28] published a paper with method of LiDAR system calibration basing on planar patches from photogrammetry. Nakano and Chikatsu [29] increase the accuracy of LiDAR data registration by usage of results of image block self-calibration basing on pseudo GSPs. Angelats and Colomina [30] present application of straight lines as calibration and orientation features for scanner and camera mobile mapping data. Another approach is presented by Habib et al. [31]. Assessment of LiDAR system calibration uses check points of photo triangulation, which was calculated before and after calibration basing on control linear features extracted from the LiDAR data. Different calculation order was used be Gneeniss et al. [23, 24]. In this case camera calibration method was based on reference of LiDAR data.

The orientation (registration or georeferencing) stage is the most popular stage for data integration. Then the integration is executed only at the stage of orientation, all data are prepared for this process like in a separated, traditional approach of photogrammetric data orientation and independent data scanning. Usually the relation of the data is found and applied to the adjustment. Sometimes the corresponding objects (features, surfaces, etc.) are measured on one set of data and used in another one. For example, Chunjing and Guang [32] use linear tie feature and introduce the unknown parameter for least-square adjustment. Armenakis et al. [33] register LiDAR and photogrammetric DSM in two steps. The first step is a robust orientation based on points and planes. The second step uses Iterative Closest Points (ICP) algorithm on corresponding building point clouds. Rönnholm and Haggrén [34] use natural and artificial tie feature and compare the accuracy. Another interesting approach is presented in the paper of Zhang et al. [35]. They use an inherent geometrical constraint for registration of image and laser scanning data. "It is based on the phenomenon that the back-projection of LiDAR point cloud of an object should be located within the object boundary in the image."

The third stage of data processing is the stage of product generation, when data can be used for orientation integration. The corresponding objects can be 3D models or surfaces as the result of LiDAR data or imagery processing. Habib and Schenk [36] propose "to compare two surfaces by computing the shortest distance between points in one surface and locally interpolated surface patches of the second".

The last possibility is a mixed solution. There are examples of orientation integration using the calibration and orientation stage [30]. Another example from literature describes the use of data at the stage of orientation and product generation [37, 38].

2.3. Criterion of data capture technology

The data capture technology is the third main criterion of the division suggested by the author. There are three main technologies of data capture connected with the nature of the raw data; they are very important for the correct understanding of data nature and features. Thanks to the profound understanding of the nature of data, the most correct and efficient method of data integration can be formulated and tested. There are three kinds of data or three acquisition technologies: aerial data, terrestrial/close-range data and mobile mapping data. The study of the publications presents several examples of the integration of photogrammetric data with terrestrial laser scanning (TLS) data [4,10,39], aerial laser scanning (ALS) with aerial photogrammetry [17,40] and mobile mapping imagery with mobile laser scanning (MLS) data [11, 30]. There are also examples of interesting integration of different technology data: TLS with aerial imagery [35], ALS with close-range photogrammetry data [37] and MLS data with close range [41] and aerial photogrammetry [42].

2.4. Criterion of calculation order

The criterion of the order of calculation is the fourth criterion of the division of orientation integration methods proposed by the author. There are many papers, which describe the experience of orientation integration and this criterion seems to be a natural, robust criterion of these methods. The criterion is also important because of the importance of the calculation order in the theory of geodesy and data adjustment theory and practice. It is obvious that the one-step, simultaneous calculation and adjustment are the most correct.

There are three approaches to this problem in the reviewed papers.

The first one is the use of image data to acquire reference data for LiDAR data registration [43, 44].

The second one is the opposite case: reference data coming from LiDAR data for image external orientation [18, 23, 45].

The most elegant solution is the third case. Both sets of data are adjusted in the same process. Chunjing and Guang [32] use observation equations basing on collinearity equations and straight lines observed on images and LiDAR data introducing, mentioned before, unknown parameter. Yang et al. [12] use 2 kinds of error equations for combined adjustment. The equations of the first kind are relevant with tie points, the equations of the second kind are "the error equation of the pseudo observation equations relevant with elevation".

Summarizing, each of these four criteria of division of the methods is very useful when approaching the problem and considering different aspects of data integration. The first one presents the aspect of reference objects. The second one accentuates the level of data preparation, the third one – the nature of data and the fourth one – the details of the orientation process. However, such a multi-criteria problem description is quite complex. To simplify the problem and present it clearly the general, two-step classification can be applied.

3. Proposal of General Classification

Based on the experience of all authors, the author proposes the general classification of data integration methods at the stage of orientation (Table 3).

Tab. 3. Two-step division of orientation integration methods

Id.	Step 1 Criterion of the order of calculation	Item	Step 2 Criterion of the method of registration
1.	Image data for LiDAR registration:	1.1	Feature-b. registration
		1.2	Surface-b. registration
		1.3	Intensity- and frequency-b. registration
2.	LiDAR data for imagery EO:	2.1	Feature-b. registration
		2.2	Surface-b. registration
		2.3	Intensity- and frequency-b. registration
3.	Co-registration	3.1	Feature-b. registration
		3.2	Surface-b. registration
		3.3	Intensity- and frequency-b. registration
		3.4	Others

The two-step classification of the methods emphasizes two important aspects from a theoretical and practical point of view: the flow of registration and the method of reference objects or correspondence object application.

3.1. Image data for LiDAR registration

The first position of the first step criterion is "Image data for LiDAR registration" (Table 3, item 1.1).

There are three positions of the classification of 2-step (criterion of registration method) for "image data for LiDAR registration" in the first step criterion.

The first one is feature-based registration using several objects such as ground control points [18, 44], lines [17] and planes [20, 43]. The second one is surface-based registration represented by the already mentioned paper [21] (Table 3, item 1.2). The third method for the use of image data for LiDAR registration is intensity- and frequency-based registration [25, 26] (Table 3, item 1.3). The paper [44] presents a very interesting example of the application of conjugate points derived by an aerial triangulation block of photos simultaneously captured with laser scanning for LiDAR data georeferencing and adjustment. The presented approach involves the use of conjugate points, which "are automatically matched between the LiDAR intensity image and the aero-triangulated aerial image." The results of the experiment are very promising: "The planimetric correction accuracy is higher than average point distance while the vertical correction accuracy is comparable to that of the result of aero-triangulation." Another interesting solution is presented in the paper of Wienmann et al. [46]. Geometric and radiometric data of TLS are used together for point clouds registration. The photogrammetric methods are applied for intensity images generated from TLS data.

3.2. LiDAR data for imagery external orientation

The second position of the first step criterion is "LiDAR data for imagery EO." There are three positions of classification in the second step.

The first position is the case of feature-based registration (Table 3, item 2.1). Such a solution is presented in several papers. The features extracted from scanning data for external orientation of images are: points [15, 47, 48], straight lines [18], shape features [19], 3D models [21] and planes [4]. It is worth presenting the two approaches in more detail. The first approach uses GCPs for the enhancement of EO accuracy [45]. The authors use "high precision registration points (...) as Ground Control Points." Finally, they conclude that "the method which registers aerial images and LiDAR points has a great advantage in higher automation and precision as compared with manual registration." Another paper, which is worth to be mentioned here, presents an approach of semi-automatic extraction of 3D line segments of the building ridges and boundaries [40]. These 3D lines are projected to the image space and the corresponding 2D lines on the UAV images are also extracted. In the adjustment result, "the linear feature-based method directly using the LiDAR 3D data as control can provide higher registration accuracy to the sub-pixel level, resulting in higher absolute accuracy in object space positioning." LiDAR data can be used also for registration of oblique images without initial orientation [49]. DSM from optical imagery-derived point cloud and LiDAR point cloud is generated. "The novelty of the proposed approach is in the computation of salient features from the DSMs, and the selection of matching salient features using geometric invariants coupled with Normalized Cross Correlation (NCC) match validation." Then ICP algorithm for refinement of registration is used. Different approach to the registration of imagery on LiDAR data is presented by [50]. Instead of geometrical methods the authors explore statistical dependency of two datasets to be registered. The "complementary information in the LiDAR DSM and LiDAR intensity data" and application of Normalized Combined Mutual Information (NCMI) "can significantly improve registration accuracy and robustness".

The case of surface-based registration is the second position of classification. (Table 3, item 2.2) It was described for instance in the paper of Gneeniss et al. [23] already mentioned in the chapter "Criterion of workflow stage".

The third position is intensity- and frequency-based registration (Table 3, item 2.3). In this category, the paper of Meierhold et al. [27] presents the solution of matching the intensity of TLS images to register close-range imagery. Another approach is presented by Gonzalez-Aguilera et al. [51]. The images of amateur camera are matched with range images generated from TLS data. The final camera resection provides the external orientation of the images. I expand the intensity-based registration to this radiometric method to classify such an approach within this category.

3.3. Co-registration

The third position of the first step of classification seems to be the most correct one: co-registration or simultaneous adjustment process for external orientation/registration of both sets of data.

Feature-based registration is most popular in worldwide research (Table 3, item 3.1). The GCPs are basic features for co-registration [29]. Another advanced point feature approach is presented in the paper [11,12]. Before the final adjustment, three steps proceed (Fig. 2).

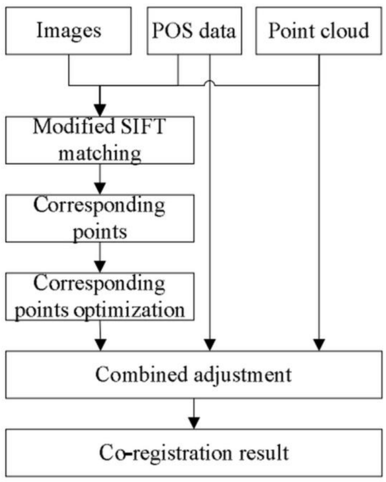

Fig. 2. Workflow of co-registration proposed by [12]

The height distribution of the point cloud surrounding feature points found with the use of the SIFT method is taken into account and the corresponding points are kept for further adjustment "only if there are enough points with similar height (…)." Later, the combined adjustment is used for the registration of the airborne laser scanning data and the synchronized digital images. The authors conclude that "the experiment shows that the method could achieve higher accuracy than the method which only considers the rotation angle." Other features are also used as corresponding data and the authors prove that the best results are achieved using linear objects [18, 35, 39, 51]. The linear features used as the control and correspondence feature give higher co-registration accuracy than other features [32]. Planes are the next kind of features presented in papers [33, 34]. In some experiments, linear and planar features are used for co-registration [28]. The conclusion is positive: "the complementary characteristics of photogrammetry and LiDAR, if exploited, can lead to a more complete surface description."

The surface-based registration methods form the next group of co-registration methods (Table 3, item 3.2). The example presents for instance already mentioned paper of [36].

The intensity- and frequency-based registration methods are the last ones in the proposed classification (Table 3, item 3.3). It is represented, for instance, by the paper of [52] describing an advanced approach based on LPFFT (Log-Polar Fast Fourier Transform), Harris corners and RANSAC applied for intensity and optical images.

4. Conclusions

The profound studies of the state of the art of analytical integration of photogrammetric and laser scanning data at the stage of orientation confirm that majority of the authors using different methods are able to obtain more coherent and more accurate data.

The presented two-step classification of the methods permits to present the whole complexity of all the variants of the orientation integration clearly and entirely. Firstly, the four criteria have been presented to look at the problem from a different point of view. But the proposed classification method seems to be the most adequate.

The studies of actual publications lead to the following main conclusions being also the research challenge and the basic direction of the future research of the author.

Universal data format for vector and imagery data would be helpful for profound data integration. The raw data named "pix-point" should include all pixels (image) and scan point information. The redundancy of the data would be a disadvantage of such an approach. The most important advantage would be the flexibility of the usage of such a data format for co-registration, with an ability to change according to partial accuracy results.

There are several levels of potential feature-based registration as a data integration process. One potential classification can be: point/pixel, stereo model/point cloud, dense matching point cloud/LiDAR data. Another potential classification would be based on a number of dimensions of the feature: 1D features/2D features/3D features. As Chunjing and Guang [32] declare: "In order to enhance the universality of algorithm, the registration method using various features on this basis is needed".

The plenty of possible co-registration solutions provide the opportunity to define the most effective procedures of co-registration, for instance, to combine an intensity-/frequency-/image-analysis-based adjustment process with a feature adjustment process. This conclusion is compatible with the following citation: "(…) effort should focus on automation with the extraction of common features from photogrammetric and LiDAR data, as well as the matching of the conjugate primitives" [40].

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