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Enhancement of Lidar Planimetric Accuracy using Orthoimages

Krzysztof Bakuła, Wojciech Dominik & Wojciech Ostrowski, Warsaw, Poland

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Summary: In this study the planimetric accuracy of lidar data was verified by registration of laser reflection images, point cloud modelling results and true orthophoto. The presented research is the basis for improving the accuracy of the lidar processing products, which is particularly important in issues related to surveying measurements. In the experiment, the true orthophoto generated by dense matching of aerial images was used to check for the planimetric accuracy of lidar data in two proposed approaches. The first (intensity-based) analysis is carried out by comparing coordinates of manually selected, salient points in the true orthoimages and rasters of the lidar reflection intensity. The second (feature-based) method to verify planimetric accuracy is based on matching roof ridges extracted from lidar data and true orthoimages. Both analyses were carried out for 3 fragments of lidar strips. A detected systematic planimetric error in the centimetre level range enabled the implementation of appropriate local correction for the analyzed data. The presented solutions provide an opportunity to improve the planimetric accuracy of lidar data that allow its efficient usage.

Zusammenfassung: *Die Verbesserung der Lidar Lagegenauigkeit mit Orthofotos.* In dieser Studie wurde die Lagegenauigkeit von Daten aus Airborne Laserscanning (ALS) unter Verwendung von Messungen der aufgezeichneten Reflexionsintensität des Laserstrahls und der Modellierung von Punktwolken analysiert. Die Ergebnisse wurden verwendet, um die Genauigkeit der Verarbeitung von Lidar-Daten zu verbessern. Diese Art der Verarbeitung ist bei geodätischen Messungen besonders wichtig. Orthofotos wurden verwendet, um die Lagegenauigkeit von ALS Ergebnissen zu bewerten. Die Genauigkeit wurde mit zwei Verfahren bestimmt. Das erste basierte auf einem Vergleich der Position ausgewählter Punkte auf Luftbildaufnahmen mit Punkten auf dem Raster der Reflexionsintensität (Intensität-basiertes Verfahren). Das zweite Verfahren (Feature-basiertes Verfahren) verwendet zur Prüfung der Lagegenauigkeit Dachfirste von Gebäudemodellen aus Lidar-Daten. Diese Analysen erlauben die Erkennung systematischer Fehler von wenigen Zentimetern und damit die Berücksichtigung der entsprechenden lokalen Änderungen. Insgesamt, ermöglicht dieser Ansatz, die Genauigkeit der Lidar-Daten zu verbessern und deren Nutzung effizienter zu gestalten.

1 Introduction

Aerial 3D data acquisition is currently dominated by two leading technologies. The first is the usage of aerial images and their subsequent matching, and the second is airborne laser scanning (ALS). Both technologies are often considered as alternatives for 3D data collection and for the generation of consecutive products, such as digital elevation models and 3D city models. Moreover, products resulting from a fusion of these two data sources have become increasingly more common in recent years. Their interaction for accuracy improvement of the final products has also been observed recently (Park et al. 2011, Beger et al. 2011, Parmehr et al. 2013, Gerke & Xiao 2014).

Aerial images have been acquired since the beginning of photography. Over more than a century of development of photogrammetry very sophisticated methods of image processing and data acquisition were elaborated. Aerial images have been the main primary

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source of data for most cartographic products for decades. Image data allow for the precise identification of control points. This results in centimetre-level planar accuracy of the exterior orientation of the images and facilities measurement accuracy better than the ground sampling distance (GSD). However, image-based approaches tend to fail in areas covered with vegetation and are labour-intensive. The advantage of automatic image-based data acquisition methods is the collection of 3D information from one source. Dense matching of images has revolutionised photogrammetry in the last decade and given an impulse to further development of automatic photogrammetric measurement methods. Since the publication of the semi-global matching (SGM) algorithm (Hirschmüller 2008) much research into its application to aerial images has been conducted. The main areas of research are related to the application of the very dense point cloud for the generation of high quality digital surface models (DSM), digital terrain models (DTM) and 3D building models. The accuracy and other quality aspects of point clouds generated by dense image matching have been investigated in Rothermel & Haala (2011) and Hirschmüller & Bucher (2010). This research leads to the assumption that point clouds derived by dense image matching and subsequent fusion techniques are characterized by very high accuracy – less than 1 GSD both horizontally and vertically. It opens a very broad field of potential applications for this data source.

ALS, often called lidar (light detection and ranging), was initially seen as a technology for height measurements of the terrain to generate high-resolution DTM. After its commercial implementation the vertical accuracy of lidar point cloud was mainly considered (Shan & Toth 2008). In later years, with the increasing density of point clouds provided by lidar, its potential use in the context of other applications was recognized. The issue of the planar accuracy of lidar data also became a subject of discussion because vertical and planar accuracy are interdependent – which is particularly important for more complex DTM in sloped parts of terrain (Aguilar et al. 2010). High horizontal accuracy is crucial in studies associated with point cloud processing including: feature extraction, i.e. 3D modelling of buildings, engineering objects, roads, railways or river embankments, obstruction surveys as well as the merging of different datasets. Lidar datasets are frequently collected in country-wide or regional projects to generate elevation products such as DTM, DSM and 3D buildings models. The example of such a national program is the Polish IT System of the Country's Protection against extreme hazards (ISOK) where much higher vertical than planimetric accuracy is noticed (Kurczyński & Bakuła 2013). This is the reason why further using of lidar datasets collected within ISOK is sometimes limited in tasks requiring high planimetric accuracy specified by other legal restrictions related to surveying techniques.

The solution is to develop a method that can increase the horizontal accuracy. This could also be of interest for the alignment of lidar and photogrammetric data for subsequent data fusion. The main scope of the presented research is to develop and analyze methods for the improvement of the planar accuracy of lidar data. In this context, a true orthophoto generated from a DSM based on SGM can be very helpful due to its higher point density and its high planar precision. The proposed techniques might be utilized for applications in which the use of lidar is essential, e.g. for the determination of ground points in vegetated areas, for mapping small entities such as power lines (Jwa et al. 2009) or railways (Marmol & Mikrut 2013), where high penetration of vegetation and high vertical accuracy as provided by lidar as well as a high planimetric accuracy offered by images are required.

Modern technologies of 3D data collection acquire lidar point clouds with a relative accuracy of 2 cm – 3 cm (Vosselman 2008). Csanyi & Toth (2007) demonstrate that the use of specially designed targets may enable a similar level of absolute accuracy considering a dense point cloud of 16 points/m^2. However, the large amount of manual interaction associated with the use of control targets as well as the need for their installation before the flight makes it an impractical solution (Ray & Graham 2008). Having in mind these problems and limitations, in this paper two methods for the validation of lidar point clouds and their correction for local biases are proposed. In contrast to the concept of using back-projection of laser points to images by the collinearity equation as proposed by Seo et al. (2001), in this article the use of independent measurements derived from a true orthophoto and their use for the assessment and improvement of the planimetric accuracy of lidar point clouds is examined. Images provide a very large number of features which may be measured for a reliable evaluation of the accuracy and the estimation of local planimetric corrections for lidar data. In particular, the key advantage of using a true orthophoto is the opportunity for the selection of reference measurements not only at the ground level, but also on building roofs. A true orthophoto is a metric data source providing valuable spatial and spectral information for various GIS and mapping applications (Bang et al. 2007, Kowalczyk et al. 2010). On the other hand, it cannot be disregarded that creating true orthophotos requires serious efforts and costs. The production of true orthophotos is justified particularly in urban areas with densely located and high buildings. They provide a continuous visualization with the exception of obscured areas which still enables the selection of corresponding features for the registration of lidar and other data sources. True orthophotos can be used for quality assessment of lidar data, and they can even support the georeferencing of these data without additional ground control. In this paper, they are used to validate and to improve the planar accuracy of lidar point clouds.

Methods for registration of images might be divided into two main groups: feature-based and intensity-based techniques (Goshtasby 2012). In addition, Hui et al. (2012) proposed a frequency-based approach for the registration of lidar data and optical images.

With the ability to register the intensity of the reflected signal, studies on the reflectance image have been carried out (Maas 2002). Although the intensity images look similar to optical images, they have different characteristics. In addition, the intensity images are usually much noisier, which was noticed by Vosselman (2002). Despite the limitations indicated in his research, Vosselman (2002) showed that it is possible to use edges obtained from lidar intensity data to determine the offsets between scanning strips. Another proposal for using reflectance images to compensate for systematic errors in the alignment of lidar strips can be found in Maas (2001). He proposed fitting the surface fragments in a TIN structure where, instead of elevation, the intensity value was applied. Maas states that it is possible to determine planimetric discrepancies between scanning strips with the accuracy of ¼ of the distance between points. The application of the intensity images as one of the observation types used to define boresight misalignment is proposed by Burman (2000). Another example is presented in Toth et al. (2007), where intensity is used to improve the absolute planimetric accuracy of lidar data by matching corresponding pavement markings on roads generated from GNSS surveying measurements with the same features identified in the lidar reflectance image. Similarly, Ray & Graham (2008) propose the digitalization of road markings in the orthoimage from lidar intensity and their usage in the absolute orientation improvement.

Many attempts have been made to co-register image and lidar data. Some of them use lidar data as a reference for image registration (Habib et al. 2005, Kwak et al. 2006, Mitishitaa et al. 2008, Choi et al. 2011, Chunjing & Guang 2012) while others consider the improvement of lidar data using photogrammetric images, e.g. Armenakis et al. (2013). The character of lidar data makes it difficult to extract precise features that would enable for co-registration of image and lidar data. To overcome this limitation more complex features extracted from the point cloud, e.g. edges (Chunjing & Guang 2012, Choi et al. 2011), centre points of buildings (Ahocas et al. 2004), planes (Armenakis et al. 2013) or centroids of planes (Mitishitaa et al. 2008, Kwak et al. 2006) have been used. Another possibility is to use features extracted from the intensity raster, e.g. points (Toth et al. 2007, Burman 2000), lines (Vosselman 2002, Ray & Graham 2008). In this paper the authors propose to use methods based on two types of features that enable a precise horizontal survey, namely roof ridges extracted from point clouds and points extracted from raster images generated from the lidar reflection intensity.

The novelty of the methods presented in this paper is the use of a true orthophoto that is a side-product of SGM, generated by an orthogonal projection of the coloured point cloud from SGM rather than by back-projection of points interpolated from a DSM into the images (Miller 2004). Despite of many shortcomings (incompleteness of the coverage, distortions in shadowed and vegetated areas) it is worth emphasizing that such a true orthophoto can be obtained fully automatically as a side product of photogrammetric projects without significant additional costs. The authors claim that it is worthwhile to look for applications that take advantage of the accessibility and great potential of this product.

In the presented research we show empirically that such a true orthophoto is characterised by a very high absolute horizontal accuracy, which give rise to its application as a reference for the lidar point clouds. Two independent methods of validation and correction of lidar horizontal accuracy are presented based on photogrammetric data source. Similar results obtained from both methods show that using true orthophotos generated as a side-product of SGM allows for the detection and correction of local lidar biases.

This paper is structured as follows. First we present the proposed methodology for validation and improvement of the planimetric accuracy of lidar data based on the calculation of the local (sub-block) error. The first method is based on manual measurement of points on the lidar intensity images and a true orthophoto. The second method is based on the distances between ridges generated automatically from lidar data and ridge lines extracted from the true orthophoto. After the description of these methods an experimental area is presented. The results obtained from both methods are compared to draw conclusions concerning the possibility of using true orthophotos from dense matching in the assessment and correction of the horizontal accuracy of lidar data. Future developments of the presented methods with the ultimate aim of a higher degree of automation are outlined in section 5.

2 Methodology

2.1 *The Intensity-Based Approach*

The first method proposed in this paper was to measure planimetric discrepancies between homologous points on the true orthophoto and lidar intensity image. The points were usually selected as distinct points in the lidar intensity image, because of its lower spatial resolution and the noise they are affected with (Maas 2001). After that, they were also measured in the true orthophoto. The most frequently selected point types were associated with centres of white road markings, manhole covers and centres of visible small patterns on pavements surface because of their high contrast in the intensity images with respect to surrounding objects. Furthermore, they are expected to be less biased than the ends of linear objects or edges of surface objects.

Considering the methodology for the georeferencing of a lidar block, the accuracy is not constant over the area and can vary locally. Therefore, the local fragments (sub-blocks) are created to adapt best to local errors and help to minimize the overall error budget. The errors for X and Y co-ordinates are analyzed separately in the proposed approach by the estimation of appropriate corrections for both directions. The correction model is a simple shift, determined independently for each sub-block requiring an improvement of planar accuracy. Potential discontinuities at the sub-block boundaries can be limited by using overlapping sub-blocks. The values of potential planimetric corrections (1) are computed as the negative median value of the horizontal displacement for the whole test area:

$$\begin{aligned} v_x &= -Median(D(x)) \\ v_y &= -Median(D(y)) \end{aligned} \tag{1}$$

where

$D(x)$, $D(y)$ are measured displacements between homologous points,

v_x, v_y are estimated corrections.

The estimated planar correction can be implemented locally. The aim of such a procedure is to obtain a limited area (sub-block) with augmented horizontal accuracy.

2.2 *The Feature-Based Approach*

The second method evaluated in this study was based on normal distances between the ridge lines of buildings which can be extracted from the lidar dataset automatically and digitalized on the true orthophoto to estimate the planimetric displacement. Ridge lines of gable roofs, obtained as the intersection lines of two planes fitted into the point cloud, are one of most accurate features extracted from lidar data and they can be used to improve the relative planimetric accuracy of the point clouds (Vosselman 2008).

Automatic classification of point clouds and building roof extraction was performed using the TerraSolid software. Building models are generated by the TerraScan module, which is based on an algorithm for fitting planes to parts of point cloud classified as 'buildings', combining these planes in order to create roof models (Soininen 2014).

Ridge lines of all detected buildings are also measured manually in the true orthophoto. In contrast to Vosselman (2012), who measured the distance between centres of ridges, the displacement between the corresponding roof ridges from both data sources was calculated as the distance from the middle point of a ridge line on the true orthophoto in the normal direction, i.e. perpendicular to the direction of the ridge line from the true orthophoto. In the case of two ridges from the lidar data, it can be assumed that they are equal in length. However, in the case of ridges from different data sources, their lengths might not be identical. This may result in problems associated with determining the start and the end of the line and, consequently, centre point. Nevertheless, the directions of the ridges from both of these data sources are maintained. They should be approximately parallel and the normal displacement vector between pairs of ridge lines from two sources should indicate the magnitude of planimetric error of lidar data in this particular direction.

The polar coordinates of a local displacement vector were estimated by a least-squares adjustment in order to minimize the squared sum of the normal distances between the corresponding ridge lines after applying the displacement vector. The objective function (2) was defined as:

$$\min \sum_i (D \cdot \cos(\Phi - \varphi_i) - d_i)^2 , \qquad (2)$$

where

d_i is the observed length of the normal displacement vector between a pair of ridges,

φ_i is the observed polar angle of the normal displacement vector between a pair of ridges,

D is the unknown length of the local displacement vector and

Φ is the unknown polar angle of the local displacement vector.

The estimated corrections (v_x, v_y) were calculated as follows:

$$\begin{aligned} v_x &= -D \cdot \cos\Phi \\ v_y &= -D \cdot \sin\Phi \end{aligned} \qquad (3)$$

The proposed method for the implementation estimated correction in this approach can be applied the same way as in the first approach – as simple shift for both directions.

3 Experiments

3.1 *Data used in this Study*

In the presented research, aerial images and lidar data were used. Such datasets were collected in flight missions involving the whole city of Elbląg (about 100 km^2). Both flight missions were conducted in March 2011 before the vegetation period with an interval of three weeks. As a test area for the experiments a fragment of the block (approximately 0.5 km^2) with densely located buildings was selected.

Aerial images were acquired with an Intergraph DMC II 230 camera with 80% overlap, 40% side lap and a GSD of 5 cm. A block of 2.243 images was triangulated with the use of 86 GCPs. The obtained accuracies estimated by comparison of object coordinates to 96 check points were as follows: RMSE of 2.9 cm (Easting), 3.8 cm (Northing), 4.5 cm (Z). On the basis of the adjusted image block, point clouds were generated using the modified version of SGM that is implemented in the SURE software (Rothermel et al. 2012). Such point clouds with assigned RGB values from images were subsequently used to create raster images of point clouds in an orthogonal view, providing a true orthophoto without much effort and cost requirements.

These images were used to create a true orthophoto mosaic of the test area with a spatial resolution of 7 cm. The absolute accuracy of such a true orthophoto was verified because it is used as the reference for further research concerning planimetric accuracy. We determined 21 check points located in the test area using real time kinematic global navigation satellite system (RTK GNSS). The differences between the coordinates were manually measured on the true orthophoto and the surveying observations determined the accuracy characteristics of the true orthophoto. Based on the results presented in Tab. 1, it can be concluded that the true orthophoto shows no bias and the RMSE is 3 cm – 4 cm which is comparable with the accuracy of RTK GNSS measurements. This shows that the true orthophoto is a product of high planimetric accuracy and can be used as reference data for the assessment of the horizontal error in the lidar data.

Tab. 1: Accuracy characteristics of the true orthophoto.

Parameter	X (Easting) (m)	Y (Northing) (m)
Average residual	-0.001	0.014
RMSE	0.038	0.034
Std	0.038	0.031

Lidar data was acquired with a Riegl LMS-Q680i airborne laser scanner with 60% sidelap between scanning strips. A total of 70 strips were acquired. The average density of the point cloud in a single scanning strip was approximately 10 points/m^2. The data were subjected to a process of internal, relative alignment and fitted to reference planes surveyed in situ. This process was carried out using the RiProcess software, which is applied to raw lidar data acquired by Riegl scanners. The roofs of the buildings in 5 locations were used as reference planes. In each location two roof planes oriented perpendicularly to each other were surveyed. The relative alignment of the block was carried out using 117,875 observations on the tie planes – as a result, the

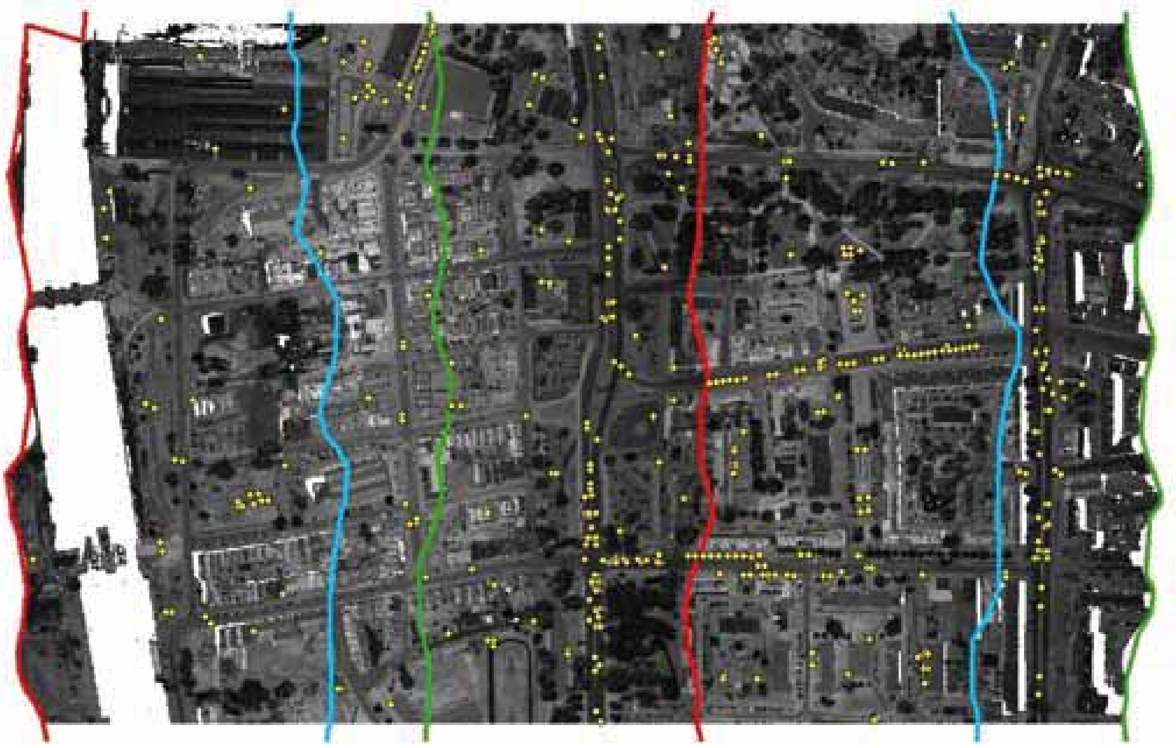

Fig. 1: Spatial distribution of points manually measured on the intensity image and the true orthophoto overlaid with the presentation of the scanning strips edges.

correction for each scanning strip trajectories was made. After this process, the whole lidar block was fitted to the previously mentioned reference planes and the residuals indicate a global shift of 4.4 cm (X), 6.0 cm (Y) and 2.8 cm (Z) for the whole block. After the adjustment, the RMSE calculated from normal distances to the reference planes was 4.2 cm with the highest residual value of 8.8 cm. As a result of the described procedure the whole lidar block is best fitted into the reference planes by applying a global correction. However, the remaining residuals on the reference planes show that the georeferencing accuracy varies in different regions of the block. Therefore, we can still expect local errors at a level of a few centimetres.

In the presented research, fragments of three scanning strips were selected and intensity images with 15 cm GSD were prepared. Each of the intensity images was created by assigning the average intensity value to each pixel. The average intensity value scaled to the 8-bit greyscale of all lidar points was located inside this pixel. The intensity values for pixels with no points in its range were determined by bilinear interpolation.

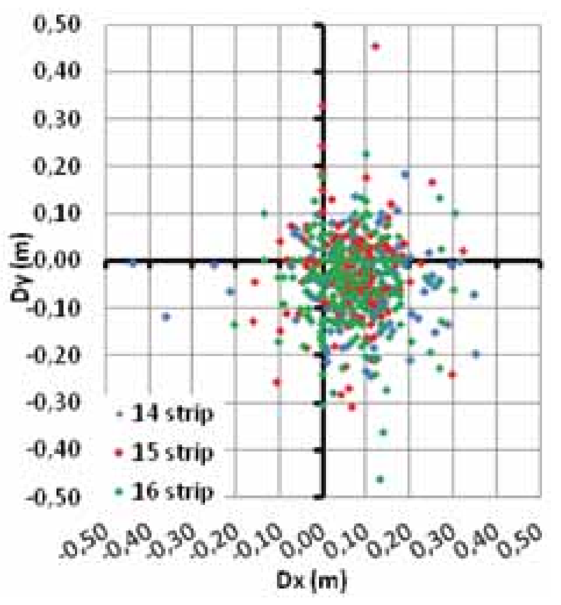

Fig. 2: Planimetric residuals of points measured on the intensity raster in reference to their location on the true orthophoto for 3 analysed scanning strips in the intensity-based approach.

3.2 *Results of the Intensity-Based Approach*

After the georeferencing procedure the intensity-based approach is applied. Though its accuracy is minor it helps to compensate local errors because the global approach is only based on a limited number of surveyed planes. The spatial distribution of observations in this approach is shown in Fig. 1. The results of the measurements on the intensity raster (planimetric displacement for each point) for single scanning strips are presented in Fig. 2. Measurements were carried out for 550 points totally in three strips: 150 points were measured in strip 14, 150 in strip 15 and 250 in strip 16.

In Fig. 2, significant shifts in the X direction for all strips are clearly visible. This is also confirmed by statistical parameters (Tab. 2). The final correction caused by shift parameters obtained in this method were calculated as -0.07 m in X direction and +0.04 m in Y direction.

Due to the large number of outliers which were expected in manual measurement, the

Tab. 2: The result of corresponding points measurements on ALS intensity image and true orthophoto for planar shift estimation.

Strip	Parameter	X (m)	Y (m)
14	mean	0.09	-0.05
	median	0.10	-0.05
	Std	0.11	0.08
150 points	RMSE	0.14	0.09
15	mean	0.07	-0.02
	median	0.07	-0.01
	Std	0.08	0.10
150 points	RMSE	0.10	0.11
16	mean	0.06	-0.05
	median	0.07	-0.05
	Std	0.08	0.09
250 points	RMSE	0.08	0.08
all 3 strips	mean	0.07	-0.04
	median	**0.07**	**-0.04**
	Std	0.09	0.09
550 points	RMSE	0.11	0.10

corrections were computed based on the median value instead the mean value. The measured points and the results were evaluated by the standard deviation of the observations (Std) and the root-mean-square error (RMSE) for the assessment of the planimetric accuracy of the lidar data.

In this paper we just want to show that such a method is possible for the error estimation without caring whether the measurement process is manual or automatic. Nevertheless, in these studies the automation of measurements was also attempted (Fig. 3), but it was associated with many difficulties caused by different geometry and radiometry of the images from different sources. Such activity which can lead to the synergy of lidar with optical imagery can be very sophisticated and it is still a big challenge (Hui et al. 2012). These datasets are derived from a different source and different flight missions. Consequently, they have a different distribution of occluded areas. Shadows are another problem that can be observed in optical images. In addition, the spectral characteristics of the reflectance in the visible and the near-infrared spectrum and of lidar reflected intensity are different. This is especially evident for the vegetation. When analysing true orthophotos in the near-infrared spectrum, vegetation is characterised by high radiometric values. In contrast, because of the low value of reflection of the laser beam, trees are represented by low radiometric values on the intensity raster images. These problems hinder the automation of the measurement of corresponding points with area-based matching methods. In order to solve this problem only regions without occluded areas (intensity raster) and no shadows (true orthophoto) were analysed. It was therefore decided to analyze only fragments of roads without any difficulties related to distinguishable radiometry differences of the two data sources. Small pieces of true orthophoto and intensity raster were subjected to a least-square matching procedure. The experiments performed led to some interesting results (Fig. 3). The majority of automatically selected points was related to road markings as the most contrasting features in intensity raster. The experiment showed that there is the potential to enable automation of the proposed method. However, the above-mentioned problems related to co-registration of a whole sub-block led the authors to only use manually measured points, as they were considered reliable enough for the assessment of the lidar horizontal error estimation.

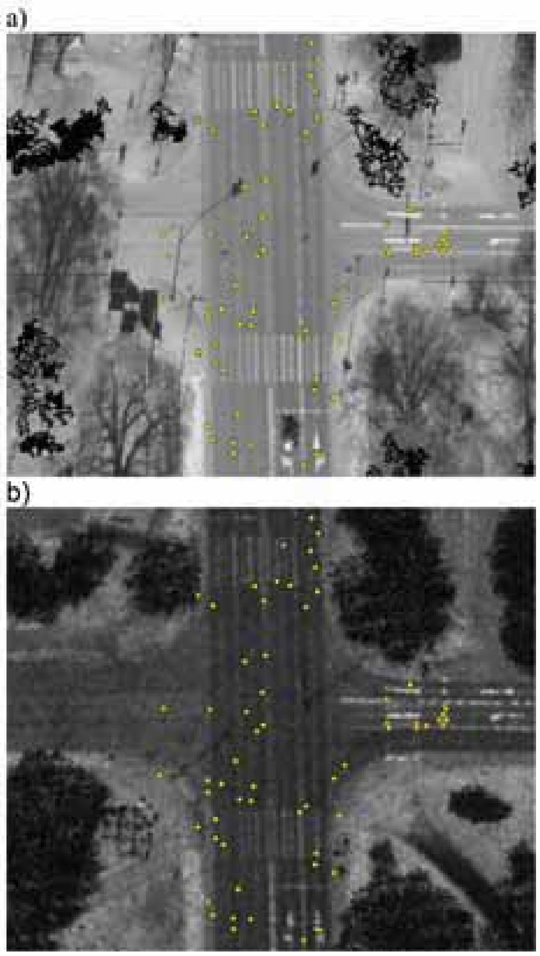

Fig. 3: Example of automatically generated corresponding points from image matching between true orthophoto (a) and raster of reflectance intensity (b).

3.3 *Results of the Feature-Based Approach*

For the experiments reported in this section a total number of 321 building models were used. Fig. 4 shows the distribution of the extracted ridge lines in the test area. The detailed view depicts automatically extracted building models based on lidar data. The background represents the true orthophoto generated by dense image matching. We determined 126 ridge lines from strip number 14, 130 from strip 15 and 67 from strip 16. The estimation of the er-

Fig. 4: An overview of all ridge lines extracted from true orthophoto in the test area and a detailed view presenting automatically lidar-extracted building models with true orthophoto from dense image matching in a background.

ror was performed individually for each of the scanning strips and also for all scanning strips together in order to characterize the planimetric error in the whole sub-block. Fig. 5 shows the values of the offset vectors between ridges digitized on the true orthophoto and those obtained from the 3D building models from the ALS data. It is worth noting that the concentration of points along the X-axis and Y-axis is caused by the orientation of roof surfaces in the test area. Points located around the X-axis are related to ridges oriented in the N-S direction and they have significant influence in determining the error in the X direction. On the other hand, points around the Y-axis are associated with ridges oriented in the E-W direction and they have a key impact on the estimation of the error in the Y direction.

In this method shift values were computed using the least-squares method. The results are presented in Tab. 3. The displacement estimated from ridge lines is similar to those measured on the intensity images (Tab. 2). In all three strips, the errors determined are compa-

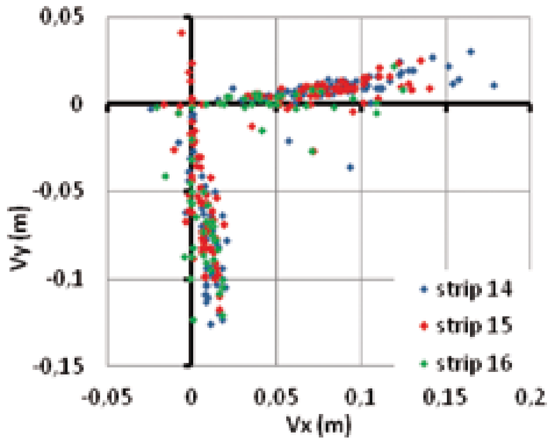

Fig. 5: Offset vectors between ridges digitized from the true orthophoto and those obtained from 3D building models from lidar data in feature-based approach.

Tab. 3: Horizontal shifts and their accuracy characteristics obtained from the measurements of roof ridges on the true orthophoto and from 3D building models.

Strip	Parameter	X (m)	Y (m)
14	Shift	0.09	-0.06
	Std	0.04	0.03
126 ridges	RMSE	0.10	0.07
15	Shift	0.08	-0.05
	Std	0.05	0.03
130 ridges	RMSE	0.09	0.06
16	Shift	0.05	-0.07
	Std	0.03	0.04
67 ridges	RMSE	0.06	0.08
all 3 strips	Shift	**0.08**	**-0.06**
	Std	0.04	0.03
323 ridges	RMSE	0.09	0.07

rable. Only results for scanning strip 16 differ slightly from the others, which can be caused by a lower number of ridges measured in this strip due to the topography of the selected urban area. The key point of the analysis of this approach is the fact that values of the standard deviations are much lower than with the previous method. The final corrections caused by shift parameters obtained in this approach were -0.08 m in X and +0.06 m in Y.

4 Discussion

Both of the methods resulted in similar values of planimetric error for the analyzed area. Lower standard deviations in the feature-based approach indicate that the usage of measured roof ridges of buildings was more reliable. However, this method is more labour-intensive and difficult to automate. It is worth mentioning that both methods have some limitations. First of all, a suitable topography of the area is required. For the feature-based approach, an appropriate number of roof ridges oriented in different directions must be provided. The application of points measured on the intensity image in the first method requires clearly defined features in both images. Consequently, there is no doubt that both methods are best suited for urban areas.

The results for both, the whole test object and individual strips, are quite comparable in the two presented methods, which confirm the correctness of both approaches as well as the possibility of the planimetric error detection in the sub-blocks on the basis of true orthophoto. Such data fitting approaches (similarly to Vosselman 2008, 2012), without considering the rotation parameters correlated locally with the displacement are the least complicated methods for large-scale applications due to many factors that influence the lidar accuracy. The presented methodology shows that it is possible to determine the errors whose value is much lower than the point spacing in lidar datasets. The results are in accordance with the authors' expectations and some small differences between the estimations for separate strips can also be related to the accuracy of their relative alignment.

The results of point measurements are characterized by a visible, large dispersion of residual values. Manually measured points were difficult to identify in the intensity images, a fact that is also mentioned by Ray & Graham (2008). However, the investigation carried out in this research indicates that in the case of good quality data, it is possible to select many corresponding points and the redundancy allows finding the expected value of the planimetric shift of ALS data, limiting the influence of gross errors. Nevertheless, the approach based only on manual measurements is time-consuming for the whole block error estimation, because different planar errors can be expected for various parts of the block. On the other hand, this paper shows the potential of this type of analysis. In such approaches it is very important to have a large contribution of automation in the matching of corresponding points (Burman 2000, Maas 2002) which is, however, related to the problems previously mentioned. In contrast to other publications considering the analyzed subject, the detected errors are relatively small, which is caused by the increasingly higher quality of modern photogrammetric data characterized by a very small GSD (aerial images) and high density of the lidar point clouds.

In this study the intensity of laser beam reflection was applied to determine the absolute accuracy of ALS data with the product of aerial image processing (orthoimages) as a reference, while in the literature it is more likely to find approaches using the intensity images for analyzing only the relative lidar data orientation (Burman 2000, Maas 2002). The presented research differs from some other methods regarding the absolute accuracy (Csanyi & Toth 2007), because in contrast to those approaches, it is not based on control targets. This is particularly important when considering lidar data already acquired and archived in repositories. There are usually no control targets for such data because the main objective of their acquisition was not necessarily very high planimetric accuracy.

The presented research has shown that the use of a true orthophoto that is a side-product of SGM can allow for the enhancement of horizontal accuracy of lidar data. The application of this type of imagery has a considerable potential for the automation which would allow obtaining lidar data with an augmented horizontal accuracy in urban areas and hence the possibility of integration with other image data and GIS databases.

5 Conclusion

Using a true orthophoto with high planimetric accuracy as a reference, the presented methods allow for the calculation of the planimetric displacement of lidar data. It can correct it to a level that enables wider utilization of lidar data for applications which require a horizontal accuracy of a few centimetres. The determined systematic error can be corrected by the implementation of an appropriate correction to the point cloud or products of its processing. The basic condition of a successful application of the proposed methods is the high redundancy of the measurements. At present, this requirement is fulfilled by manual measurements which become inefficient for large areas. The effectiveness of the methods for such correction can be only guaranteed by automatic techniques of corresponding features matching (points, lines). The application of intensity-based matching algorithms, with true orthophoto as a reference can be difficult due to the different characteristics of both data sources.

Future work should focus on larger and less fallible automatic techniques for the planimetric comparison and bias estimation of lidar by matching of orthophotos from aerial images and intensity of laser reflectance. It is expected that such automation is achievable in feature-based approaches based on true orthophotos. However the subject of horizontal accuracy, which is sometimes omitted, is still not exhausted assuming that it does not have to be limited to investigations in 2D. These analyses could also involve 3D features: ridge lines and even entire roof planes which can provide both vertical and planar discrepancies. Future activities in this work should also consider the evaluation of such methodologies as well as the assessment of intensity images or building ridge potential in improving the horizontal accuracy of lower quality lidar data that are usually available for large areas. The presented approach could then be used for the data already acquired in country-wide or regional systems for applications requiring high planimetric accuracy.

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Address of the Authors:

Krzysztof Bakuła, Wojciech Dominik & Wojciech Ostrowski, Warsaw University of Technolgy, Faculty of Geodesy and Cartography, Plac Politechniki 1, PL 00-661 Warsaw, Poland, Tel. +48-22-234-76-94, e-mail: {k.bakula}{w.ostrowski}@gik.pw.edu.pl, wojciech.a.dominik@gmail.com

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