Digital Surface Model Generation with Aerial Surveying System "LEICA ADS80"

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Abstract: The aerial imaging system LiDAR is data collection technology for Digital Surface Models (DSM) and Digital Elevation Models (DEM). Digital line Pushbroom scanner Leica ADS80 can be used to obtain DSM / DEM thanks to the recorded material. The data obtained using the ADS80 provide several advantages over LiDAR results, especially since the generation of orthophotos can be based on the same data set. As a fundamental approach, the principle of Semi-Global Matching (SGM) it is used, which is suitable for the process of calculating digital models of high-performance and high-resolution surfaces. This paper presents the SGM approach during processing images obtained by the ADS80 system, as well as comparing the results obtained using the LiDAR system - in terms of data processing. A comparative analysis and comparison of SGP and LiDAR ALS80 HP properties was performed, which is illustrated on a specific example. It has been shown that SGM can be used as an alternative to the LiDAR system. For certain applications for which it is necessary to generate a digital model of a high-resolution surface or to make orthophotos - thus saving additional flight costs - SGM is the priority choice.

1 INTRODUCTION

In the last decade an aerial scanning system known as LiDAR (Light Detection and Ranging) has been affirmed as a key technology for obtaining high-resolution digital surface models (DSM) as well as/or for obtaining digital elevation models (DEM). At the same time, there is a growing need to improve the accuracy and higher resolution of digital surface models and digital elevation models. The LiDAR system is usually used to meet the above requirements for various needs, including obtaining orthophotos. However, considering the significant cost of procurement, its use only for orthorectification purposes is avoided. Taking into account the fact that the application of the aerial photogrammetric recording camera ADS80 from Leica Geosystems provides multiple stereo coverage, the recorded material can and should be used for photogrammetric acquisition of digital surface models. Therefore, in addition to the LiDAR system intended for data acquisition, there is a need to develop procedures-algorithms for generating digital surface models based on data recorded by the ADS80 line scanner - a digital camera for aerial photogrammetric recording.

Depending on the size of the pixels in the field (Ground Sampling Distance - GSD), a high-resolution DSM is generated, striving to match the current image resolution. In other words, each point of generated DSM corresponds to one pixel. Algorithms that minimize both values and various constraints at the global level are called global image matching and are ranked among the best algorithms in terms of achieving high quality and resolution. The advantages of these algorithms are the performance related to the Semi-Global Matching (SGM) principle developed by Hirschmüller (Hirschmüller, 2008; Hirschmüller and Bucher, 2010).

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Semi-global matching approximates two-dimensional, global aggregation of value matching by a number of one-dimensional value trajectories. Similar accuracy is still achieved as the application of full global matching, but much faster - such as by systematically comparing SGM with local and global matching algorithms using different value functions according to Hirschmüller and Scharstein (Hirschmüller and Scharstein 2007; Szeliski, 2010). As a result, SGM is further researched and improved by different researchers for different types of applications and data sets including aerial photographs, terrestrial and satellite data or video sequences.

It has been noticed that SGM meets customers need for a high-resolution, high-performance digital surface model. Taking into account the fact that the SGM principle is well accepted with regard to the quality of the results, the algorithm is adapted to the unique properties of the ADS80 line Pushbroom scanner using the existing software environment, with a special highly optimized module.

The rest of this paper describes the process of obtaining a digital surface model based on ADS80 data based on the SGM principle.

2 SEMI-GLOBAL MATCHING

SGM represents an approach to image (Hu at al., 2015). The essence of the algorithm is in the method of solving the coincidence or pairing of individual identical parts of stereo pairs, so that the principle of SGM is based on computer vision. Images (snapshots) usually represent a two-dimensional projection of a three-dimensional world.

2.1 Algorithm

To generate a digital surface model of the expected accuracy, it is necessary to ensure the redundancy of the input data, which is achieved thanks to multiple images with a continuous pushbroom scanning with 100% overlapping. Since it is generated using stereoscopic images, the DSM is usually represented by a landscape dome which contains elevation information about all the details above the surface, including the tops of buildings in trees (Milonjic et al., 2016).

Digital system for aerial photogrammetric recording ADS80 represents the integration of three technologies into one system for data collection in digital form:

- Sensor Head (SH82),
- Global Positioning System (GPS) and
- Inertial Navigation System (INS) also known as Inertial Measurement Unit (IMU).

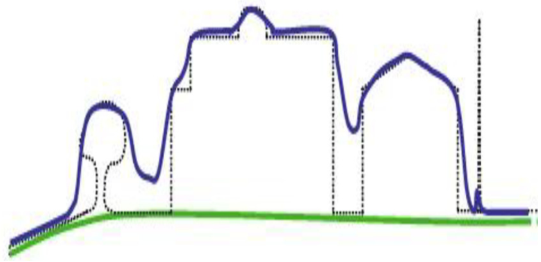

Figure 1: Display of actual shapes (black), digital surface model (blue) and digital terrain model (green).

Their combination can determine the coordinates of points on the earth's surface with high accuracy.

As mentioned, the complete solution for generating DSM is presented with Leica XPro software, ie. DSM Extraction module based on Semi-Global Matching principle.

Computer spatial stereo vision refers to the registration of data, ie, the capture of images from two or more cameras that are horizontally spaced from each other (from different databases). In the case of the ADS80 digital aerial photogrammetric recording system, this was achieved by using a Pushbroom line scanner with three shooting angles: backward - nadir - forward:

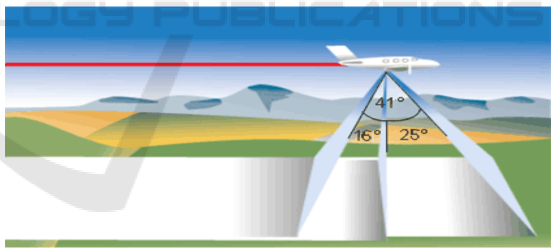

Figure 2: Three different shooting angles.

In this way, it is possible to capture objects from different angles (each object is captured three times), so that based on the analysis of similarities and differences in views, parameters used in computer vision applications such as the reconstruction of the original three-dimensional scene can be calculated. So, each object and scene are recorded three times, where, at first glance, they are slightly different. By comparing derived stereo pairs, additional information about the depth of the scene can be obtained. The process of obtaining the depth of a scene from a stereo pair is called space calculation (Zhang et al., 2017).

Since the geometry of the camera is known, it can be concluded that the base distance $B = C_l - C_r$ is constant. Comparing similar triangles, it is possible to determine the distance to the point (X, Y, Z) of the object in space or the depth of the object Z by applying triangulation:

$$\frac{X}{Z} = \frac{x_l}{f} \quad \text{and} \quad \frac{X - B}{Z} = \frac{x_r}{f} \tag{1}$$

so that the following equation can be derived:

$$Z = \frac{B \cdot f}{x_l - x_r} = \frac{B \cdot f}{d} \tag{2}$$

The problem of pairing identical points or areas based on stereo pairs is called the matching problem, where the procedure is performed by algorithms that include searching and comparing details. This process can be greatly simplified by introducing certain assumptions and limitations into the algorithms. The assumptions applied in the algorithms of SGM principles are:

- epipolar correction,
- Uniqueness pairing,
- smooth surface,
- pairing order.

2.1.1 Epipolar Correction

If the camera geometry is known, two-dimensional search of matching points on images can be simplified by one-dimensional search by applying image correction based on epipolar geometry (Wang et al., 2018).

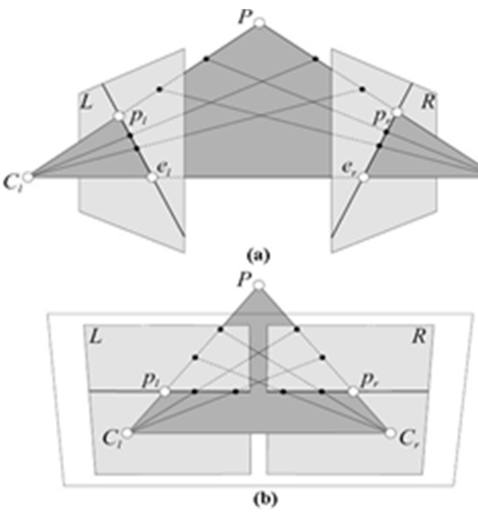

Figure 3: Epipolar correction.

The epipolar correction of the images is shown in Figure 3. The optical centres of the two cameras are represented by points C_l and C_r, while a point on the earth's surface is represented by point P. The projection of that point P in the plane of the left camera L is at point p_l, and in the plane of the right camera R is at point p_r. Any other point located in the P-C_l direction will be projected on the p_r-e_r direction called the epipolar projection line p_l, where e_r represents the epipole where geometrically represents the image of the optical center of the left camera C_l in the right camera. The points can be projected in the same way in the left chamber as in Figure 3a. Correction of the images is achieved by straightening the planes L and R so that p_l-e_l and p_r-e_r form a line in the same plane as in the figure 3b:

If the projections of all points are corrected in the same way, the result is that the matching elements of the stereo pair are on the same horizontal line, which allows the matching problem to be simplified and solved by searching only in the direction of one axis:

$$x_r = x_l + d \quad \text{while} \quad y_r = y_l \tag{3}$$

In equation (3), the value d represents the horizontal shift between two matching elements of the image called the disparity. By calculating the disparity for all elements of the image, a disparity map is obtained.

2.1.2 Uniqueness of Pairing

The details in the stereo pair must be uniquely paired to allow further processing in computer stereo vision applications (Ye et al., 2018). This means that an element of one image is paired with only one element of another image. If the image contains large regions of constant intensity (monochrome parts), then within such a region a point from one image based on the same intensity can be paired with any point or more of them within the same region on another image and vice versa. The biggest problem with stereo pair pairing occurs due to the fact that certain elements do not exist on both images. This phenomenon occurs because not all details are visible for all cameras, example, some scene parts are sheltered by objects even though they are visible to another camera (Figure 4).:

If there is no possibility of matching an element of the image, the depth for that element cannot be calculated and it is said that this element is sheltered for another camera.

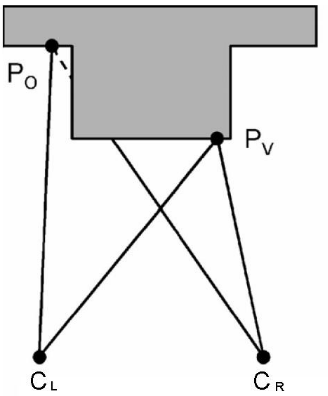

Figure 4: Example of shelter: P_V - visible point for both cameras; P_0 - sheltered point for the right camera.

Uniqueness pairing is applicable for opaque surfaces. For transparent surfaces, one element of the image can have two depths - the depth of the transparent surface as well as the depth of the surface in the background that is visible through the transparent surface. The problem with uniqueness pairing also occurs with oblique surfaces when during the left and right projection of the same line there is a difference in the projection length.

2.1.3 Smooth Surface

In terms of disparity, the smoothness of the objects surface means that the values of disparities of adjacent points differ very little. Larger differences in the value of disparity occur at the boundaries of objects where depth jumps occur between adjacent elements of the image. Applying the surface smoothness assumption increases the efficiency of the stereopair pairing algorithm.

2.1.4 Pairing Order

If could be noticed two points of the scene *P1* and *P2*, whereby on one image the projection *p1L* of the point *P1* is located to the left of the projection *p2L* of the point P2, then, in the case of the correct pairing sequence, on the second image the projection *p1R* of the point *P1* is located to the left of the projection *p2R* of the point *P2*. The assumption of such a pairing sequence can be applied to most real scenes, and the pairing order may change in certain situations.

The easiest way to pair the images is to pair each element of one image individually with an element of another image that completely matches or is most similar to that element in terms of colour and contrast. This approach, which is based on the pairing of individual pixels, does not assume the smoothness of the surfaces, i.e., the continuity of the disparity values within the surfaces, whereby results with incorrectly paired elements can be obtained. The cause of errors when pairing individual pixels is found in a large number of "candidates" that can match in colour. In order to overcome this problem, the simplest implementation of the surface smoothness assumption is that adjacent pixels have a constant disparity value. If a "window" is formed (for instance of the size of 8x8 of image elements), for such a window can be calculated the sum of the absolute values of the differences in the intensity of individual pixels within the window (Sum of Absolute Differences), the sum of the absolute values of the squares of the intensity of individual pixels within the window (Sum of Squared Differences), a normalized circular-correlation function or some other function that measures the intensity of a window. By dragging windows through the left and right images and comparing the window intensity measure, windows of the most similar intensity can be paired. Since the window intensities are compared, it is possible to calculate the disparity for the whole window, so that for each element of the image inside the window (x, y) a three-dimensional structure (x, y, d) is obtained which is called the Disparity Space Image.

The biggest challenge when pairing certain parts of the image using windows is choosing the window size. If the windows are too small, errors may occur as when pairing individual pixels due to the large number of pairing candidates. In contrast, if larger windows are used, the possibility of pairing the wrong parts is reduced but an error occurs due to local treatment of smoothness (constant disparity values within the window) on the oversized part of the image. The best results of pairing the appropriate parts of the image using windows are achieved by applying a variable window size in such a way that smaller windows are used near depth jumps, while larger windows are used in places that are further away.

This value function is most used in semi-global matching and is called the Mutual Information (*MI*) function. *MI* function depends on entropy *H* both from individual images and from the common entropy of stereo pairs $H_{1,2}$ as well:

$$MI_{1,2} = H_1 + H_2(D) - H_{1,2} \tag{4}$$

By using quality images, the value of the common entropy is small because one image can be predicted by another, which increases their common information (*MI*). All stereo image pairing algorithms define a pairing consumption function when performing a process of pairing pixels with common information. The pairing consumption function is the smallest for exact pairing and vice versa, in case of incorrect pairing the pairing consumption function increases.

The SGM approach is suitable for generating a high-resolution DSM which matches the pixel value in the field (Ground Sample Distance - GSD).

2.2 DSM Generation

The complete solution for generating DSM (Yang et al., 2020) is presented with the Leica Xpro software with DSM extraction module:

Figure 5: Leica XPro software main window (starting the DSM Extraction module).

Software Leica Xpro consists of several modules (applications). Unlike other modules, a module DSM Extraction takes up the most system memory, so it is necessary to provide a minimum of 8 gigabytes of RAM for its operation. Since the significant time is spent during the process of generating digital surface models, it is recommended to use a local network of high-performance computers (High Performance Computing – HPC).

2.2.1 Input Data - Selection of Blocks and Recordings Rows

As input data are used ADS L0[3] images (recording rows) which are previously inserted in the Block (module Block Preparation). The images can be of the panchromatic or infrared spectrum and must have a pyramidal structure formed.

Figure 6: Opening the block.

2.2.2 Defining Options for DSM Generation

After loading the block and selecting images to generate DSM, additional adjustment of the digital surface model extraction was performed:

- Exclusion features (exclusion from the generation process) and Area of Interest – for this step is necessary to provide shape file with defined coordinate system (*.*prj* file); if coordinate system (*.*prj*) file was not provided, the module would use automatically WGS84 coordinate system,
- Stereo Bands – selection of stereo coverage, where the following variants are possible:

- panchromatic: Backward – Nadir – Forward
- panchromatic: Backward – Nadir
- infrared: Backward – Nadir

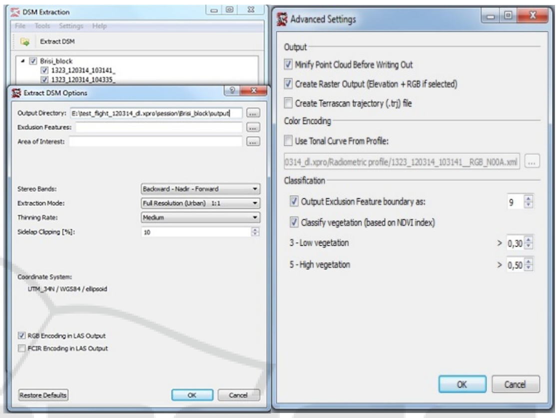

Figure 7: Defining options for DSM generation.

To generate DSM using two stereo angles is a significant waste of time but also better coverage of point cloud. Otherwise, in specific cases (snow, etc.), the use of the infrared spectrum is recommended (Yang et al., 2020).

Possible variants of digital surface model generation:

- Quick – a fast generation method used to gain insight into the appearance of the model. The time to generate the model is very short, but the point density is also low,
- Full Resolution – full resolution - used for orthorectification purposes. After processing of the obtained point cloud, it is possible to derive a digital terrain model (DTM),
- Full Resolution (Urban) – the full resolution for urban areas is applied for the purposes of modelling and visualization of urban areas. After processing of the obtained point cloud, a digital surface model can be derived (DSM).

There are three different degrees of point filtering:

- Mild – slightly, where the eye is filtered 95 % points,

[3] Georeferenced images without radiometric and geometric correction ("raw" images).

- Medium – mediocre, where the eye is filtered 97 % points and
- Aggressive – aggressively, where the eye is filtered 99 % points.

After the generation process is completed, the following results are obtained:
- A file with a dense point cloud in the format LAS 1.2,
- A file with a refined point cloud in the format las 1.2 and
- Processing results (*.log files).

All points contain GPS time of registration (recording) in Nadir. Depending on need, the outputs may contain both RGB and FCIR information.

3 RESULTS OF DIGITAL SURFACE MODEL GENERATION

The generation of a digital surface model was performed using aerial survey data of urban area Slankamen. The set of equipment consists of the Piper Seneca V aircraft from the American manufacturer Piper Aircraft and digital aerial photogrammetric camera ADS80 from the Swiss manufacturer Leica Geosystems AG, as well as the associated software.

Figure 8: Slankamen - test area.

The digital surface model was generated using the module DSM Extraction, while data preparation was done using the appropriate software modules Leica XPro.

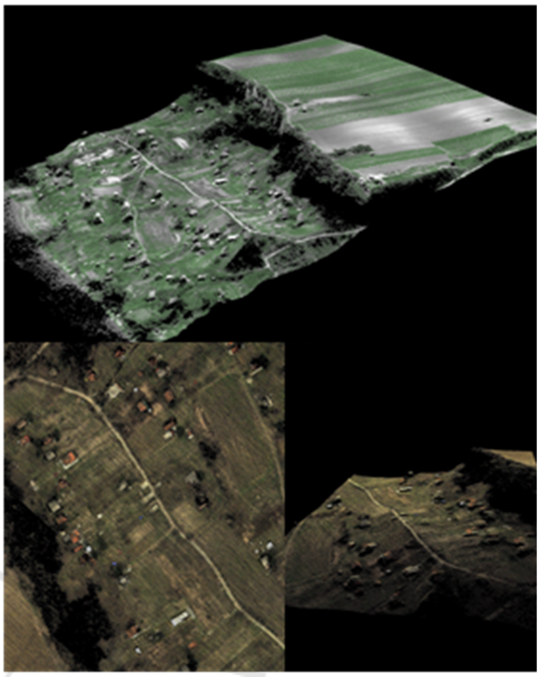

Figure 9: Details of the digital surface model - terrain profile.

Similar to the Leica ADS80 digital aerial photogrammetric camera, LiDAR is the result of integrating three technologies into one system:
- Laser Scanning and Ranging System,
- Global Positioning System – GPS,
- Inertial Navigation System – INS (also known as Inertial Measurement Unit – IMU) for registering position changes between two GPS readings, as well as to determine orientation and
- RGB/NIR (Red-Green-Blue/Near Infrared) high resolution camera (optional).

Laser scanning represents a method of collecting digital spatial data. The principle of the LiDAR system is based on the emission of a high-frequency laser beam that is partially reflected and partly absorbed by the ground or other objects in space. The time difference between the emitted and reflected part of the laser beam gives the length between the instrument and the points on the field, while the coordinates of the points are obtained based on measured distances, laser beam angles (mirror angles) and elements of external orientation.

As an example of new technology for generating digital surface models, the ADS80 system is increasingly being used as an alternative. Digital surface models are generated based on images taken in ideal conditions (angle of sunlight, avoidance of clouds and turbulence, ...). The accuracy of DSM generation depends on the accuracy of aero triangulation - about 0.5 GSD in position and about 1.5 GSD in height, whereby turbulence during flight can affect the reduction of image quality; thus, and to reduce the quality of DSM. Typical high resolution is up to 5 cm and only top of the surface is measured with processing time of 10.000-20.000 pts/s. Considering LiDAR, vertical accuracy is up to 5 cm, both top and ground of the surface are measured with processing time of 1.000.000 pts/s.

In both cases, DSMs with many points are obtained, so additional processing is necessary prior to usage for certain purposes. The data can be classified automatically with the aim of determining a digital terrain model (DTM), urban areas or vegetation with minimal manual interventions. Significantly higher points density obtained by applying the SGM algorithm facilitates the identification of the data structure and reduces errors during manual editing. In addition, the advantage in addition to the possibility of using image matching procedures is in the geometry of the image and the continuous processing of the recorded aerial data (Yang et al., 2020).

4 APPLICATION

- Basic survey (very suitable for orthorectification),
- Storing altitude data for the purposes of making digital topographic maps,
- Production of digital and analogue orthophoto plans and maps,
- Solving the problem of construction profiles in the design of roads and military engineering projects,
- Three-dimensional representations of landforms and flight simulations,
- Landscape architecture and spatial planning (3D modelling of urban areas for the needs of spatial analysis and visualization),
- Surveillance analyses,
- Management of natural resources and aboveground infrastructure (data can be used for classification of vegetation, forests, calculation of forest wood volumes as well as for development of information system of natural resources),
- Communication planning,
- Determining locations for dams and bridges,
- Hydrological and ecological modelling,
- Hydraulic modelling simulation,
- Analysis of geomorphological parameters (exposure, slopes, curvature of the terrain),
- Basis for other types of spatial information (satellite images, thematic maps, etc.)

5 CONCLUSION AND PERSPECTIVES

This paper presents the acquisition of digital surface models using the principle based on Semi-Global Matching (SGM) using data obtained by ADS80 pushbroom scanner, as well as a comparison of ADS80 and LiDAR systems. It can be concluded that by applying the SGM principle can be derived very consistent surface models comparing with the models derived by the LiDAR sensor and which in the future do not have to be only an alternative for generating a digital surface model. Thanks to the high-resolution images obtained using the ADS80 digital aerial photogrammetric camera it is possible to derive high density point clouds. Increasing the points density reveals details which are difficult for a LiDAR sensor to detect.

To conclude, it is shown that the obtained digital surface models using the ADS80 system are an effective alternative to data obtained using LiDAR technology, especially in conditions where high resolution is required. Although both data sets can generally be used for orthorectification purposes, it is better to choose the ADS80 system as it is based on the same data set of identical geometry and resolution - avoiding the additional cost of a LiDAR system procurement.

Based on this practical experience and forthcoming needs, the SGM principle will continue to be refined and applied in practice. The goal is definitive integration into the working environment of the ADS system in the process of generating digital surface models.

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