TESTING THE EFFECT OF FLIGHT AND SCAN STRIP ALIGNMENT PARAMETERS ON THE ACCURACY OF THE POINT CLOUD OBTAINED BY THE DJI ZENMUSE L1 LIDAR SYSTEM

Martin Boušek*,[1]

*martin.bousek@fsv.cvut.cz

[1]Department of Special Geodesy, Faculty of Civil Engineering, Czech Technical University in Prague, Thákurova 7, 166 29 Prague, Czech Republic

Abstract

This paper deals with testing the effect of flight and scan strip alignment parameters on the accuracy of the point cloud obtained by the UAV-mounted DJI Zenmuse L1 lidar system. The flight parameters tested are the scanning mode, the cross-strip overlap size, and the flight speed. The strips were aligned in the TerraMatch software by using the vector tying features and the ICP algorithm.

The accuracy of the aligned point clouds was determined by comparison with a triangular terrain model obtained by photogrammetry.

Keywords

Lidar, UAV, point cloud, TerraMatch

1 INTRODUCTION

Until recently, the airborne laser scanning was very expensive and involved large equipment carried mostly by manned aircraft. Significant cost reductions have occurred with the evolution of unmanned aerial vehicles (UAVs), and recently, the DJI company has come up with the much more affordable DJI Zenmuse L1 lidar system carried by the DJI Matrice 300 RTK unmanned quadcopter. The availability of aerial scanning has thus moved much closer to drone photogrammetry, and could, due to its advantages, eventually begin to compete with it in various applications.

With the new technology, however, comes the need to address its inherent problems or shortcomings. These include mainly the inertial navigation system (INS) measurement errors – the GNSS-RTK method errors and the IMU unit errors, which also deteriorate over time. These errors are directly transmitted to the position of the measured points, resulting in a spatial mismatch of the scanned strips at their overlap. This mismatch must be removed, which is done by aligning the overlapping scan strips (Fig. 1).

The first objective of this work is to test the effect of flight parameters on the spatial accuracy of the aligned point cloud. The flight parameters tested are the scan mode, the overlap size of the scan strips and the flight speed. A non-repetitive scanning mode can potentially improve the point coverage of the scanned object. This should not affect the alignment of the strips in the overlap but it may increase the effect of some systematic errors of the scanner (which has the highest accuracy when scanning straight down). The size of the overlap can then have a direct effect on the quality of the strip alignment and higher flight speeds can degrade the accuracy of the INS.

Furthermore, this work tests the TerraMatch software which contains multiple different functions with different algorithms for the scan strip alignment. These functions have various parameters and the software provides no clear guidelines as to how they should be set; however, the optimum settings may be different for each type of object or terrain. Thus, the multiple functions and the different parameter settings for each one of them are tested. Their influence on the quality and spatial accuracy of the resulting digital terrain model is then monitored.
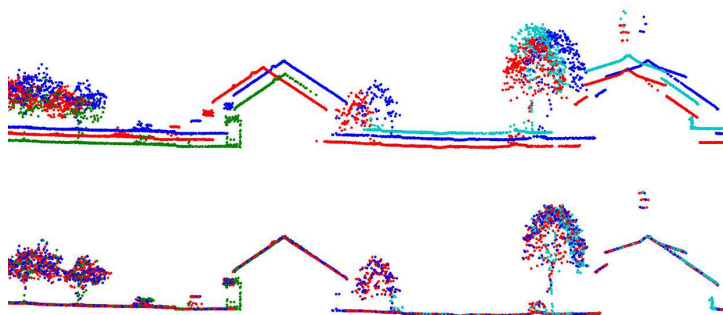
Fig. 1 Alignment of mismatched scan strips (a propagation image of the TerraMatch software) [1].

2 METHODOLOGY

DJI Matrice 300 RTK

The DJI Matrice 300 RTK is an Unmanned Aerial Vehicle (UAV) that was used as a carrier for the lidar system and the photogrammetric camera. The drone is equipped with an onboard GNSS-RTK receiver. The control is provided by a DJI RC Pro with the DJI Pilot software. The basic technical parameters of the drone are shown on the producer's website [2].

Lidar DJI Zenmuse L1

The DJI Zenmuse L1 Lidar system combines a Livox Avia laser scanner, an IMU unit, and an RGB camera, which, in conjunction with a GNSS-RTK receiver, allow to capture dense point clouds supplemented with color information added by RGB imagery.

Two scanning modes are available (Fig. 2 a)) - in the repetitive mode, the points below the drone are scanned in a line perpendicular to the flight path over a range of 70.4°.

In the non-repetitive mode (Fig. 2 b)), the scan line is gradually rotated and the laser trace creates a flower-like pattern which scans points both behind and in front of the drone.

The standard deviation of the laser rangefinder is 2 cm per 20 m and 3 cm per 100 m [3]. The accuracy of the whole system (1 σ) is 10 cm horizontally and 5 cm vertically when scanning at 50 m.

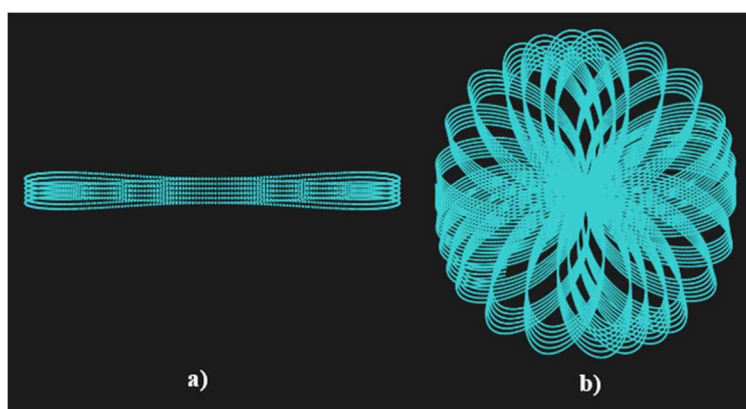Further technical parameters of the lidar are given on the producer's website [4].

Fig. 2 a) repetitive scanning mode, b) non-repetitive scanning mode [3].

DJI Zenmuse P1 camera

The DJI Zenmuse P1 is a photogrammetric camera designed for the use on UAVs. It was used in the experiment to create a control model for testing the lidar system. A DJI DL 35 mm F2.8 LS ASPH lens was used for imaging.

The technical parameters of the camera are presented on the producer's website [5].

Trimble R2

Trimble R2 is a geodetic GNSS receiver. According to the manufacturer, the maximum achievable horizontal measurement accuracy in the network RTK mode is 10 mm + 1 ppm and the vertical accuracy is 20 mm + 1 ppm [6].

Locality

To ensure that the tested point cloud compared well with the control model, an object was selected which contained both slopes (i. e. was spatially rugged) *and* large flat areas. This choice of object ensured that neither of the methods had advantages over the other. Furthermore, it was essential to find an object with no vegetation as it could distort the results.

A soil stockpile which had a flat upper platform was selected as a suitable object to meet these conditions. The dimensions of the object were approximately $110 \times 35 \times 6$ m.

Variants of scanning flight parameters

To test the effect of the flight parameters on the resulting spatial accuracy of the lidar point cloud, six flight parameter variants were performed. In the process, three parameters were tested; the scanning mode (*r* - repetitive, *n* - non-repetitive), the cross-strip overlap (50%, 70%), and the flight speed (3 m/s, 6 m/s). The flight height was 50 m above the terrain. The number of parameters would have allowed the creation of eight variants; however, for time reasons, only six combinations of parameters that we expected to have the greatest impact on the accuracy of the results were selected. Tab. 1 contains the parameter settings for each variant.

Tab. 1 Scanning flight variants and their parameters (scanning mode *r* - repetitive; *n* - non-repetitive).

Variant	Scanning mode	Cross-strip overlap [%]	Flight speed [m/s]
1	r	50	6
2	r	70	6
3	r	50	3
4	n	50	6
5	n	70	6
6	n	50	3

Testing of scan strip alignment methods

Since a very large volume of data would have been generated when testing the different alignment methods on all scanned variants, the variant with the smallest *RMSD* (root mean square difference) from the control method was chosen. The different alignment methods and procedures offered by the TerraMatch software were then tested on this variant. The parameters of these alignment algorithms were set according to the software documentation [7] and experience.

Next, the same variant was aligned with one of the tested procedures but the parameters were being systematically changed to determine their effect on the spatial accuracy of the resulting aligned point cloud.

Control method

The control method was photogrammetric imaging, from which a point cloud and then a triangular 3D model (mesh) were obtained using the Structure from Motion (SfM) method. The assumed internal accuracy of this method is higher than the accuracy of the point cloud obtained by the lidar system and is therefore considered error-free.

The coordinates of the image centers and eight ground control points obtained by the GNSS-RTK method were used to place the point cloud into the S-JTSK coordinate system.

Comparison of lidar point cloud with control method

The comparison of the spatial accuracy of the point cloud obtained by the lidar system with the control mesh model was performed in the CloudCompare software. The shortest distance of the point cloud from the triangular mesh of the control model was calculated. The output of the calculation was the mean (p_k) and standard deviation (s_k) of these distances. From these, a summary statistic, *RMSD*, was calculated using the following formula,

$$RMSD = \sqrt{p_k^2 + s_k^2} \qquad (1)$$

where *RMSD* is the root mean square difference in m, p_k is the average deviation in m, and s_k is the standard deviation of the differences in m [8].

Next, the internal precision of the point cloud was evaluated which was characterized by the standard deviation in height (s_v) – i.e. the height dispersion of the point cloud itself.

Ground control points

Prior to the measurement, 8 ground control points were evenly distributed around the object. They were 50 cm square plates covered with a highly reflective foil for easy identification through the intensity of the reflected signal from the lidar. They also had a contrasting cross on them so that they could be identified during photogrammetric processing.

The ground control points (centers of the plates) were measured using the GNSS-RTK method with a Trimble R2 receiver.

Airborne measurements

Using a DJI Zenmuse P1 photogrammetric camera, aerial photogrammetric imaging of the examined object and its surroundings was performed. The pattern of the flight trajectory was a simple grid, as shown in Fig. 3 a). The flight parameters were as follows: height of 50 m above the terrain, overlapping of adjacent frames by 80% longitudinally and laterally. The imaging mode where photographs are taken consecutively in nadir and at a tilt of 15° from the vertical in four basic directions relative to the direction of flight was selected. A total of 849 images were taken.

The scanning flights with the DJI Zenmuse L1 lidar system were again performed in a single raster (Fig. 3 b) and a total of 6 flights were performed according to the method design.
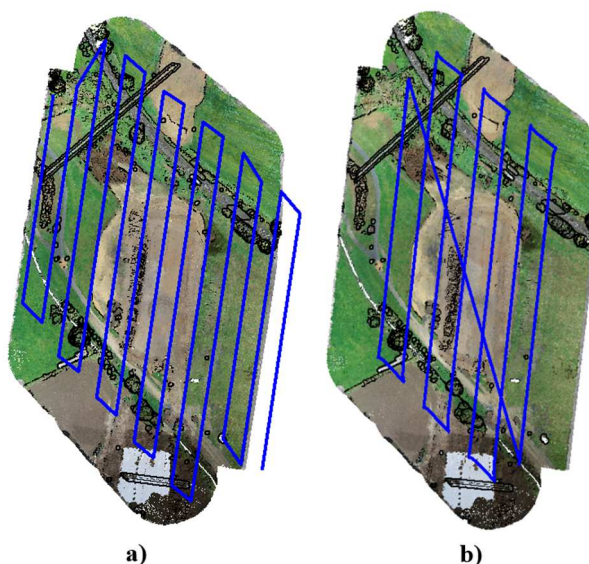

a)   b)

Fig. 3 Flight trajectory of a) photogrammetric, b) lidar measurements.

Processing of acquired data

The photogrammetric image processing was performed in Agisoft Metashape 1.8.5.

For the *Align Photos* and *Build Dense Cloud* functions, the resolution (quality) parameters were set to *High*. The *Depth Filtering* parameter was set to *Aggressive*. After processing, an average ground sample distance of 6.7 mm was achieved.

The DJI Terra software was used to pre-process the lidar data. The output was a point cloud in the LAS format and a file with flight trajectory coordinates. The point cloud was stored in the UTM coordinate system.

In the case of Variant 1, a problem occurred with the scan data file. The problem could not be solved and therefore this variant was removed from the experiment.

Processing in the TerraSolid software group followed. The preparation of the point cloud for alignment was done using the TerraScan module - the point cloud was divided into scanned strips. The points in the cloud that were likely to best represent the terrain were then classified (hereafter referred to as the Ground class). These terrain points were used for alignment only, further data analysis was performed on all points.

In the case of variants with non-repetitive scanning mode, it was necessary to choose a modified procedure and filter these points due to the more significant occurrence of noise under the terrain.

General procedure for aligning scanned strips

In the Ground class of the whole point cloud, the *Search for Tie Lines* function first searched for vector tie elements which were either lines interpolated in terrain points (*Flat ground* or *Surface lines* for sloped terrain) or circular surfaces representing points with flat surroundings (*Planar points*). For lines, the following parameters need to be set: the spacing between the adjacent lines, the length of the line, and the depth of the cloud section in which the software interpolates the line. In the case of *Planar points*, the spacing, the radius of the circle, and the interpolation tolerance (maximum deviation of the point of the cloud from the plane) can be set. The use of lines helps to adjust rotations about the primary axes, whereas *Planar points* can be used primarily to adjust coordinate shifts. To find the *Flat ground lines*, the line length was set to 2 m, and for the *Surface lines,* the length was 0.5 m. The section depth was set to 10 and 20 cm, respectively. The chosen spacing was 1 m.

Furthermore, the *Find Tie Line Match* function was used twice consecutively. This function uses the found vector features to adjust the coordinate shifts and rotations about the axes (heading, roll, pitch). The *Mirror scale* parameter, which describes the systematic deviations of the points on the edges of the scan strip, can also be selected for adjustment. This function was first applied to all the strips together (they were taken as a whole) and then it was applied to each strip individually (each strip received its corrections relative to the other strips).

Finally, the *Find Tie Line Fluctuations* function was used to compensate for local variations between the scan strips.

In addition to using *Tie Lines*, the strips were also matched by means of the *Surface-to-surface* method using the ICP (Iterative closest point) algorithm. For this purpose, similar functions called *Find Match* and *Find Fluctuations* were used. An automated function, namely the *Process Drone Data* function, was also tested. This function uses only *Planar points* with the preset feature search and alignment parameters.

All flight variants were aligned using procedure 1 in Fig. 4. This procedure is recommended in the TerraMatch documentation [7].

In addition, other alignment procedures were tested on the flight variant 2 (*r*, 70%, 6 m/s), as presented in Fig. 4 where the colored hexagons show the alignment parameters of each variant.
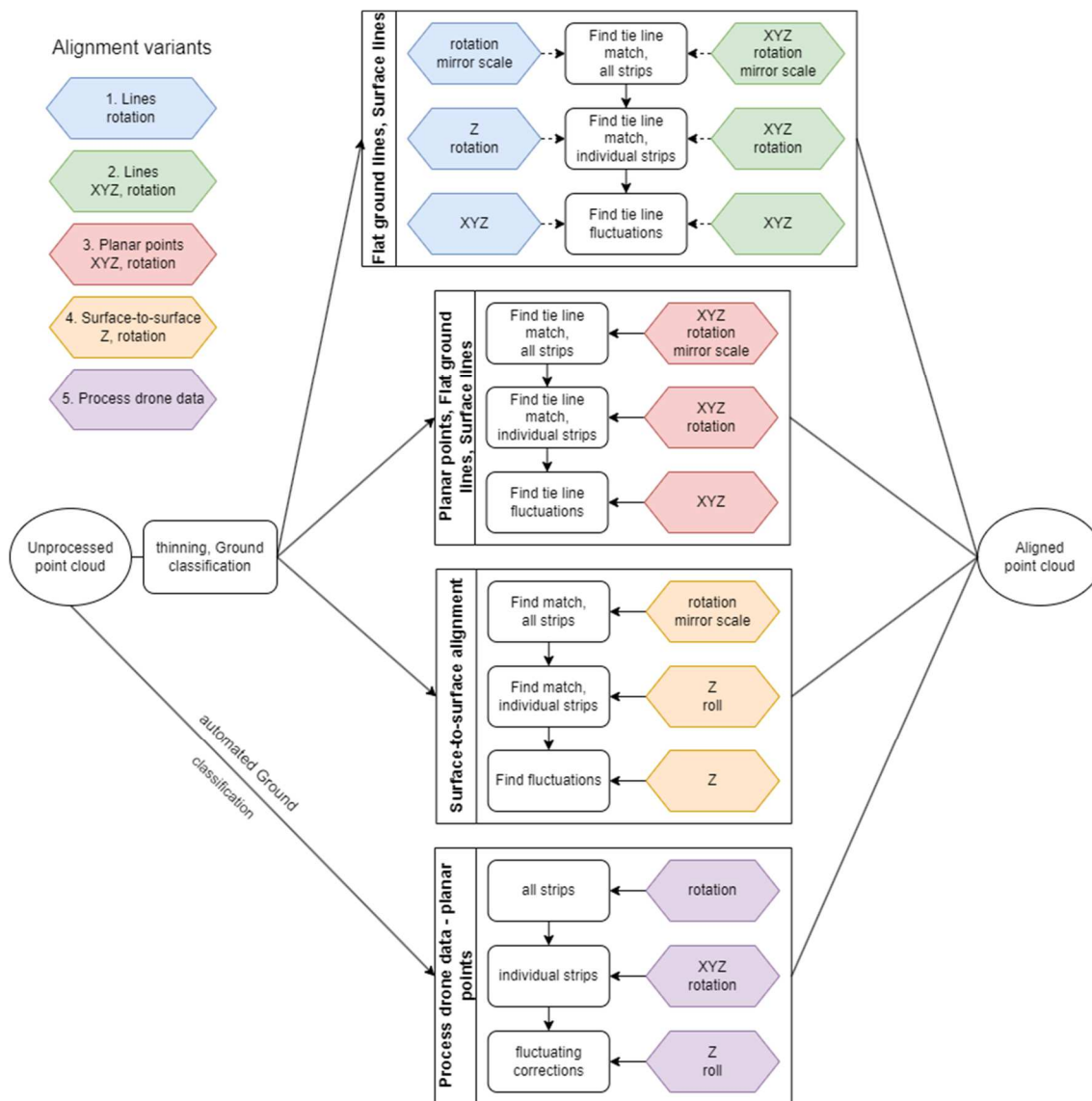
Fig. 4 Diagram of scan strip alignment methods and their variants.

Testing the Tie Lines parameters

In order to find the optimum settings for the *Search for Tie Lines* function, the length of *Tie Lines* and the section depth were systematically varied in this test. The line length was set to 0.5 m, 1 m, 1.5 m, and 2 m and the section depth was set to 0.1 m, 0.2 m, and 0.6 m. By combining the settings of these two parameters, 12 variations were created, all of which were aligned using procedure 1 described above.

Testing the spatial accuracy

The spatial accuracy of the aligned point clouds was evaluated in CloudCompare.

To remove the inaccuracies of the transformation from the UTM to the S-JTSK coordinate system, the aligned lidar point clouds were linearly transformed using the ground control points. For this purpose, the procedure proposed by Štroner et al. [9] was used where the ground control points are identified as the centers of groups of points with high intensity (highly reflective foils).

For comparison purposes, the dense photogrammetric point cloud obtained by the SfM method was rasterized. The cell size was chosen to be 10 cm and the cell value was the average height of all points within it. A mesh model was created from the raster of points.

The cloud/mesh distance of the lidar cloud from the control model was calculated in CloudCompare. The value of this distance was assigned to each point as an additional parameter. Then, the mean p_k and the standard deviation

of the distances s_k of all points in the cloud from the control model were calculated. From these, the summarizing parameter *RMSD* was finally calculated using formula (1).

The internal accuracy of the lidar clouds s_v (2) was determined from rasterization where the standard deviation in height was calculated in each raster cell. Thus, the formula for the s_v is

$$s_v = \sqrt{\frac{\sum_{i=1}^{n}(s_i^2)}{n}} \tag{2}$$

where s_v is the overall standard deviation in height in m, n is the number of cells and s_i is the standard deviation in height of the i-th cell in m.

A detailed description of the processing and evaluation of the data is provided in the author's thesis [10].

3 RESULTS

Comparison of variants of scanning flight parameters

The results of testing the effect of flight parameters on the resulting spatial accuracy of aligned lidar clouds are presented in Tab. 2.

Tab. 2 Statistical evaluation of aligned point clouds obtained by different flight variants.

Flight variant	p_k [m]	s_k [m]	*RMSD* [m]	s_v [m]
2 (r, 70%, 6 m/s)	*0.009*	*0.030*	***0.031***	*0.022*
3 (r, 50%, 3 m/s)	*0.016*	*0.027*	***0.031***	*0.022*
4 (n, 50%, 6 m/s)	*0.015*	*0.038*	***0.041***	*0.039*
5 (n, 70%, 6 m/s)	*0.012*	*0.044*	***0.046***	*0.037*
6 (n, 50%, 3 m/s)	*0.014*	*0.044*	***0.046***	*0.042*

Variants 2 and 3, both with the repetitive scanning mode, have the lowest *RMSD* (31 mm) and the internal standard deviation in height s_v (22 mm). The variants with the non-repetitive scanning mode have results by 1 to 2 cm worse.

Fig. 5 shows the difference in the histograms of cloud deviations from the control model between variants 2 and 5.
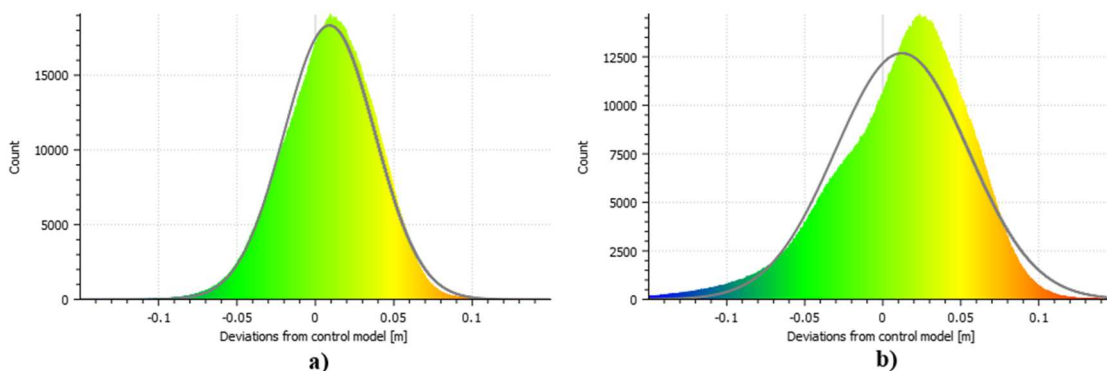

Fig. 5 Comparison of histograms of deviations from the control model of flight variants 2 (a) and 5 (b).

Comparison of scan strip alignment methods

Flight variant 2 was selected for further testing. A total of five different alignment procedures were tested. The results are shown in Tab. 3.

Tab. 3 Statistical evaluation of strip alignment methods and procedures (flight variant 2).

Alignment variant	p_k [m]	s_k [m]	RMSD [m]	s_v [m]
1 Lines – Z, rotations	*0.009*	*0.030*	***0.031***	*0.022*
2 Lines – XYZ, rotations	*0.009*	*0.030*	***0.031***	*0.023*
3 Planar points – XYZ, rotations	*0.010*	*0.038*	***0.039***	*0.030*
4 Surface-to-surface	*0.010*	*0.028*	***0.030***	*0.022*
5 Process Drone Data (points)	*-0.002*	*0.069*	***0.069***	*0.037*

The *Surface-to-surface* procedure shows the lowest *RMSD* (30 mm), but its results are essentially identical to those of both *Lines* variants. The highest *RMSD* has the *Process Drone Data* function with the value of 69 mm. A histogram of the point cloud deviations aligned by this function is shown in Fig. 6.
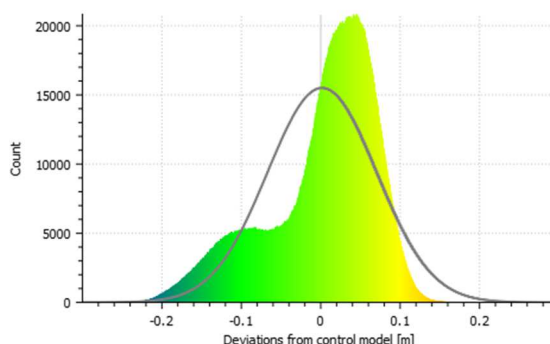

Fig. 6 Histogram of deviations from the control model of the *Process Drone Data* variant.

Effect of Tie Line parameter settings on alignment

Testing of the *Tie lines*, or more precisely the *Flat ground lines* and the *Surface lines*, was again performed on flight variant 2. The results are shown in Tab. 4.

Tab. 4 Statistical evaluation of strip alignment using different *Tie lines* parameters.

Line length [m]	Section depth [m]											
	0.1				0.2				0.6			
	p_k [mm]	s_k [mm]	RMSD [mm]	s_v [mm]	p_k [mm]	s_k [mm]	RMSD [mm]	s_v [mm]	p_k [mm]	s_k [mm]	RMSD [mm]	s_v [mm]
0.5	*14*	*28*	***31***	*24*	*11*	*29*	***31***	*22*	*12*	*27*	***30***	*22*
1	*11*	*29*	***31***	*22*	*11*	*30*	***32***	*23*	*11*	*30*	***32***	*23*
1.5	*10*	*31*	***33***	*23*	*9*	*31*	***32***	*23*	*10*	*31*	***33***	*24*
2	*8*	*34*	***35***	*25*	*10*	*34*	***35***	*29*	*10*	*35*	***36***	*29*

The *RMSD* deviations of all variants range between 30 and 36 mm. The best spatial alignment accuracy (*RMSD* of 30 mm) was achieved with a line length setting of 0.5 m and a section depth of 0.6 m. The highest *RMSD* of 36 mm was achieved with a line length of 2 m and a section depth of 0.6 m. Alignment accuracy deteriorates slightly with increasing line length.

4 DISCUSSION

The objective of the testing described in this paper was to determine the effect of flight parameters and scan strip alignment methods and parameters on the resulting accuracy of point clouds acquired by the DJI Zenmuse L1 airborne lidar system. The selected scan area was characterized by the absence of vegetation and had a smooth but spatially rugged terrain. The control model for testing the lidar point clouds was the terrain model obtained by the SfM method.

The scanning flight parameters tested were the scanning mode (repetitive and non-repetitive), the size of the cross-strip overlap (50% and 70%) and the flight speed (3 m/s and 6 m/s). Six variants were created by combining these parameters, with the first variant eliminated due to problems with the scan data. The most accurate results were achieved with variants 2 and 3, both using the repetitive scanning mode. Both have the same *RMSD* of 31 mm and an internal height standard deviation s_v of 22 mm. The other variants, acquired with the non-repetitive scanning mode, had *RMSDs* by 1 to 1.5 cm worse and s_v even 1.5 to 2 cm worse. This indicates that the scanning mode has a significant effect on alignment quality.

Therefore, the result of this test is that the repetitive scanning mode should be used for the highest accuracy. The effect of the overlap size and flight speed on the spatial accuracy of the result was not proven within the limits tested.

Next, different alignment methods and procedures were tested in TerraMatch. In total, one point cloud (var. 2 - r, 70%, 6 m/s) was aligned using five variants, four of which used some kind of *Tie lines*, i.e. lines or circular surfaces interpolated in the point cloud. Variant 4 used the *Surface-to-surface* alignment which uses the point cloud directly. This is how the lowest *RMSD* (30 mm) and s_v (22 mm) were achieved. However, this method is computationally demanding. Variants 1 and 2, using vector lines for alignment, have an *RMSD* only 1 mm higher. Variants using the *Planar points* and automatic data processing lead to less accurate results (*RMSD* of 69 mm and s_v of 37 mm).

In the last test, the parameters of the lines searched in the point cloud were changed in one alignment procedure. The length of the line (L - 0.5, 1.0, 1.5, and 2.0 m) and the depth of cut (D - 0.1, 0.2, and 0.6 m) were varied. The quality of the alignment was very consistent across all variations according to the magnitudes of *RMSD* and s_v. The *RMSD* ranged from 30 mm (L0.5_D0.6) to 36 mm (L2.0_D0.6) and the standard deviation s_v ranged between 22 mm and 29 mm (for the same variants).

This test revealed that the spatial accuracy of alignment decreased slightly with increasing line length. The effect of section depth was not proven. The visual inspection of the object in terms of its coverage with the lines showed that fewer lines were found on sloped surfaces when longer lines were used. The insufficient coverage then results in imperfect positional alignment.

5 CONCLUSION

The result of this paper is a proposal of general recommendations for setting the parameters of the scanning flight, as well as the method and parameters of the alignment of the scanned strips to achieve the highest spatial accuracy of the resulting point cloud. The TerraMatch software, whose terminology is used here, was used for the scan strip alignment. The basic findings of the experiment conducted are as follows:

- For georeferencing the resulting point cloud, it is advisable to use ground control points with a highly reflective foil.
- Use the repetitive scan mode (simple line scan) to scan most of the area with minimal distortion (Mirror scale).
- Use the *Surface-to-surface* method or *Tie lines* (*Flat ground*, *Surface lines*) to align scan strips.
- When using *Tie lines*, check that the entire area of interest is evenly covered with the lines – mostly in areas with a lower density of points, such as steeper slopes.
- It is advisable to follow the recommended procedures from the TerraMatch documentation [7].

The results are applicable to the scanning of objects similar to the one used for this work. It was characterized by flat surfaces, absence of vegetation and spatial ruggedness.

When these rules were followed, an internal point cloud accuracy of 22 mm (standard deviation in height in a 10cm grid) was achieved on the test object. This corresponds to the standard deviation of the lidar rangefinder used, which is given by the manufacturer as 2 to 3 cm at 20 and 100 m, respectively. This accuracy is significantly better than the accuracy of the entire DJI Zenmuse L1 system provided by the manufacturer (10 cm horizontally, 5 cm vertically).

Further research would be useful to test these settings for other types of objects and more lidar systems.

References

[1]   TerraMatch. *TerraSolid: Point Cloud Intelligence* [online]. Helsinki, c2023, [accessed 2023-05-02]. Available at: https://terrasolid.com/products/terramatch/

[2]   Matrice 300 RTK. *DJI* [online]. Shenzhen, China: SZ DJI Technology Co., 2023 [accessed 2023-04-29]. Available at: https://www.dji.com/cz/matrice-300

[3]   Avia LiDAR sensor. Livox [online]. c2023 [cit. 2023-04-29]. Dostupné z: https://www.livoxtech.com/avia

[4]   DJI Zenmuse L1 - specifications. DJI [online]. Shenzhen, China: SZ DJI Technology Co., 2023 [accessed 2023-04-03]. Available at: https://www.dji.com/cz/zenmuse-l1/specs

[5]   DJI Zenmuse P1 - specifications. DJI [online]. Shenzhen, China: SZ DJI Technology Co., 2023 [accessed 2023-05-01]. Available at: https://www.dji.com/cz/zenmuse-p1/specs

[6]   Trimble R2: Datasheet. Trimble Geospatial [online]. c2016-2023 [accessed 2023-05-01]. Available at: https://geospatial.trimble.com/products-and-solutions/trimble-r2

[7]   TerraMatch User Guide. TerraSolid: Point Cloud Intelligence [online]. Helsinki, c2023, 1. 2. 2023 [accessed 2023-04-03]. Available at: https://terrasolid.com/guides/tmatch/index.html

[8]   HAMPACHER, Miroslav and ŠTRONER, Martin. Zpracování a analýza měření v inženýrské geodézii. 2nd ed. Prague: Czech technical university in Prague, 2015. ISBN 978-80-01-05843-5.

[9]   ŠTRONER, Martin, URBAN, Rudolf and LÍNKOVÁ, Lenka. A New Method for UAV Lidar Precision Testing Used for the Evaluation of an Affordable DJI ZENMUSE L1 Scanner. Remote Sensing [online]. 27 November 2021. Vol. 13, no. 23, p. 4811 [accessed: 2023-04-03]. DOI 10.3390/rs13234811. Available from: http://dx.doi.org/10.3390/rs13234811

[10] BOUŠEK, Martin. Testování vlivu parametrů letu a parametrů vyrovnání na prostorovou přesnost mračna bodů získaného lidarovým systémem DJI Zenmuse L1. Prague, 2023 [accessed: 2023-10-03]. Thesis. Czech technical university in Prague, Faculty of civil engineering. Available from: http://hdl.handle.net/10467/110588