

TIE VOXEL METHOD AND ITS QUALITY FOR 3D AIRBORNE LIDAR BLOCK ADJUSTMENT

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ABSTRACT:

For achieving high-quality LIDARgrammetry and performing surface reconstruction by 3D point clouds acquired at different locations or in different coordinate systems, a novel method was proposed and is called *tie voxel* method, in which voxel denotes "volume element". The motivation, ideas and concrete formulation of the tie voxel method are to be given. Its potential applications are discussed. On the one hand, the theoretical quality of the tie voxel method is studied by using simulated data points. On the other hand, some tests are also done by using real airborne LIDAR points. One of diverse types of tie voxels is tie cuboid. This paper describes the tie cuboid method. This method can be used for multi-strips airborne LIDAR points registration. It is hoped that the blunder LIDAR points and the systematic errors could and must be detected somehow. The theoretical accuracy and reliability of the tie cuboid method is then studied by using simulated LIDAR points. Test results verify that the tie cuboid method provides good accuracy and reliability for airborne LIDAR point registration, even in the case of improper point distribution on a side plane. The method exploits all implicit geometric conditions such as coplanarity, colinearity and perpendicularity so that it can provide good geometric strength for 3D point cloud registration. Also, the test results using multiple tie cuboids between two neighboring LIDAR strips show that this method can determine an accurate vertical drift parameter S_z with the a posteriori standard deviation $\pm 0.0494m \sim 0.25\sigma_z$, where $\sigma_z = \pm 0.20m$ denotes the a priori standard deviation of Z-coordinate of a LIDAR point. Moreover, some tests are also done by using real airborne LIDAR points with a priori standard deviations $\pm 0.15m$ and $\pm 0.30m$ in vertical and horizontal direction, respectively. The root mean square distance 0.213m of a LIDAR point to the corresponding plane is achieved. These test results verify the applicability of the proposed tie cuboid method.

1. INTRODUCTION

For the present, different geomatics technologies are available for the acquisition of geometric, radio-physical and semantic data and information about interest objects. For instance, the light detection and ranging (LiDAR) system is a currently popular direct georeferencing method and can acquire a huge number of high precision 3D points on local surfaces of interest objects in a very short time duration. Both airborne and ground-based LiDAR systems must scan objects of interest from multiple strips or at different ground stations, respectively, so that the 3D points acquired can be further processed to reconstruct complete 3D object models and generate diverse products such as DTMs (Digital Terrain Models) and cyber city models. In the meanwhile, long strips are also adopted for data collection in a larger area.

1.1 Motivation and Aims

In general, the direct geo-referenced 3D LiDAR points scanned at diverse ground stations and from (longer) strips have high precision, but they still possess various types of errors including all kinds of systematic errors, blunders, stochastic errors and total errors that cannot be described by the aforementioned error types. In general, LiDAR errors comprise GPS positioning error, boresight error, timing error, GPS/IMU tracking error, imperfect LiDAR system calibration, scanning error, deflection of vertical, angular resolution and mechanical vibration and so on (Schenk, 2001; Wang and Tseng, 2003). For example, the GPS/IMU tracking error and timing error causes respectively planimetry and height discrepancies in airborne laser scanner

data (Maas, 2002). Also, the real error model of LiDAR points is often unknown a priori. Tsay and Liu (2007) demonstrated an example showing that there is a significant height bias of about 25cm between the two LiDAR point sets acquired from two neighbouring strips in a flat area of 100m x 100m on a playing field in NCKU, Taiwan. Similarly, Shih (2007) also verified that there are significant height offsets of about -1.67m and planimetry shifts from -0.08m to 0.204m (up to 0.61m).

The beforementioned LiDAR errors must be detected and corrected somehow. Furthermore, the 3D LiDAR point clouds of separate strips or ground stations must be registered somehow in order to cover a complete surface of an interest object or an entire terrain surface. Therefore, 3D point clouds in a LiDAR block must be adjusted for data snooping, error correction, point clouds registration and datum transformation as well as for generation of high-quality LiDAR products.

1.2 Overview of Related Works

A number of approaches are developed for LiDAR error detection and processing. They can be roughly classified into (1) the approaches based on physical models such as Burman (2000) and Tsai (2004); (2) the approaches based on mathematical model such as Kilian et al. (1996), Crombaghs et al., (2000), and Vosselman and Maas (2001). For instance, Burman (2002), Vosselman and Maas (2001), Crombagh et al. (2000) utilized some ground control points and tie points for the adjustment of laser altimeter height data. The adjustment involves the positional shift parameters, positional drift ones (for long strips), boresight angle (roll/pitch/heading) shift and drift parameters.

For registration of 3D LiDAR point clouds, another solution methods were developed e.g. by Akca (2003), Csanyi and Toth (2005), and they utilized LiDAR specific ground targets which can be easily recognized from a huge number of LiDAR points.

Also, a large number of methods are developed for registering all LiDAR point clouds scanned at different ground-based stations or from multiple airborne strips. They can be roughly classified into (1) point-based methods, (2) line-based ones and (3) planar polygon-based methods. One of the most well-known point-based methods is the Iterative Closest Point (ICP) approach presented by Besl and McKay (1992), Chen and Medioni (1992), and improved by Zhang (1994), Masuda and Yokoya (1995) and Bergevin et al. (1996). Mitra et al. (2004) developed a registration method from a geometric optimization perspective for faster convergence. Gruen and Akca (2005) proposed a method tackling the difficult problem on 3D surface and curve matching in a least squares manner. Makadia et al. (2006) proposed a fully automatic registration method with the property of robustness against weak overlap.

Stamos and Allen (2002), Stamos and Leordeanu (2003) presented approaches for automated feature-based range registration of large scale urban scenes by adopting 3D lines on the so-called supporting planes which make the matching task easy. Jaw and Chuang (2005) presented an approach for automatic 3D line-based matching and registration of LiDAR point clouds. Lee et al. (2005) used linear features for detecting discrepancies between LiDAR data strips. Habib et al. (2005) utilized straight-line segments for photogrammetric and LiDAR data registration. Kager (2004) used planar patch features for simultaneous fitting of aerial laser scanner strips. Moreover, both line-based and planar polygon-based methods for LiDAR registration are given by (Ghanma, 2006).

2. TIE VOXEL METHOD

2.1 Meaning and Idea

Tsay (2007) presented a novel method for 3D LiDAR block adjustment without utilizing any accessory such as reference targets. Its main idea is to exploit the implicit information and geometric conditions on some specific types of volume elements (voxels) and to utilize them as “tie voxels”. The novel terminology “tie voxel” possesses a similar meaning to the “tie point” in aerotriangulation. All corresponding tie voxels try to “tie”, namely connect, all neighbouring point clouds to generate a larger point cloud in a least squares manner. In our present model, all points in a point cloud are assumed to have a common coordinate datum.

It is well-known that diverse types of implicit features such as feature points, lines, curves, planes, surfaces and volumes can be extracted somehow from 3D LiDAR points. They are the so-called derived features. The aforementioned implicit information might be then simultaneously utilized for 3D LiDAR block adjustment.

2.2 Types of Tie Voxels

Figure 1 illustrates an example of one type of tie voxel, namely tie cuboid. There are also surely different types of tie voxels such as buildings with pent roof, gable roof, pavilion roof, hip roof, hipped-gable roof, cone roof, and half-check roof as well as a building with cylindrical side and hemispheric roof. They

emerge in building areas everywhere on our real world and can be formulated by specific mathematical functions.

2.3 Main Sides of A Tie Voxel

On our real world, almost always no building owns the ideal surface that can be described completely and exactly by the related mathematical function. Therefore, the 3D LiDAR points on the main sides of a tie voxel must be selected somehow. The so-called “main side” means that it is one plane (or surface) of the processed voxel. For a tie cuboid building, there should be more points well-distributed on the aforementioned main sides and main roof plane.



Figure 1. One type of tie voxel – tie cuboid

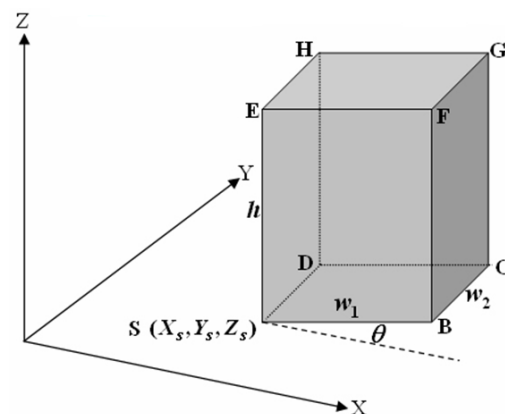


Figure 2. A simple tie cuboid and its parameters

2.4 Parameters of A Tie Cuboid

Figure 2 illustrates a simple tie cuboid with seven parameters: 3D coordinates of its corner point $S (X_s, Y_s, Z_s)$, width, length and height of the cuboid (w_1, w_2, h) and the orientation angle θ . The simple cuboid is assumed to have horizontal ground side and roof plane. In this 7-parameter model, the 3D coordinates of any corner points, any edges and any side planes of the cuboid can all be formulated definitely and explicitly by these seven parameters $X_s, Y_s, Z_s, w_1, w_2, h$ and θ . Moreover, if a corner point is a ground control point, its observation equation can also be formulated by them.

Furthermore, Figure 2 illustrates apparently that a tie cuboid contains point features (8 corner points), linear features (12 edges) and planar features (6 sides). They are implicit features derivable from LiDAR points. After the tie voxel method completes the 3D LiDAR block adjustment, these features are also determined simultaneously.

2.5 Brief Formulation of Tie Cuboid Method

A plane in 3D space can be formulated by

$$AX + BY + CZ + D = 0 \quad (1)$$

where (X, Y, Z) = 3D coordinates of any point on the plane

For our tie cuboid method, the four coefficients A~D are also functions of these seven parameters $X_S, Y_S, Z_S, w_1, w_2, h$ and ρ illustrated in Figure 2. For a LiDAR point i on the plane, the following equation holds:

$$AX_i + BY_i + CZ_i + D = 0 + v_i \quad (2)$$

where (X_i, Y_i, Z_i) = the observations of 3D coordinates measured by the LiDAR system
 v_i = residual of the pseudo distance observation d_i of the LiDAR point i to the corresponding plane

The equation (2) also depicts that a *pseudo* observation is adopted. It is the pseudo distance observation d_i of the point i to its corresponding plane:

$$d_i = \frac{|AX_i + BY_i + CZ_i + D|}{\sqrt{A^2 + B^2 + C^2}} = \frac{|v_i|}{\sqrt{A^2 + B^2 + C^2}} \quad (3)$$

The object function of least squares adjustment in the tie cuboid method is

$$\sum d_i^2 = \sum \frac{v_i^2}{A^2 + B^2 + C^2} \quad \text{MIN} \quad (4)$$

If $A^2 + B^2 + C^2 = 1$, then the equation (4) becomes

$$\sum d_i^2 = \sum v_i^2 \quad \text{MIN} \quad (5)$$

The planar functions of the six side planes prove that the condition $A^2 + B^2 + C^2 = 1$ holds for our simple cuboid model.

2.6 Brief Review on Algorithm of Tie Cuboid Method

In a computation area, 3D LiDAR points scanned from multiple strips are to be processed. Figure 3 illustrates an example that shows the 3D spatial distribution of LiDAR points scanned from two neighbouring strips. Each strip has specific strip parameters, e.g. the horizontal coordinates of two end points, strip length and strip width, that can be determined automatically. In their overlapping scanning region, some *tie areas* are to be selected somehow. Figure 4 illustrates the distribution of tie areas. The interval between any two neighbouring tie areas depends on the accuracy requirement of LiDAR block adjustment. Then, some candidate tie cuboids are to be selected somehow in each tie area. For example, Figure 5 shows three tie cuboids are chosen in a tie area manually.

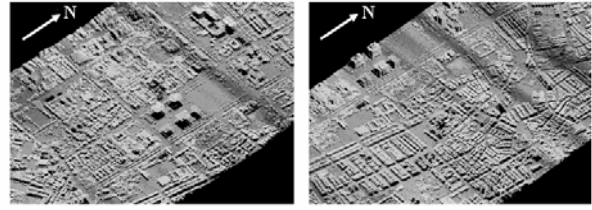


Figure 3. 3D LiDAR points scanned from two neighbouring strips

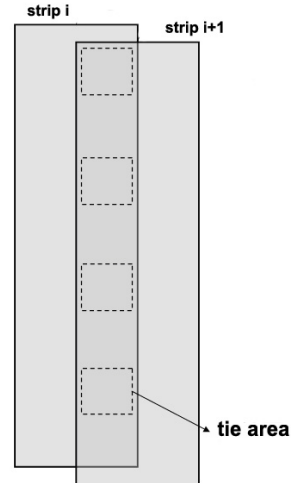


Figure 4. illustration of “tie areas”

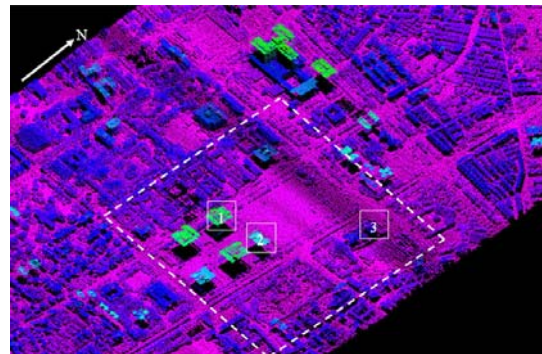
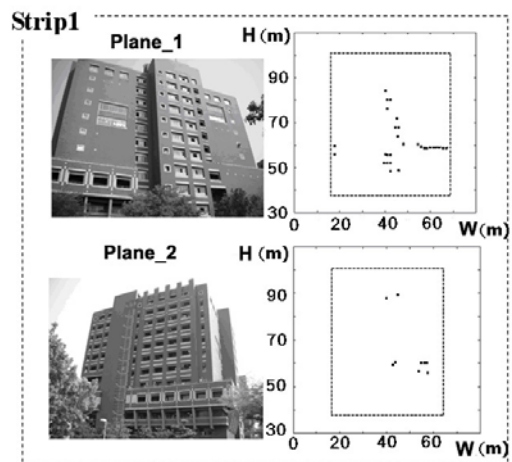


Figure 5. Tie cuboids in a tie area



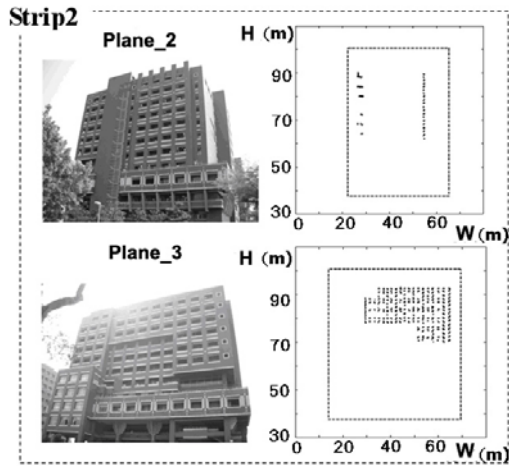


Figure 6. LiDAR points on each main side plane of a tie cuboid scanned from two strips

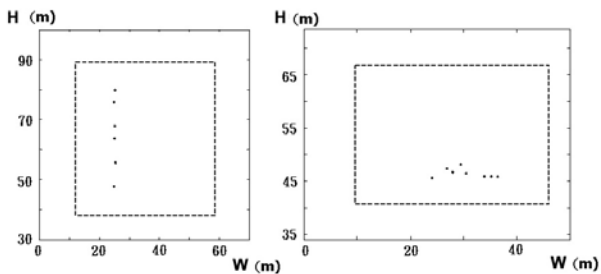


Figure 7. Bad distribution of LiDAR points on a main side plane

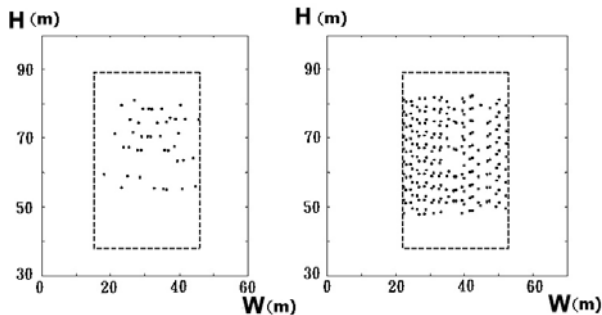


Figure 8. Well-distributed LiDAR points on a side plane

Figure 6 illustrates the distribution of LiDAR points on each main side plane of a tie cuboid scanned from two neighbouring strips. Apparently, their distribution seems to be not good, and the number of points on each main side plane seems to be not enough due to occlusion and scanning direction as well as the surface topography of each side of the tie cuboid. Figure 7 and Figure 8 show an example of badly- and well-distributed 3D LiDAR points on a main side plane of a tie cuboid, respectively.

3. TEST RESULTS

3.1 Simulated Data

Tsay (2007) and Tsay and Liu (2007) reported some tests using simulated airborne LiDAR points scanned from two strips. The *a priori* standard deviations are $\sigma_x \approx 0.5m$, $\sigma_y \approx 0.5m$, $\sigma_z \approx 0.2m$, respectively. The simulated points have the root mean square distances (RMSD) of 0.43m, 0.40m, 0.42m to the

three buildings, respectively. Also, the points of the strip 2 are shifted in Z with $S_z=25cm$. Test results express that the least squares adjustment (LSA) needs 4 iterations and the *a posteriori* standard deviation is $\hat{\sigma}_0 \approx 0.40m$. Also, the RMSD is about 0.38m and 0.40m respectively for the points of strip 1 and 2 to the cuboid buildings. The estimated shift in Z is $S_z=19cm$ with the true error of about -6cm.

3.2 Real Data

Figure 9 illustrates the aerial image of a cuboid building with the dimension of 30m x 20m x 45m and the 3D LiDAR points on its cuboid sides. These LiDAR points are acquired by Leica ALS50 at the flight height $H \approx 1500m$. The *a priori* vertical and horizontal standard deviations are $\sim 0.15m$ and $\sim 0.30m$, respectively. Three iterations are needed. The *a posteriori* standard deviation is $\hat{\sigma}_0 \approx 0.21m$ which expresses the fitting accuracy very well.

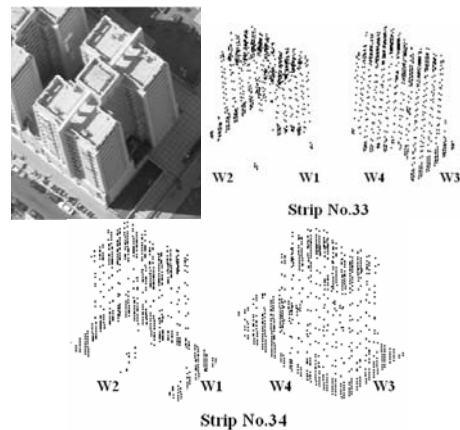


Figure 9. Tests using real airborne LiDAR points

3.3 Reliability

The well-known reliability theory developed by Baarda (1968) is used to analyze the quality of the aforementioned tie cuboid method. The related equations are briefly summarized as follows:

$$\text{Idempotent matrix } Q_{vv}P_{ll} = I - A(A^T P A)^{-1} A^T P_{ll} \quad (6a)$$

$$\text{Redundancy numbers } r_i = (Q_{vv}P_{ll})_{ii} \quad (6b)$$

$$\text{Internal reliability } \nabla_0 l_i = \sigma_{l_i} \frac{\delta_0}{\sqrt{r_i}} = \frac{\sigma_0 \delta_0}{\sqrt{p_i r_i}} = \delta'_{0,i} \sigma_{l_i} \quad (6c)$$

$$\text{External reliability } \bar{\delta}_{0,i} = \delta_0 \sqrt{\frac{1-r_i}{r_i}} \quad (6d)$$

where σ_0 = standard deviation of unit weight

α_0 = significance value (= probability of type I error)

$1-\alpha_0$ = significance level

β_0 = power

$1-\beta_0$ = probability of type II error

r_i = local redundancy

p_i = weight of the *i*-th observation l_i

σ_{l_i} = standard deviation of the *i*-th observation l_i

δ_0 = statistic figure dependent on α_0 and β_0

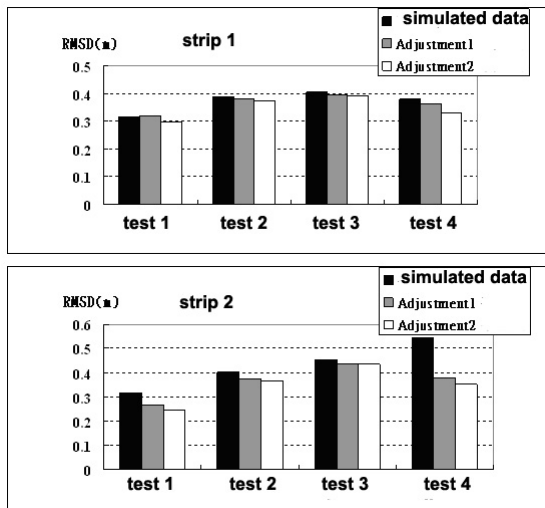


Figure 10. the root mean square distance (RMSD) of points to the corresponding main side plane

○0 = 4.13 (↔0=0.1%, ↕0=80%)		internal reliability $\delta'_{0,i}$		external reliability $\bar{\delta}_{0,i}$	
		avg.	min ~ max	avg.	min ~ max
test 1	Adj_1	4.79	4.42~5.17	2.38	1.56~3.10
	Adj_2	4.90	4.64~5.17	2.62	2.12~3.10
test 2	Adj_1	4.33	4.24~4.42	1.28	0.95~1.56
	Adj_2	4.36	4.27~4.51	1.39	1.10~1.81
test 3	Adj_1	4.19	4.17~4.22	0.72	0.56~0.88
	Adj_2	4.20	4.18~4.22	0.78	0.62~0.88
test 4	Adj_1	4.79	4.42~5.08	2.38	1.56~2.97
	Adj_2	4.90	4.64~5.08	2.61	2.12~2.97

Table 1. internal and external reliability of test results

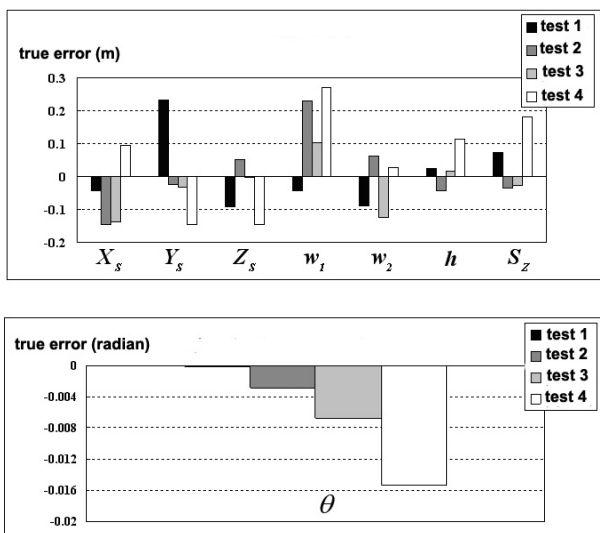


Figure 11. true errors of determined unknowns

The 3D coordinates of LiDAR points on a cuboid of 20m x 35m x 45m are simulated with the *a priori* standard deviations $\sigma_z = \sim 0.2m$, $\sigma_x = \sim 0.5m$, and $\sigma_y = \sim 0.5m$. The points are assumed to be scanned from two strips with a vertical datum bias $S_z = 25cm$. Test 1 adopts four points near the corner on each main

side plane. Test 2 and test 3 use the points with point interval of 10m and 5m, respectively. Test 4 applies four points near the center on each main side plane. Both strip 1 and strip 2 possess points on the roof plane and ground plane, but they have points only on main side plane 1, 2, and 3, 4, respectively. Test results are briefly summarized in Figure 10, Figure 11, and Table 1, where Adjustment1 (Adj_1) and Adjustment2 (Adj_2) denotes the LSA doesn't involve and involves the unknown S_z , respectively. Figure 10 expresses that the goodness of point distribution is more important than the number of points and can still provide better fitting accuracy and the most accurate azimuth parameter θ even though only very few points (four per side plane) are adopted. The total number of points is 14, 39, 116, and 14 per strip for test 1, test 2, test 3, and test 4, respectively. Table 1 shows that four tests have approximately the same internal reliability. The more points the tie cuboid method adopts, the better the external reliability.

4. CONCLUSIONS

The proposed tie voxel method enables simultaneous adjustment for (1) determination of voxel/cuboid/strip parameters (derivation of different implicit features), (2) fitting of LiDAR points onto voxels, (3) LiDAR point clouds registration and (4) 3D LiDAR block adjustment. Test results verify that the tie cuboid method provides good accuracy and reliability for airborne LiDAR point registration, even in case of improper point distribution on each main side plane. The method exploits all implicit geometric conditions such as coplanarity, colinearity and perpendicularity so that it provides good geometric strength for 3D point cloud registration. The test results using multiple tie cuboids between two overlapping LiDAR strips show that this method can determine an accurate S_z parameter with the *a posteriori* standard deviation $\sim 0.05m \triangleq 0.25\sigma_z$, where $\sigma_z = \sim 0.20m$ denotes the *a priori* standard deviation of Z-coordinate of a LiDAR point. Some tests are also done by using real airborne LiDAR points with *a priori* standard deviations $\sim 0.15m$ and $\sim 0.30m$ in vertical and horizontal direction, respectively. The root mean square distance of a LiDAR point to the corresponding plane is about 0.21m. These test results verify the good applicability potential of the proposed tie cuboid method.

In principle, the tie voxel method can be used for airborne, terrestrial and hybrid LiDAR block adjustment. The related functional and, if necessary, stochastic models must be extended somehow. Also, airborne/terrestrial/hybrid 3D block adjustment with GCPs and/or other control entities/conditions must be further developed. Moreover, semi- or fully automated extraction of LiDAR points on proper tie cuboid/voxel surfaces must be developed.

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