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A Method for the Calibration of Vehicle-borne Laser Scanning and the Accuracy Analysis

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Abstract: The contents and purpose of calibrating Vehicle-borne Laser Scanning System are introduced. And then a method to build calibration field for this system with GPS and Total Station are discussed. The accuracy of the method is analyzed. The result of measurements from a calibration test reveals that the accuracy in theory is consistent with that in practice. The method introduced in this paper is simple and suitable for its application.

Keywords: Vehicle-borne Laser Scanning; GPS; Total Station; System Calibration

1. Introduction

Vehicle-borne Laser Scanning System, which consists of several sensors such as GPS, IMU (Inertial Measurement Unit), laser scanning and digital camera, is a system for collecting spatial information rapidly. This system mounted on the roof of a vehicle can collect information from target surface using laser scanning and digital camera, get position coordinates in real time using RTK GPS and get attitude using IMU. It can be used as a mobile mapping system in the rapid collection of survey grade 3D data of buildings, roads, tunnels and other constructions in city circumstance.

The scanner of this system transmit pulse laser with high frequency when it works and rotates around its center in a plane simultaneously. The observation data is the distance from scanner center to target and the angle in its scanning plane. This is a 2-D polar coordinate system in scanning plane actually. The origin of this coordinate system is the center of laser scanning and the polar axis is certain fixed direction, denoted by O-XYZ, as shown in Fig. 1, where XY is the scanning plane, vector Z is the normal of scanning plane and O-XYZ is a right hand Cartesian coordinate. One of the purposes of mobile mapping system is to get the coordinates of target in terrestrial coordinate system, so, in the system, position of the site is get by GPS, and attitude (yaw, pitch and roll) of laser scanner is determined by IMU, then, a topocentric coordinate system is established, also called local horizontal coordinate system, as shown in Fig.1, the coordinate system GPS-NEU. If the vector from the center of GPS antenna to laser scanner and the attitude angles between the axes of IMU and scanning plane are known, then the terrestrial coordinates of target will be gotten by coordinates transform. Unfortunately the vector and angles are unknown, and will vary every time when this system is mounted. Therefore these systematic parameters (three rotation angles, three translation parameters and one

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scale factor) should be determined, namely external parameters calibration for vehicle-borne laser scanning system.

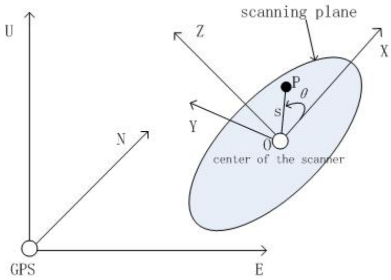

Fig.1. The coordinates of laser mobile mapping system

The currently method is: selecting a number of characteristic points in a suitable field and getting there coordinates belonging to terrestrial coordinate system in advance , these characteristic points act as common points. And then getting there coordinates using laser scanner, the seven parameters of BURSA-WOLF transformation model will be obtained by the method of least squares adjustment at last. A method for measuring those common points using GPS and Total Station is presented in this study. The data demonstrated below are taken from acceptance check for a vehicle-borne laser scanner.

2. The calibration field and characteristic point

Calibration is necessary before acceptance check for a product of vehicle-borne laser scanning system. According to the specification and conditions in the calibration field, some common points are chosen. These points can be classified into two groups. One is located uniformly on the ground before a building; the other is located on the wall of the building. Marking on the wall is not allowed, so, window corners of second and third floor are chosen as common points, as shown in Fig 2. There are about 100 points chosen on the wall. The white circles in the picture upstairs denote the position of window corners, which is the target aimed at by reflectorless Total Station. An enlarged picture is shown on the picture downstairs in Fig.2.

Fig.2. The characteristic points on the wall

Upstairs: layout of some characteristic points, denoted by white circle in picture
Downstairs: one point on corner of a window, where aimed at by total station

3. Schemes

It is about 250m along the east-west direction of the calibration field and 160m along the south-north, see Fig.3. The point P1 is selected as datum point on account of GPS constellation visibility. The horizontal accuracy of common points should be better than 20mm and 30mm vertically relative to the datum point according to the specification. So, GPS RTK (Real Time Kinematic) survey technique is suitable for common points on the ground, but for those points on the wall reflectorless Total Station had to be used.

Control points are needed when Total Station is set up. Taking the condition of this calibration field into account, the control networks were divided into two orders, i.e. the primary network and secondary network. The primary network consists of 3 control points: p1, p4 and p7. Every baseline in the triangle was measured using GPS static survey mode for 30 minutes with sampling interval 10 seconds and the elevation cut-off angle 15°. Then all baseline observations were processed and the network was adjusted with free network adjustment. The accuracy of points in primary network is about 3mm.

The secondary network consists of 11 control points, denoted by circle as shown in Fig 3. The location of those points should be suitable for data collection for GPS as well as for Total Station. So, it should be intervisible between adjacent control points. These points were measured using GPS RTK technique and the base station is set on control point P1. Control point P4 and P7 in primary network are measured using GPS RTK too for checking the accuracy of RTK survey.

Control points in primary and secondary networks are marked using steel nail with crossing lines on the head. The diameter of crossing center is less then 0.5mm.

The common points on the wall are measured using reflectorless Total Station. Before every sides of the building there was set two stations, left station and right station, for the reason of accuracy. There are 8 station sites, which are P10, P9, P8, P7, P6, P5, P4 and P3.On each station the Total Station measures only those points on the right or left half of the opposite wall in case of bad accuracy due to long range or big angle of incidence. The maximal range from control points to common points on the wall is 43m among all observations. The most vertical angle is less then 8 degree except for very few to 17 degree. Big vertical angles are among observations of station on the east of the building. Because another building are close to the east of our building and the narrow space between the two buildings lead to big vertical angle.

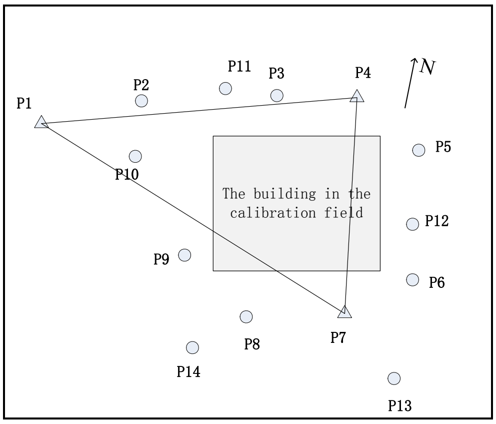

Fig.3. Calibration field and control points

4. Measurement in topocentric coordinate system

The geodetic coordinates or Cartesian coordinates of every point are provided in WGS84 reference system. While plane coordinates are needed for Total Station sets up. Usual conversion method is projection such as Gauss- Kueger firstly, and then setting up Total Station upon a control point, plane coordinates of common points can be measured. Inverse solution of projection is performed to turn back geodetic coordinates at last. Both because of the complication of the algorithm and because of extra systematic error due to direct solution and inverse solution of projection, another simple algorithm is presented in this paper. That is: data collection and processing is performed in topocentric coordinate system firstly and then transition is carried out to obtain geodetic coordinates of target points.

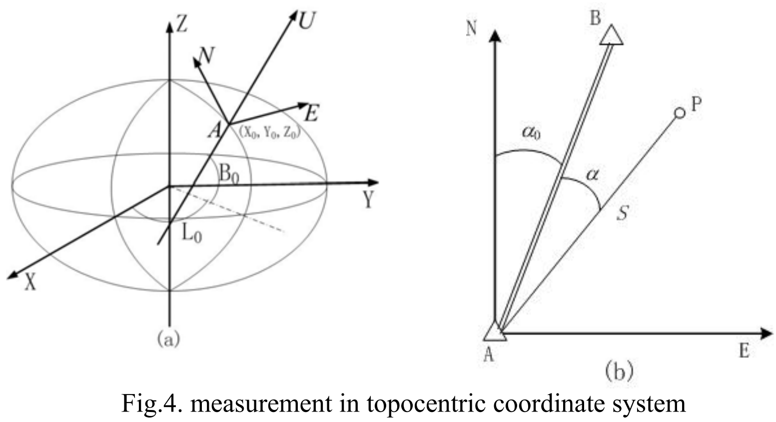

Fig.4. measurement in topocentric coordinate system

The relationship between topocentric coordinate system and geodetic coordinate system is shown in Fig.4 (a). Where A is the origin of topocentric coordinate system with geodetic coordinates (B_0, L_0, H_0) and Cartesian coordinates (X_0, Y_0, Z_0). For any point whose coordinates in the geodetic and topocentric coordinate system are (X, Y, Z) and (N, E, U), respectively, one has relation given by (1)

$$\begin{bmatrix} N \\ E \\ U \end{bmatrix} = \mathbf{T} \cdot \left(\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} - \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} \right) \tag{1}$$

where:

$$\mathbf{T} = \begin{bmatrix} -\sin B_0 \cos L_0 & -\sin B_0 \sin L_0 & \cos B_0 \\ -\sin L_0 & \cos L_0 & 0 \\ \cos B_0 \cos L_0 & \cos B_0 \sin L_0 & \sin B_0 \end{bmatrix} \tag{2}$$

In small area the deflection of the vertical and surface bend of the earth can be omitted. That's mean the normal line of reference ellipsoid and the plump line of the gravitational field coincide as well as the surface of the earth is treated as plane. Then a topocentric coordinate system is defined as shown in Fig. 4(b). The origin of the local horizontal coordinate system is the site of the Total Station denoted by A. And B in the Fig. 4(b) is another known orientation control point. P is an unknown point. α_0 denotes known coordinate azimuth of $\overrightarrow{AB}$. And α, β, s denotes horizontal angle, vertical angle and distance respectively to be measured using Total Station. h_A is instrument height. Then the coordinates of point P in topocentric coordinate system is given by (3).

$$\begin{aligned} N &= s \cdot \cos(\alpha_0 + \alpha) \\ E &= s \cdot \sin(\alpha_0 + \alpha) \\ U &= h_A + s \cdot \sin \beta \end{aligned} \tag{3}$$

The coordinates in geodetic coordinate system can be obtained with inverse transition of (1).

5. The accuracy assessment and the result

The error sources of common point coordinates include: the coordinates error of control points, height error of instrument, the errors of horizontal angle, vertical angle and distance. Then the error of common point coordinates can be derived from (3) by error propagation theorem. Let the coordinates error of station site lie over then one gets (4):

$$\begin{aligned} m_N^2 &= (\cos(\alpha_0 + \alpha) \cdot m_s)^2 + (s \cdot \sin(\alpha_0 + \alpha) \cdot m_{\alpha_0})^2 + (s \cdot \sin(\alpha_0 + \alpha) \cdot m_\alpha)^2 \\ m_E^2 &= (\sin(\alpha_0 + \alpha) \cdot m_s)^2 + (s \cdot \cos(\alpha_0 + \alpha) \cdot m_{\alpha_0})^2 + (s \cdot \cos(\alpha_0 + \alpha) \cdot m_\alpha)^2 \\ m_U^2 &= m_{h_A}^2 + (\sin \beta \cdot m_s)^2 + (s \cdot \cos \beta \cdot m_\beta)^2 \end{aligned} \tag{4}$$

In (4), m_{α_0} is described by

$$m_{\alpha_0}^2 = \left(\frac{N_B}{N_B^2 + E_B^2} m_{E_B}\right)^2 + \left(\frac{E_B}{N_B^2 + E_B^2} m_{N_B}\right)^2 \tag{5}$$

m_{E_B} and m_{N_B} are assumed equal and rewritten as m_B, then (5) turn out to be (6):

$$m_{\alpha_0} = m_B / S_B \tag{6}$$

where S_B is the distance from station site A to orientation control point B. So, orientation control point should be selected as far as possible from the station site for the sake of smaller m_{α_0}.

Let $m_B = 10mm$, $m_\alpha = 5''$, $m_\beta = 5''$, $m_s = 10mm$, $m_{h_A} = 5mm$, $\beta = 20°$, $s = 50m$, $S_B = 200m$, then the horizontal accuracy is 10mm and vertical accuracy is 6mm according to (4) and (6). Now taking coordinates error of control points into account, it is a translation effect. Let assume the horizontal accuracy of station site is 10mm and vertical accuracy is 20mm, and then the accuracy of common points meet the demands as well. It's has to be reminded that the assumption above is derived from bad conditions.

All common points in the calibration field were measured using Total Station Leica TRC402 according to the method presented above. Some control points were measured using Total Station also for the sake of accuracy assessment. The coordinates of those control points derived from Total Station and RTK were compared. The difference is shown in table Ⅰ.

TABLE I. THE RESULT OF CHECKED POINTS

Check-up	dN(m)	dE(m)	dU(m)
Station:P10,op: P1,check: P2	0.003	0.000	0.000
Station:P9,op:P1, check: P2	-0.022	0.020	0.006
Station:P8,op:P14, check: P13	-0.031	0.000	0.013
Station:P4,op:P11, check: P5	-0.017	0.023	-0.016
Station:P3,op:P2, check: P4	0.019	0.000	-0.010

Station: the site where Total Station was set up
Op: orientation control point used for total station set up
Check: the point used for check-up.

Taking for the tolerance as twice mean square error, then the tolerance in horizontal is 40mm and vertical is 60mm. Every item in table Ⅰ is satisfied.

Some common points were measured twice respectively from adjacent station sites. Then there coordinates respectively derived from different station sits can be compared. Part comparison are listed in table Ⅱ. Taking for the tolerance as twice mean square error still, then the tolerance in horizontal is 56mm and vertical is 84mm. Every item in table Ⅱ is satisfied.

TABLE II. COMPARISON RESULT

Coincidence point: S2-15	B(°′″)	L(°′″)	H(m)
Station :P8, Op:P14	** ** 38.3491	*** ** 08.0400	47.920
Station :P7, Op:P14	** ** 38.3487	*** ** 08.0410	47.906
difference(m)	0.013	-0.024	0.014
Coincidence point: N2-14	B(°′″)	L(°′″)	H(m)
Station :P4, Op:P11	** ** 40.7828	*** ** 06.2560	47.922
Station :P3, Op:P2	** ** 40.7837	*** ** 06.2560	47.922
difference(m)	-0.028	0.000	0.000
Cincidence point: P12	B(°′″)	L(°′″)	H(m)
Station :P6, Op:P7	** ** 40.6275	*** ** 09.7540	44.478
Station :P5, Op:P6	** ** 40.6266	*** ** 09.7550	44.469
difference(m)	0.028	-0.023	0.009

Station: the site where Total Station was set up
Op: orientation control point used for total station set up

Parts of these common points are used for calibration of certain Vehicle-borne Laser Scanning, and then others are used for check-up. The result of comparison is listed in table Ⅲ.

TABLE III. RESULT OF COMPARISON BETWEEN COORDINATES DERIVED FROM DIFFERENT WAY (UNIT IN TABLE: m)

Point Number	Coordinates from laser scaner			Coordinates from Total Station			Difference		
	East	North	Height	East	North	Height	DE	DN	Du
1	**4637.43	**25573.49	49.56	**4637.44	**25573.49	49.60	-0.01	0.00	-0.04
2	**4638.94	**25569.84	49.61	**4638.96	**25569.80	49.60	-0.02	0.04	0.01
3	**4641.26	**25564.20	49.55	**4641.25	**25564.21	49.59	0.01	-0.01	-0.04
4	**4642.78	**25560.61	49.64	**4642.78	**25560.59	49.59	0.00	0.02	0.05
5	**4644.26	**25556.89	49.59	**4644.28	**25556.87	49.60	-0.02	0.02	-0.01
6	**4647.33	**25549.49	49.55	**4647.36	**25549.48	49.59	-0.03	0.01	-0.04
7	**4648.86	**25545.80	49.55	**4648.87	**25545.79	49.59	-0.01	0.01	-0.04
8	**4658.00	**25523.68	49.61	**4657.98	**25523.67	49.59	0.02	0.01	0.02

9	**4659.54	**25519.94	49.62	**4659.50	**25519.93	49.59	0.04	0.01	0.03
10	**4661.05	**25516.25	49.62	**4661.03	**25516.24	49.59	0.02	0.01	0.03
11	**4662.57	**25512.55	49.55	**4662.56	**25512.55	49.59	0.01	0.00	-0.04
12	**4664.08	**25508.88	49.54	**4664.09	**25508.86	49.56	-0.01	0.02	-0.02
13	**4667.93	**25499.58	49.55	**4667.90	**25499.62	49.58	0.03	-0.04	-0.03
14	**4638.01	**25571.88	47.87	**4638.03	**25571.86	47.90	-0.02	0.02	-0.03
15	**4639.53	**25568.16	47.88	**4639.54	**25568.16	47.90	-0.01	0.00	-0.02
16	**4641.84	**25562.65	47.90	**4641.83	**25562.66	47.90	0.01	-0.01	0.00
17	**4643.35	**25558.92	47.91	**4643.36	**25558.91	47.90	-0.01	0.01	0.01
18	**4644.88	**25555.21	47.88	**4644.89	**25555.22	47.89	-0.01	-0.01	-0.01
19	**4646.40	**25551.52	47.89	**4646.41	**25551.53	47.90	-0.01	-0.01	-0.01
20	**4647.95	**25547.80	47.88	**4647.93	**25547.84	47.89	0.02	-0.04	-0.01
21	**4657.07	**25525.69	47.87	**4657.04	**25525.67	47.88	0.03	0.02	-0.01

Twenty one points are selected for check-up. Then there coordinates are compared with that derived from certain Vehicle-borne Laser Scanning. The maximal difference is 4cm and standard deviation is 2cm in horizontal. In vertical that is 4cm and 3cm respectively. These meet the specification.

6. Conclusions

Nowadays, it shows grate advantages that the Vehicle-borne mapping system is being popularized. The method presented in this paper which used for building calibration field for Vehicle-borne Laser Scanning with GPS and TPS based in topocentric coordinate system is simply but rigorous in theory. This method can meet the demands of specification. It is still necessary to give some explanation that higher accuracy of this method can be achieved by further improvement. For example, GPS static survey mode instead of RTK and Total Station with more precision instead of TC402 can be adopted in this method.

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