Error Compensation for 3D Digital Laser Scanning Data Based on the Surface of Aluminum Coated F-12 Aramid Plain Weave Fabric and a Test of Configuration for Large Balloon

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Abstract. The measurement of the configuration parameters for the large balloon is an important content, including volume, surface area and specific size under a certain internal pressure. Non-contact measurement techniques using laser scanning have the advantage of fast acquiring large numbers of points. However, compared to their contact-based counterparts, these techniques are known to be less accurate. Furthermore, this accuracy depends on different parameters such as materials properties, surface texture, product color, etc. The large balloon is made by aluminum coated F-12 aramid plain weave fabric pieces. The digitizing errors for high-speed 3D digital laser scanning data based on the surface of F12 fabric material are analyzed and characterized in this paper. With error characterisation, an empirical model is obtained relating the errors to the influencing factor. Establishing a reasonable test scheme and using the technology of laser scanning, the spatial information of the surface for large balloon can be obtained quickly. The empirical formula is used to compensate for 3D laser scanning data of large balloon. The problem of compensation for 3D laser scanning data for improved test accuracy is addressed. The more accurate parameters of the configuration for large balloon are quickly obtained. This provides a method for the rapid, high-efficiency and high-precision test of configuration for large balloon.

1. Introduction
The configuration parameters of large balloon in an inflated state are important data for evaluating the performance, such as size, volume, and surface area. Cathey H M et al.[1,2] used the photogrammetry technique to obtain the configuration of the super pressure balloon. Then the overall shape of the balloon was estimated by the local shape of the balloon. Welch J V et al.[3] conducted a test study on the deformation and strain of the surface of the balloon by photogrammetry technology. The three-dimensional local shape of the balloon was obtained. When using digital photography to measure the configuration parameters of the balloon, the spatial coordinates of few reflective points on the surface can be obtained. And these data of reflective points is used to evaluate the configuration of the balloon. Although the precision of data of the spatial coordinates of reflective points is high, the number of reflector points is small, which will lead to deviation when used to evaluate the overall configuration parameters of large balloon. At the same time, the method takes long time, large workload, and inefficiency for large balloon. For the structure of inflatable reducer, NASA[4] proposed a measurement method for the configuration by the three-dimensional laser scanning. Non-contact measurement techniques using laser scanning have the advantage of fast acquiring large numbers of
points. However, the compensation problem of scanning data is not considered. Furthermore, this accuracy depends on different parameters such as materials properties, surface texture, product color, etc. The influence of the surface characteristics of the material of the balloon for the accuracy of scanning data is not considered.

Some scholars have studied the error compensation problem of 3D line laser scanning. The laser sensors currently on the market do not have the accuracy of the classical dynamic contact sensors. Taking into account and correcting these induced errors can be considered in two manners: either by developing a theoretical model that allows taking them into account during the calibration phase, or by developing an experimental model of correction of the systematic errors after the measurement. Developing a theoretical model to cope with these drawbacks is rather complex. Determining its parameters through calibration is all the more difficult. Moreover the parametrical correction models do not automatically take into account the local defects. The use of a non-parametrical model can prove more accurate and easier to implement when calibrating an imager with a flecked test pattern freely moving in the field of view[5]. Therefore, in order to solve this problem, the approach of a correction after measurement from an experimental model has been chosen usually. Xie J et al.[6] have used a look-up-table (LUT) combined with a complex interpolation algorithm to correct or adjust rectify the non-linearity between the scanning speed of the laser focus on the image field and the angular velocity. Prieto F[7] has determined a model of errors based on the repeatability of the positioning and orientation parameters. However, his study was carried out with static measurement positions that do not correspond to real functioning conditions. Feng H Y and Liu Y[8,9] have studied the effect of the distance d and the ortho-incidence angleβon the measurement of the distance between a plane and the center of a sphere. To carry out the design of the model, Feng and Liu’s experimental setup, including the influence of the angleα, has been used. The setup consists of a ceramic plate (gauge block) as well as a reference sphere also in ceramic. VanGestel N et al.[10] have studied the influence of the three parameters (d, α, β) on the distribution of measurement points of a reference plane, when taking into account the thermal effects. Isheil A et al.[11] presented aims at improving the accuracy of the line laser scanning techniques through an error correction procedure based on an experimental process that concerns mechanical parts. And the influence of the three parameters, defining the relative position and the orientation between the sensor and the surface, is studied.

The large balloon is made by aluminum coated F-12 aramid plain weave fabric pieces. The digitizing errors for high-speed 3D digital laser scanning data based on the surface of F12 fabric material are analyzed and characterized in this paper. With error characterisation, an empirical formula is obtained relating the errors to the influencing factor. The problem of compensation of 3D laser scanning data for improved inspection accuracy is addressed. The empirical formula is used to compensate for 3D laser scanning data of a large balloon. The more accurate parameters of the configuration for large balloon are quickly obtained.

2. Error characterisation

2.1. Definition of error influencing factors

As shown in figure 1, a typical 3D digital laser scanning process can be described by principle of laser ranging. The principle of point cloud coordinate acquisition is to measure the horizontal and vertical angles, as well as the distance between the pulsed laser emission and recovery time difference. The \( X_P Y_P \) as the plane, and the \( Z_P \) is the vertical direction. The space coordinates of the target point \( P \) relative to the origin of the coordinate are obtained by the distance \( L \) and the angle between the point and the axis, which can be described as

\[
\begin{align*}
x_P &= L \cos \alpha \cos \beta \\
y_P &= L \cos \alpha \sin \beta \\
z_P &= L \sin \alpha \\
L &= \frac{c \cdot t}{2}
\end{align*}
\]
where the $c$ is the speed of light, $t$ is the time between the pulsed laser emission and recovery. Where the $t$, $\alpha$ and $\beta$ are obtained by the internal modules of the scanner. The distance $L$ is calculated by the $t$. And the distance $L$ is determined by the actual distance $d$. The distance $d$ is the distance from the scanner to the measured surface. Considering the working mode of the scanner, the parameter $d$ is considered as the influencing factor investigated in this paper.

2.2. Error evaluation

The test set-up for error evaluation is shown in figure 2. The testing system consists of laser scanner, a reference plane and a reference ball. The laser scanner is a high-speed 3D digital laser scanner named the Trimbe TX5. The scanner can measure with 976,000 points per second and an optimum 120 meters. The reference plane is made up of F12 fabric material with a length and width of 0.5m. The front of F12 fabric material is aluminized. The back of F12 fabric material is scanned in this paper. The reference ball is rigidly mounted with a distance of $D_0$ onto the reference plane. The diameter of the reference ball is 100.025mm. The spherical deviation of the ball is 6μm. The error evaluation covers a range of the distance $d$ from 1m to 7.5m. The distance increment is 0.5m, and, hence, there are 14 distance set-ups. And five tests is chose for each distance setup. In total, there are 70 tests. Each test corresponds to one distance. The reference ball and reference plane are both scanned. The distance between the ball and the plane, as shown in figure 2, is determined from the scan data and compared against the value measured by 3D line laser scanner that is considered as the benchmark. So, the error is defined as

$$e = (D_0 - D) \frac{d}{D_0}$$  \hspace{1cm} (2)

where $e$ denotes the error, $D$ and $D_0$ denote the measured distance by laser scanner and that by the 3D line laser scanner, respectively. The selection of $D$ for the tests takes into consideration the spherical nature of the ball. Scanning of the ball would be the same for different projected angle set-ups. The scene diagram of test is shown in figure 3. The results of the 3D laser scanning and the line laser scanning is shown in figure 4.
2.3. Empirical formula
In each test conducted, the error is averaged over five scans. The figure 5 shows the error map based on the test data. The least-squares method is applied for data fitting, considering the one variable, the distance \( d \). This suggests that the systematic error can be effectively modeled by a linear relationship with the distance \( d \). The empirical formula obtained from the least-squares fitting is given as
\[
e = -0.27338d + 0.31439
\]  

(3)

3. Error compensation
To carry out error compensation, first, the concerned parameters are computed, based on the original scan data set. Secondly, the distance \( d \) of each scan point is computed, and then the scan point is compensated based on equation (3).

3.1. Case study
A case study is conducted to compensate for the scan data of a large balloon. The large balloon is made by F12 fabric pieces. The size of the balloon is larger. The laser scanner TX5 is placed inside the balloon. The laser scanner TX5 is located at the center of the bottom of the balloon. And the bottom of
the balloon is in contact with the horizontal ground. The cloud of scanning points for the large balloon under a certain internal pressure is shown in figure 6. Under each state of the balloon, only one station is needed to scan the entire surface of balloon. And each station takes less than 3 minutes. Therefore, with this method, the complete configuration information of the surface for the large balloon can be quickly obtained.

![Figure 6](image)

**Figure 6.** The cloud of scanning points for the large balloon under a certain internal pressure: (a) front view, (b) side view.

3.2. Estimation of the distance \(d\)

In light of equation (3), compensation is carried out based on the distance \(d\), and it’s values may be estimated based on the scan data set. A spatial coordinate system is established with the coordinate origin close to the scanner position and the direction perpendicular to the horizontal ground as the \(z\)-axis direction. The spatial coordinate system \(XYZ\) is shown in figure 6. So the distance \(d\) of the \(i\)th scan point may be estimated as below

\[
d_i = \sqrt{x_i^2 + y_i^2 + z_i^2}
\]

(4)

where the \(d_i\) denotes the estimated distance, the \(x_i\), \(y_i\) and \(z_i\) represent the coordinates of the \(i\)th scan point.

3.3. Error compensation

Based on the estimated distance \(d\), the compensation value is computed using equation (3). The method of the compensation is based on point adjustment. The compensation follows the principle of azimuth invariance, that is, the point after compensation is located on the connecting line between the point before compensation and the origin. \(\alpha_i\) and \(\beta_i\) represent the azimuth of the \(i\)th scan point in the coordinate system. As is shown in figure 7. So the error compensation is applied to the components in the \(x\)-, \(y\)- and \(z\)- directions, and may be given as

\[
\begin{align*}
  x_i^{+1} &= x_i - |e_i| \cdot \cos \beta_i \cos \alpha_i \\
  y_i^{+1} &= y_i - |e_i| \cdot \cos \beta_i \sin \alpha_i \\
  z_i^{+1} &= z_i - |e_i| \cdot \sin \beta_i
\end{align*}
\]

(5)

where \(x_i^{+1}\), \(y_i^{+1}\) and \(z_i^{+1}\) represent the coordinates of the \(i\)th scan point after compensation. The \(e_i\) represents the the error of the \(i\)th scan point. The \(\alpha_i\) and \(\beta_i\) can be calculated by the values of the coordinates for the \(i\)th scan point.
4. Results and discussions
The method of the compensation proposed in this paper is used to compensate the scanning data of surface for the large balloon. And it can improve the accuracy of the scanning data. So the more accurate values of volume, surface area and space size for configuration parameters can be obtained under internal pressures. This provides an important data reference for the flight tests of balloon and so on.

The volume and surface area of configuration parameters calculated before and after the compensation of the scanning data are shown in the figure 8 and figure 9. The $V_B$ is expressed as the inside volume of the balloon. The $S_B$ is the surface area of the balloon. The $\Delta V_B$ denotes the difference between the volume of the balloon before and after compensation. The $\Delta S_B$ denote the difference between the surface area of the balloon before and after compensation. It can be seen from the diagram that the values of volume and surface area which calculated after the compensation are smaller than those calculated before compensation under the same internal pressure. The values of the volume and surface area of the balloon gradually increase with the increase of the internal pressure, and increase almost linearly. With the change of the internal pressure of balloon, the difference of the volume and surface area is little fluctuating.

**Figure 8.** The volume of configuration parameters calculated before and after the compensation of the scanning data for the large balloon.

**Figure 9.** The surface area of configuration parameters calculated before and after the compensation of the scanning data for the large balloon.

Therefore, according to the method of surface configuration test for large balloon and the compensation of the scan data, the more accurate configuration parameters of the large balloon can be
quickly obtained. This provides a more efficient, fast, and accurate method for surface configuration testing of the large balloon. After that, the balloon can be further analyzed. The scanned data of the flap of the balloon can be intercepted after compensation, and the model of flap can be reconstructed. Then the finite element analysis method is used to analyze the strain field of the surface of the balloon. The finite element numerical results of the balloon is shown in figure 10.

![Finite element numerical results of the balloon](image)

**Figure 10.** The finite element numerical results of the balloon:

(a) displacement U1, whole,  (b) maximum principal strain, flap.

5. Conclusions
The large balloon is made by aluminum coated F-12 aramid plain weave fabric pieces. In this paper, a methodology is put forward for compensating the error of the 3D laser scanning data. This includes error characterisation and compensation. The digitizing errors for high-speed 3D digital laser scanning data based on the surface of F12 fabric material are analyzed and characterized.

The laser scanner TX5 is placed inside the balloon. Under each state of the balloon, only one station is needed to scan the entire surface of balloon. And each station takes less than 3 minutes. The complete configuration information of the surface for the large balloon can be quickly obtained. Therefore, according to the method of surface configuration test for the large balloon and the compensation of the scan data, the more accurate configuration parameters of the large balloon can be quickly obtained. This provides a new method for the rapid, high-efficiency and high-precision test of configuration for the large balloon.

6. References
[1] Cathey H M 2009 The NASA super pressure balloon – A path to flight Advances in Space Research 44 pp 23–38
[2] Rabha M B, Boujmil M F, M and Cathey H M 2007 Evolution of the NASA Ultra Long Duration Balloon AIAA Balloon Systems Conf. (Williamsburg VA) p 2615
[3] Welch J V, Wang S R, Joseph R and Blandino K M 2005 Super pressure balloon non-linear structural analysis and correlation using photogrammetric measurements AIAA 5th Aviation, Technology Integration and Operations Conf. p 7447
[4] Leo L, Christopher K, Ben T, David J, Glen B, Brian G, Dennis B, Robert D and Charles P 2012 Design and testing of the inflatable aeroshell for the IRVE-3 flight experiment 53rd AIAA/ASME/AHS/ASC Structures, Structural Dynamics and Materials Conf. (Honolulu, Hawaii) p 1515
[5] Orteu JJ, Comille N, Garcia D, Sutton, S A and Mcneill S R 2005 Calibrage d’imageurs avec prise en compte des distorsions Instrumentation Mesure and Métérologie (Lavoisier) 4 p 105-24
[6] Xie J, Huang S, Duan Z, Shi Y and Wen S 2005 Correction of the image distortion for laser galvanometric scanning system Optics and Laser Technology 37 p 305–11
[7] Prieto F 1999 Me’trologie assisté’e par ordinateur: apport des capteurs 3D sans contact PhD Thesis (INSA Lyon, France)
[8] Xi F, Liu Y and Feng H Y 2001 Error compensation for three-dimensional line laser scanning data *International J. of Advanced Manufacturing Technol* 18 p 211–6

[9] Feng H Y, Liu Y and Xi F 2001 Analysis of digitizing errors of a laser scanning system. *J. of the International Societies for Precision Engineering and Nanotechnology* 25 p 185–91

[10] VanGestel N, Cuypers S, Bleys P and Kruth J P 2009 A performance evaluation test for laser line scanners on CMMs *Optics and Lasers in Engineering* 47 p 336–42

[11] Isheil A, Gonnet J P, Joannic D and Fontaine J F 2011 Systematic error correction of a 3D laser scanning measurement device *Optics and Lasers in Engineering* 49 p 16–24