Measurement of Blast Furnace Refractory Lining Thickness with a 3D Laser Scanning Device and Image Registration Method

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This paper presents a method for blast furnace lining thickness measurement with a 3D laser scanner and image registration method. A laser scanner is used to measure the inner profile through an opening on the upper part of the furnace. Two data point sets are obtained before and after the lining repairing process respectively, and data registration algorithm is employed to acquire rigid body transformation so as to compare the difference between both point clouds based on the same coordinate system. The difference represents thickness added to the initial lining. Furthermore, by comparing mechanical dimensions with the measured profile, residual lining thickness can be obtained.

KEY WORDS: 3D laser scan; data registration; ICP; blast furnace.

1. Introduction

Blast furnace process has been the most effective way to produce iron for over 200 years. Among issues that affect efficiency and stability of the chemical reaction inside the blast furnace, lining condition is one of the key factors that influence thermal dissipation and temperature distribution. Insufficient lining thickness will lead to risk of gas leakage to the environment, as well as degraded productivity due to the increased thermal loss at the wall. Usually abrasion of lining surface can be attributed to mainly two factors, mechanical friction caused by burden descending, as well as erosive material and thermal damage owing to chemical reactions driven by rising hot blast. Therefore, a wall repairing method called the “gunning process” takes place to spray fire-proof material onto the wall. As illustrated in Fig. 1, a manually controlled robot is hung down from the top of the blast furnace to perform spraying. Thus the material thickness distribution, an important factor that limits the remaining life of the blast furnace, is taken as a major check point for evaluating repair quality.

Many methods have been employed to measure blast furnace lining thickness throughout years, including radioisotopes, thermal measurement and core-drilling. Temperature measurement is among the most widely used method for on-line monitoring the profile of the blast furnace inner surface, which is based on numerically solving inverse problem using heat transfer models and readings from thermocouple.1-3) Optimization methods are applied to obtain the boundary of the domain iteratively, and hence the computation is very expensive and calculation cannot be very accurate. Radioactive method uses radiation source that emits gamma ray into the wall and the wall thickness can be obtained as a function of scattering intensity.4,5) Core-drilling is an invasive method to inspect the wall thickness of a particular position on the wall by taking sample of a very small portion. These methods can only give localized information with disadvantages such as radiation safety concerns as well as accuracy issues.

This paper presents a new method for blast furnace lining measurement using a 3D laser scanner. Owing to its high data acquisition rate and large measurement range, 3D scanner is able to obtain a large amount of discrete data points in a very short time. Therefore, it is very suitable for measuring inner profile of blast furnace, especially for evaluation of lining thickness during the gunning process. The remainder of this paper is organized as follows, Sec. 2 introduce the working principle of the 3D scanner and the measurement procedure. In order to obtain accurate lining thickness, image registration algorithm is utilized to integrate two point sets with common geometries. Section 3 explains how image registration method is applied for merg-

Fig. 1. Blast furnace gunning process.
ing points taking from the specific geometry of the blast furnace. Lining thickness be obtained from registration result and is illustrated in Sec. 4. Finally, conclusions are discussed in Sec. 5.

2. Digitization of Blast Furnace Lining Profile Using a 3D Scanner

Taking advantage of recent achievements in opto-electronic and semiconductor devices, surface profiling using 3D laser technology has now become available with elevated speed and lower price. Figure 2 illustrates the working principle of a 3D scanner. A laser head that delivers range data with millimeter resolution is driven to scan all over the space by a two-axis motorized servo mechanism. The 3D surface profile is obtained by accumulating each individual range data along with encoder positions of the servo mechanism. The scanned surface can only be clearly visualized by transformation from spherical coordinate system into Cartesian coordinate system. The 3D scanner has a wide measurement range of 80°×360° rotation angle, 2 cm accuracy achieved by time-of-flight principle, with 0.2° vertical resolution and maximum horizontal resolution of 0.05°. Acquired data can be transferred to a PC through a TCP/IP port for subsequent processing.

After years of operation, the No. 4 blast furnace in China Steel Corporation was scheduled to spray about 200 tons of fire-proof material on the shaft part in May, 2006. In order to estimate the thickness of the material, two measurements were performed before and after the repair process. Afterwards, the thickness distribution of the material all over the shaft part was estimated by comparing the two surface profiles. In order to obtain the largest viewing angle, the 3D scanner was installed with an inclination sensor on a supporting frame on the north hatch of the blast furnace. After taking the first measurement, the scanner was removed from the supporting frame, and the frame was taken apart so that the spraying robot could enter the blast furnace from the same site. Figure 3 shows the measured result, in which profile of the lining furnace and cooling boxed are clearly visualized. Followed by 27 h of spraying process, the robot was pulled out from the blast furnace and the 3D scanner was installed again to perform the second measurement. Thickness distribution of the gunning material was obtained by calculating profile difference of the two measurements. Since the reinstallation could not reach exactly the previous position and orientation, a small mechanical misalignment will lead to large measurement errors at long range. For example, a tilted angle of 0.5° of the 3D scanner mechanism results in around 15 cm measurement error at a distance 17 m below the manhole level. In order to achieve precision measurement, 3D image registration method was adopted to bring one of the point cloud aligned with the other set based on their common, unchanged 3D shapes.

3. Application of 3D Image Registration Algorithm

3D image registration method combines two sets of 3D geometry using their common features. Iterative Closest Point (ICP) has been widely recognized as one of the most effective way to merge two different sets of 3D geometry.6

ICP process can be divided into several kinds of categories, including matching two point sets, matching a point set and a parametric surface, matching a point set and a triangulated surface. Generally, ICP process is accomplished by following steps, given an arbitrary point on the first geometry, the algorithm first search for the closest point on the second geometry as the corresponding point. Later, rotation matrix and translation vector is obtained and rigid body transformation is performed such that two point sets are better aligned. This process is repeated iteratively until the distance between both geometries is converged to a local minimum. In this section, ICP process is applied in two ways, in which the first one matches two point sets to obtain gunning thickness during the spray process while the second one matches a point set and a parametric surface so as to calculate the remaining lining thickness.

3.1. Registration of Two Point Cloud Sets for Gunning Thickness Measurement

In the gunning process, refractory material was spray on the surface of the lining below the throat of the blast furnace. Therefore, the geometry above the throat part was remained unchanged during the repairing process, which is an excellent choice as invariant geometry for image registration process. Point sets \{P_i\} and \{Q_i\} represents measured coordinates of the lining surface before and after the gunning process, respectively. If \(P_i\) and \(Q_i\) characterize the same geometry feature, then \((P_i, Q_i)\) forms a correspondence pair and a 3D rigid body transformation can be described as follows,
where \( N \) denotes the number of corresponding pairs. Closed-form solutions are available for solving the rotation matrix and translation vector. In real cases the equality can never be true for and hence an objective function is given as sum of squares of error

\[
J = \sum_{i=1}^{N} \| P_i - RQ_i - T \| \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (2)
\]

in which \( R \) is the rotation matrix and \( T \) is the translation vector. Since the measurement result from the 3D scanner decomposition solution as well as quaternion based algorithm that minimizes the cost function, including singular value decomposition is illustrated in Fig. 4. To search corresponding point for a given feature point \( Q_i \), it is often very difficult to recognize the corresponding \( P_i \). Suppose two point clouds are closed to each other to some extent, and considering the closest point as the corresponding point will bring closed to each other to some extent, and considering the object function (2) can be reached. 

In regarding to blast furnace measurement, the data points beyond the throat part has as many as 170,000 points, thus it is very time consuming in correspondence searching process. Using bounding box structure to partition 3D points is one of the efficient techniques to accelerate correspondence searching process, which partitions all feature points into small boxes. The searching process only applies to the points in the specific box that contains \( Q_i \).

**3.2. Registration of a Point Cloud Set and Mechanical Dimension for Residual Lining Thickness**

The blast furnace was built according to dimensions of the mechanical drawing as shown in Fig. 6, which serves as an accurate reference. By comparing the surface profile between the measurement result and the mechanical dimensions, residual lining thickness can be obtained. To accomplish this, the invariant feature must be first converted into geometry model. It is obviously seen that a cone and a cylinder can be used to model particular parts of the 3D geometry in the drawing. The base of the cone is taken as \( Z = 0 \), the height of the apex is denoted as \( Z_w \) and the Z-coordinate of the cylinder with diameter \( D \) is bounded by \( Z_u \) and \( Z_l \). The equation for both 3D shapes can be formulated as follows,

Cone: \( (Z+Z_0)^2 = X^2 + Y^2 \quad (0 < Z < Z_0) \)

Cylinder: \( X^2 + Y^2 = \frac{D^2}{4} \quad (Z_u < Z < Z_l) \)

For a given point \( Q_o \), the closest point on the shape is regarded as the corresponding point \( P_i \). As seen in Fig. 7, taking an arbitrary point \( Q = [Q_x, Q_y, Q_z]^T \) which belongs to the cone as an example, its corresponding \( P = [P_x, P_y, P_z]^T \) is expressed as

**Fig. 4.** A box structure for acceleration of correspondence matching process.

**Fig. 5.** Illustration of ICP process.

**Fig. 6.** Mechanical dimensions of the blast furnace.
\[ P = Q + tN \] ..............................(6)

in which

\[ N = \frac{-1}{\sqrt{2}} \begin{bmatrix} Q_x \\ \sqrt{Q_x^2 + Q_y^2} \\ \sqrt{Q_x^2 + Q_y^2} \end{bmatrix}^T, \]

\[ t = \frac{(Q_z - Z_0)^2 - Q_x^2 - Q_y^2}{2(Q_x N_x + Q_y N_y - (Q_z - Z_0)N_z)} \]

and \( N_x, N_y \) and \( N_z \) denotes \( x, y \) and \( z \)-axis component of the vector \( N \) respectively. Since the \( z \)-axis coordinate of the cone is bounded by 0 and \( Z_0 \), two conditions are added to confined \( P_z \),

- If \( P_z < 0 \) then \( P_z = 0 \)
- If \( P_z > Z_0 \) then \( P_z = Z_0 \) ..............................(7)

For those points on the cylinder shape, corresponding points can be obtained using similar formulations. After correspondence matching is done for every feature point, rigid body transformation can be obtained and applied to the point set such that it is aligned with 3D shapes with better accuracy. Since the material of the blast furnace outer case is made up of steel, thermal expansion cannot be neglected as temperature in the shaft part is always several hundreds Celsius degree higher than ambient environment. For throat diameter \( 10150 \) mm at room temperature, the dimension increases \( 1 \) cm by every \( 100^\circ \)C of elevation in temperature. In order to take thermal expansion effect into account, a scale factor \( s \) is included in rigid body transformation for error compensation, and the cost function is revised as

\[ J = \sum_{i=1}^{N} ||P_i - sRQ_i - T|| \] ..............................(8)

Once the rotation matrix \( R \) is obtained, \( s \) can be given explicitly as

\[ s = \frac{\sum_{i=1}^{N} P_i^T R Q_i}{\sum_{i=1}^{N} Q_i^T Q_i} \] ..............................(9)

A detailed derivation of Eq. (9) can be referred to Ref. 7). The measurement data acquired after the gunning process is used to match with the ideal 3D geometry. The cost function is minimized iteratively until the rms error converges to around 4.8 cm. The data cloud matches with the 3D shapes very well as illustrated in Fig. 8.

4. Evaluation of Lining Thickness

In the previous section, ICP process is applied such that surface profile obtained after gunning process is aligned with both ideal dimensions in mechanical drawing and the initial surface profile before gunning. Both processes guarantee alignment error less than 5 cm, which is satisfactory for the purpose of lining condition evaluation in blast furnace process. In this section, results of ICP process are visualized to provide distribution of lining thickness over shaft area.

4.1. Gunning Thickness Measurement Result

Figure 9 shows the east–west cross-section of the blast furnace inner profile before and after gunning process. It is seen that gunning thickness is not evenly distributed over the shaft surface. Furthermore, the thickness of rebounded material on the burden surface is greater than expected, resulting in a high-risk operation condition since the hot blast from beneath cannot easily break through this rebounded layer. The center part on the burden surface shows the cans that were thrown on top of the burden so as to reduce the surface tension of this layer.

Figure 10 shows another cross-section profile, in which distance from blast furnace center is plotted in polar-coordinate system, with \( 0^\circ \) and \( 180^\circ \) degree correspond to north and south, respectively. Hundreds of cooling boxes were embedded in the lining material when the blast furnace was first built, and began to expose to the burden as the material worn out gradually. Profile of cooling boxes can be clearly seen in this figure and fire-proof material fills up the eroded parts of the wall after gunning process. In order to evaluate the quality of the gunning process, a thickness map over the shaft surface is generated as shown in Fig. 11. It is observed that the thickest part is around 80 cm, while the thinnest part is less than 5 cm, indicating that the material was not being sprayed uniformly over the shaft area.
4.2. Residual Thickness Measurement Result

The cross-section profile of the inner surface profile along with its original dimension is drawn in Figs. 12(a) and 12(b). Residual thickness can be clearly visualized by comparing the both profiles. The original thickness of the wall is 78 cm, and the figure shows even after the gunning process, the thinnest residual thickness is less than half of the original thickness. Since the spraying machine cannot easily reach to the bottom of the shaft, very small amount of the material can be put onto the part of the wall closed to the burden. Figure 12(c) shows the cross-section profile as well as original inner and outer wall surface at ground level 33.91 m, which shows that the material was mainly spray on south and west part.

5. Conclusions

Because of harsh environment conditions such as high temperature, pressure and dust that hinder installation of measurement devices, blast furnace has long been treated as a black box in steel industry. Even though it is still very difficult to measure the lining profile during the operation, laser profiling technology makes it possible to measure lining profile possible during the gunning process. Integrated with 3D image registration algorithm, gunning and residual thickness can be obtained with better than 5 cm accuracy. This measurement result serves as reference information for blast furnace operation and is very important for prediction of its campaign life.

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