CMM with large working volume based on Laser technological system

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Abstract

Description of coordinate measuring machine with large working volume \((3.0 \times 2.6 \times 0.6 \text{ } m^3)\) based on Laser technological system LSP-2000 is presented. Preliminary measurement process is described. Analysis of uncertainty of measurement is presented. Prospect of system upgrade with 3D measurement functions as CMM is given.

Keywords: CMM, precision 3D measurement, large-scale 3D articles

1. Introduction

Laser technologies are widely used in scientific investigations, as well as in industry. For example, laser ablation is applied to investigations of materials’ properties and surface microprofiling. Laser cutting and welding are standard technological operations in industry. Laser processing under fabrication of high-technological articles requires high laser beam positioning accuracy, which is strongly depends on article’s measurement uncertainty. Heavy engineering and space industry takes laser processing of large-scale articles. That is why the problem of high precision measurement within large working volume (several \(m^3\)) is the actual one. There are some commercial CMM with large working volume including the CMM-750 of Limited Company “Lapik”, operated at “BelAZ” factory [1] and the CMM Bright-STRATO 305015 of Mitutoyo firm [2].

For inspection of large-scale articles one can use Laser technological system LSP-2000 developed at TDI SIE SB RAS [3] for laser processing of complicated article’s surfaces within volume of \(3.0 \times 2.6 \times 0.6 \text{ } m^3\) (Fig. 1). System is controlled by 6-coordinates CNC. Positioning error of working instrument during processing is 20 \(\mu m\), maximal speed of linear movement is 30 \(mm/s\). Two replaceable lasers are included in complete set of System.

Nowadays LSP-2000 is operating at Lanzhou Institute of Physics (LIP) of China Aerospace Corporation (CASC) as part of a production line developed by CASC. System is under upgrade to add for LSP-2000 some 3D measurement functions for construction of 3D model of object before its processing. It will allow us to significantly improve laser processing quality.

The purpose of this work is description of measurement process before LSP-2000 processing, as well as measurement error estimation.
2. Description of object and its binding by thee coordinate systems

There are three coordinate systems [4, 5] used in description of LSP-2000. First one is CNC coordinate system, which has 5 coordinates \((X, Y, Z, C, B)\) which are used to determine each drive’s position. 6-th CNC coordinate is auxiliary and is not used in calculations. Second system is three-dimensional coordinate system of working area \((x, y, z)\). This system is used to describe position of working instrument by direction of laser beam and position of working point (center of beam waist). Third system is three-dimensional coordinate system of article’s model \((e_1, e_2, e_3)\).

There are formulas of conversion of CNC coordinates \((X, Y, Z, C, B)\) into vector-point pair in \((x, y, z)\) system [4, 5]. Formulas are determined by geometry of LSP-2000 and choice of origin in both coordinate systems.

To start surface processing it is required to determine position and orientation of an article in working area. For this purpose it takes to find out formulas of conversion of \((e_1, e_2, e_3)\) coordinates into \((x, y, z)\) coordinates by determination of three points position in both coordinate systems and building rotation matrix and translation vector using coordinates of corresponding points. This operation is named as binding process.

Three binding points must be marked on article’s surface and on surface’s model. To bind \(i\)-th point operator should obtain such position of working point that it coincides with its mark on article’s surface (Fig. 2). Then by operators command current CNC coordinates \((X_i, Y_i, Z_i, C_i, B_i)\) are translated into coordinates \((x_i, y_i, z_i)\) and associated with \((e_{1i}, e_{2i}, e_{3i})\) coordinates of \(i\)-th binding point in article's model.

For binding process it was made the metallic probe with sharpened tip, which can be fixed on laser head in such way, that its tip coincides with center of laser beam waist. So to bind a point operator should obtain contact of probe’s tip and point’s mark and fix its position.

3. Preliminary measurement stage

For processing of articles with free form a problem of preliminary measuring of surface’s shape was occurred.

First method for article’s surface measuring is fixing a set of points on surface with next triangulation of this set and reconstruction of surface model. Points fixing process was made similar to surface binding process.

Operator obtains contact of probes tip and controlling surface and fixes coordinates of CNC corresponding to current position. Then \((X, Y, Z, C, B)\) coordinates are translated to \((x, y, z)\) coordinates of working area. As the model is created during measurement, then models coordinate system is equal to working area of coordinate system.

Under the next stage a set of measured coordinates is processed by mathematical software and file of appropriate format representing surface model is generated.

The advantage of this method is universality. Operator can fix various set of points. Mathematical software for triangulation and other processing is not strictly determined.
The disadvantages of method are its laboriousness and requirement of high attentiveness. If an article has complicated shape and/or high precision of model is required, then operator needs to fix a vast set of points (Fig. 3). Each point fixing takes about few minutes and there is a risk of surface damaging if operator chooses wrong direction of probe’s movement.

4. Automation of measurement process

Next stage of problem’s solution was modernization of LSP-2000 controlling software. It was introduced a new working mode, which allows us partially automate previously described process.

To start measurement process it is necessary to set the following:
- area of measurement and step of measurements grid in horizontal plane;
- position of vertical coordinate for safe movement above an article.

When process is started system automatically moves to first measurement position in the safe horizontal plane and waits for fixation of point’s coordinates. Usually operator manipulates with LSP-2000 to obtain contact of tip and surface using only vertical coordinate. When point is fixed software blocks operator’s manipulation unit and moves vertically up to safe plane, then moves to next position. Operator also can skip a number of measurement positions. It is useful for measurement in nonrectangular areas.

The advantages of this method related to first one are increased speed of one point fixation and reduced working load of operator. Besides, also the cases of surfaces damaging have been almost eliminated.

5. Requirements for measurement error

Uncertainty area of working point positioning is a sphere with radius $\Delta_p = 20 \mu m$. In case of distance measuring with uncertainty $\Delta_d$ an area of measured point position uncertainty has shape, as shown in Fig. 4.

![Fig. 4. Uncertainty area of measured point position](image)

Fig. 4. Uncertainty area of measured point position, where $P$ is measuring point, $\Delta_p$ is positioning uncertainty, $\Delta_d$ is distance measuring uncertainty along measuring direction.

There is a technological parameter $\Delta_w$, which determines tolerance of processing point’s deviation from center of laser beam waist. To use $\Delta_w$ for compensation of distance measuring uncertainty it is necessary to take a measurement along direction collinear with laser beam during processing.

![Fig. 5. Fragments of ideal and real models of surface](image)

Fig. 5. Fragments of ideal and real models of surface.

The technology used allows entire surface processing with constant laser beam orientation. Since during automate measurement operator measures distance to surface along vertical line, then article should be placed in working area in such way that it should be possible to process whole article by vertical laser beam.
Ideal surface’s model is described by set of triangles with vertexes belonging to surface. Let \( P_1, P_2 \) and \( P_3 \) are points of surface which are vertexes of approximating surface triangle. \( P_L \) is some point inside this triangle which is supposed to be processed. Further all points will be considered as vectors in system \((x,y,z)\).

\[
P_L = P_1 + k_1(P_2 - P_1) + k_2(P_3 - P_1), \text{ where } k_1 + k_2 \leq 1
\]  

(1)

Since each of points \( P_1, P_2 \) and \( P_3 \) has uncertainty area then in real (measured) model corresponded triangle has vertexes \( P_1', P_2' \) and \( P_3' \) (Fig. 5) belonging to uncertainty areas of points \( P_1, P_2 \) and \( P_3 \) correspondingly. Point \( P_L' \) corresponding to \( P_L \) is calculated by the following way:

\[
P_L' = P_1' + k_1(P_2' - P_1') + k_2(P_3' - P_1')
\]  

(2)

From (1) and (2) after introducing of displacement vectors \( D_i = P_i - P_i', \forall i \in \{1,2,3\} \) is obtained:

\[
P_L' = P_L + (1-k_1-k_2)D_1 + k_1D_2 + k_2D_3
\]  

(3)

Obviously the uncertainty area (Fig. 4) is convex figure. Total of coefficients of \( D_i \) in (3) is not more than 1. Each of \( D_i \) belongs to uncertainty area with center in origin. According to convex set determination \( P_L \) belongs to uncertainty area with center in \( P_L \). Position of \( P_L \) is position of point in real model which is supposed to be processed. During article processing it will be an additional uncertainty related to point’s positioning.

In Fig. 6 the laser beam direction coincides with the direction of distance measuring and its deviation from surfaces normal is technologically permissible. Uncertainty area of positioning of \( P_L \) consists of points which distance from uncertainty area with center in \( P_L \) is not more than \( \Delta_p \). If article’s surface coincides with ideal model then requirement \( \Delta_d \leq \Delta_u - 2\Delta_p \) is enough for quality processing. However, surfaces shape can deviate from ideal model by value of \( \Delta_m = R - \sqrt{R^2 - (S/2)^2} \), where \( R \) is minimal radius of surface’s curvature, \( S \) is maximal distance between two points of one model’s triangle. Thus the requirement to distance measurement uncertainty is:

\[
\Delta_d \leq \Delta_u - 2\Delta_p - \Delta_m
\]

During experiment with LSP-2000 the following results have been achieved. Value of parameter \( \Delta_u \) was determined as 300 \( \mu m \). From technical characteristics of LSP-2000 \( \Delta_p \leq 20 \mu m \). Surface parameters were estimated as \( R = 2000 \) \( mm \) and \( S = 40 \) \( mm \). So \( \Delta_m = 100 \) \( \mu m \). Finally the following requirement to distance measurement uncertainty was achieved \( \Delta_d \leq 160 \) \( \mu m \).

The experiment had included measurement of surface and subsequent processing of article. Processed surface passed quality check. Quality of entire processed surface was
declared as acceptable and therefore it was considered that uncertainty of distance measurement during experiment was not higher than 160 µm.

6. Conclusion
Description of coordinate measuring machine with large working volume (3.0×2.6×0.6 m³) based on Laser technological system LSP-2000 was presented. Preliminary measurement process was described. Analysis of uncertainty of measurement was presented.

Obviously, next stage of automating of measuring process is replacing the probe with a non-contact distance sensor. Observed criterion of estimation of distance measuring uncertainty allows us to choose sensor accordingly to task requirements. This upgrade and some software modifications will allow the following:
- to eliminate risk of articles damaging;
- to increase speed of measurement;
- to reduce working load of operator;
- to exclude human factor from measurement results.

After this upgrade LSP-2000 is subject for a metrological testing to become a non-contact coordinate measuring machine with high precision and large working volume.

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References