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Calibration of laser beam direction for optical coordinate measuring system

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ABSTRACT

For the purpose of measuring free form surfaces of some key parts in the aviation field accurately and effectively, such as blades, a non-contact optical coordinate measuring system is set up in the paper. A laser displacement sensor is mounted on the *Z* axis of a CMM via a turntable and adjusted to the suitable orientation according to the shape of the target surface. The combination of optical sensor and CMM can reach the full potential of them both. To enable the laser sensor to perform measurement in every direction, a calibration method used to determine the laser beam direction based on a standard sphere is proposed, the principle of which is analyzed in detail in the paper. In the calibration procedure, the sensor moves at an equal step along *X*, *Y* and *Z* axes respectively and then equation sets are established to calculate the unit direction vector of the line which the laser beam is on. In the process of solving the unknown quantities, a new parameter substitution method is applied. Finally, a gauging block and a sphere with known size are used to verify the method. As the experimental results show, the measuring errors in several directions are all smaller than 0.05 mm, which manifests that the calibration method proposed can meet the requirements of reverse engineering.

1. Introduction

Nowadays there exists an urgent need for efficient and precise measurement of workpieces with complicated surfaces in the field of aeronautics and astronautics, such as blades and gears. As to these kinds of workpieces, the measuring accuracy directly determines the manufacturing quality, because measurement is indispensible to accuracy inspection and has become a part of great importance in production process [1]. In the field of aeronautical manufacturing, there are so many blades in an aircraft engine, whose geometric parameters exert a great influence on the whole performance of the engine [2]. As a result, for producing more blades complying with the design requirements, it needs to inspect their shape parameters precisely and rapidly [3]. Traditionally, the profile inspection of parts with complex surfaces has been performed with complicated measuring equipments, such as the coordinate measuring machines (CMM), which are used widely in industrial inspection. Although having the advantages of mature technology, high precision and good generality, CMM with contact probes is not suitable for measuring complex parts owing to its inherent slow speed and inflexible operation. Therefore, it is essential to research on those methods and equipments that can speed up the measuring process.

To meet this requirement, non-contact optical measurement technology has become the research focus of industrial inspection [4]. Due to their advantages of high efficiency, high accuracy and inexistence of contact force, many non-contact sensors have been developed recently,

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such as laser displacement sensors. With the range usually about millimeters or more, optical measuring systems can perform accurate and fast measurement and are easy to implement, so they are quite popular in the field of 3D inspection [5]. As a kind of optical measurement apparatus, laser displacement sensor can be used to scan and measure 3D free form surfaces efficiently and accurately, which might be a difficult task for the traditional CMM with contact probes. Among so many kinds of laser displacement sensors, those which are based on the principle of laser triangulation reflection technique have the merits of quick response, high resolution, low cost and easy installation, making them widely applicable in non-contact measuring field [6].

Generally speaking, to scan and measure a free form surface rapidly, the laser displacement sensor should be mounted on the mobile guide of those measuring equipments, such as CMMs or CNC machines [7]. New commercial laser sensors enable the measuring equipments to realize fast, accurate and non-contact measurements, which is viewed as a feasible way to deal with the precision measurement of geometrical parameters. In practical coordinate metrology applications, the laser sensor can be installed on the Z axis of the CMM through a turntable to build up an optical coordinate measuring system. In the system, movement of X and Y axes makes the sensor to arrive at every measuring position, while that of Z axis adjusts the sensor to the height and curvature variation of the target surface. However, from the output of the sensor, only the length of the laser beam expressed by L can be derived, which denotes the distance between the laser emission point and the light spot, namely, the intersection of the laser beam and the target surface. As is known, acquisition of surface coordinate information cannot be realized merely with L. But if the unit direction vector of the laser beam described by (l, m, n) can be determined by calibration, the coordinates of the intersection mentioned above could be calculated as $(l{\cdot}L, m{\cdot}L, n{\cdot}L)$ in the coordinate system of the laser sensor. In this way, the one dimensional (1D) length of the laser beam is transformed into the three dimensional (3D) coordinates of the point on the target. Further, along with movement of the CMM axes, so many points of this kind can be gathered and then used to compose the point cloud of the target surface, which can be applied to calculate the geometric parameters of the surface through subsequent process. Thus to complete the subsequent measuring task, the orientation of the laser beam (*i.e.* the unit direction vector of the laser beam) must be determined precisely by calibration procedure.

Many researchers have made preliminary exploration on the aspect of non-contact measurement achieved by integrating a laser displacement sensor on a CMM. Zexiao et al. made the laser beam of optical sensor equivalent to the measuring pin of the contact probe. In this way, they achieved the calibration of the beam direction with iterative algorithm by means of a sphere [8]. But in the calibration procedure, the length of the laser beam must be kept unchanged, which is so difficult to realize. Also, they presented a multi-probe measurement system integrated with a CMM, a structured-light sensor, a trigger probe and a rotary table. In order to calibrate the extrinsic parameters of the structured-light sensor, a technique called 'coplanar calibration method' is proposed, which is based on the perspective collineation relationship of the points on the target plane [9].

Jiawei et al. established a calibration system for the laser probe used on the CMM with a position sensitive device (PSD) and a specially designed probe grip system [10]. Although the system can be used to adjust the surveying axis of the laser probe to be coincident with the revolving center of the turntable, it cannot be used to compute the determined orientation of the laser beam.

Bunimovich et al. set up a laser scanning machine and proposed a calibration method of the laser beam direction based on the non-linear least squares algorithm [11]. But during the calculation procedure, it is difficult to select the optimal iterative initial values and the procedure might be time-consuming as the iterative algorithm is adopted.

Smith et al. addressed the method to apply a point laser triangulation probe to inspect helical gears. They integrated a laser probe on the CMM and proposed a precise technique for extrinsic calibration of the laser probe, which used known information from a localized polyhedron and measurements taken on the polyhedron by the laser probe. However, when the orientation of the laser probe changes, it needs to change the orientation of the polyhedron at the same time, which might be time-consuming and not automobile [12,13].

Guoyu et al. presented an approach of modeling and calibration of an active laser beam-scanning triangulation system. They proposed a calibration method using the planar fitting algorithm, in which the required parameters were determined within an optimal framework through a planar fitting scheme [14].

Huiyuan et al. studied a low-cost and simple method of extrinsic calibration of the laser sensor in a four-axis CMM. In their paper, an extrinsic calibration method achieved by measuring the fixed point (the center of a standard ball) of the measuring system with the sensor in different positions was proposed, which could be used to calibrate the extrinsic matrix for transforming the position between the structured-light sensor and the measurement platform [15].

Santolaria et al. presented a method for integrating laser triangulation sensors in articulated arm coordinate measuring machines. By means of a single calibration gauge object, a one-step calibration method to obtain both intrinsic and extrinsic parameters related to the system was developed [16].

In order to perform accurate and rapid measurement of 3D surfaces, an optical coordinate measuring system is built up in the paper, which is integrated with an optical sensor, a turntable and a framework of CMM. With the system, the 1D length of the laser beam can be transformed into the 3D coordinates of the point on the target, which will lead to the construction of the point cloud of the target surface. This work is novel in that the required accuracy of dimension measurement can be achieved expediently by combination with several low cost devices. Aiming at metrology applications, the non-contact measuring system has potential performance advantages over existing