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Extrinsic calibration of a laser displacement sensor in a non-contact coordinate measuring machine

Chao BI *, **Jianguo FANG**, **Kun LI**, **Zhijun GUO**

Aviation Key Laboratory of Science and Technology on Precision Manufacturing Technology, Beijing Precision Engineering Institute for Aircraft Industry, Beijing 100076, China

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Abstract In order to implement 3D scanning of those complicated parts such as blades in the aviation field, a non-contact optical measuring system is established in the paper, which integrates a laser displacement sensor, a probe head, the frame of a coordinate measuring machine (CMM), etc. As the output of the laser sensor directly obtained possesses the 1D length of the laser beam, it needs to determine the unit direction vector of the laser beam denoted as (l, m, n) by calibration so as to convert the 1D values into 3D coordinates of target points. Therefore, an extrinsic calibration method based on a standard sphere is proposed to accomplish this task in the paper. During the calibration procedure, the laser sensor moves along with the motion of the CMM and gathers the required data on the spherical surface. Then, both the output of the laser sensor and the grating readings of the CMM are substituted into the constraint equation of the spherical surface, in which an over-determined nonlinear equation group containing unknown parameters is established. For the purpose of solving the equation group, a method based on non-linear least squares optimization is put forward. Finally, the system after calibration is utilized to measure the diameter of a metallic sphere 10 times from different orientations to verify the calibration accuracy. In the experiment, the errors between the measured results and the true values are all smaller than 0.03 mm, which manifests the validity and practicality of the extrinsic calibration method presented in the paper.

1. Introduction

1.1. Motivation

Along with the gradual formation of global economic integration, the aviation and aerospace industry has already entered a brand-new developing stage, which may represent the comprehensive national strength of a country to a certain extent. In the new era of aviation and aerospace, both of opportunities and challenges exist. Therefore, how to keep enterprises,

* Corresponding author.
E-mail address: 773721278@qq.com (C. BI).

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products, service, etc. in an invincible position has already become one of the focus topics that people pay the most attention.

In the field of aeronautical engineering, as the heart of an aircraft, the aero engine is the motive power pushing the airplane forward, whose properties may affect the safety and reliability of flights directly.[1] In an aero engine, there are so many blades, whose geometries may have a great influence on its dynamic performance. Nowadays, with the fast development of the aviation industry, an aero engine of high performance is urgently needed, which puts forward high requirements of blades in both quality and quantity.[2] However, in order to produce so many blades meeting design requirements, accurate and effective measurement of blades in their manufacturing process needs to be executed. In general, for the purpose of making blades possess special dynamic performance, their surfaces are usually designed according to the principle of hydrodynamics. Therefore, the surface of a blade belongs to a kind of spatial free surfaces appearing as the geometry of a strong twist, whose complexity and diversity will cause considerable difficulty in its measurement.[3] Consequently, new measuring methods and equipment are demanded urgently if all the blades are to be inspected.

Traditionally, the existing tactile coordinate measuring machines (CMMs) are widely utilized in the measurement of blades due to their mature technology and good applicability. A typical CMM, composed of three linear axes and one contact probe, has found its great potential in such applications as precision measurement, quality control, reverse engineering, etc. However, although high accuracy and reliability can be achieved, employing a touch probe may lead to disadvantages such as long operating time, low acquiring efficiency, deformation at the contact point by the measuring force, etc.[4] Thus, the level of automation and intellectualization is low, and the measuring efficiency cannot meet the detection demand of volume blades, which requires acquisition of lots of points on their complex surfaces.

Considering the above, many researchers have focused their attentions on new non-contact measuring methods and equipment, which are made possible by advances in sensing devices. Currently, almost all the non-contact detecting systems for 3D profilometry are based on optical technologies because they are much easier to find their applications in engineering. With advantages of small volume, high response frequency, fast measuring speed, remote and non-destructive evaluation, etc., laser sensors have become a new trend in dimension metrology.[5] In so many kinds of laser sensors, those based on the principle of optical trigonometry have already entered the market from laboratory, i.e., laser displacement sensors. At moderate ranges, laser displacement sensors perform accurate and fast measurement and are easy to implement, so they are quite popular for 3D measurements.[6] Therefore, if a piece of equipment can combine a laser sensor with a traditional CMM, the advantages of them both will be taken altogether and their disadvantages will be compensated by each other to some extent, which will lead to much faster measurement than using the tactile method alone.[7]

1.2. Related work

In order to complete 3D scanning tasks, a laser sensor is always installed on the terminal of Z axis of a CMM through a probe head. The function of the former is to drive the sensor to implement a motion trajectory, while that of the latter is to change the spatial orientation of the sensor according to the normal direction of a target surface. In the measuring procedure, along with the linear movement of the CMM and the rotation of the probe head, the laser sensor can collect the complete point cloud of the target surface. However, there are several difficulties in the integration of the laser sensor and the CMM, one of which is the extrinsic calibration of the laser sensor used for data matching. As the output of the laser sensor is a 1D length while the measured data (i.e., the 3D coordinates of measured points) must be given in terms of 3D expression in the world coordinate system, a calibration model used for determining the orientation of the sensor should be established.

Many researchers are devoting their efforts in the integration of the optical scanning technology and the traditional coordinate measuring technology, which leads to some new measuring means and devices. Nishikawa et al. developed a non-contact on-machine measuring system by installing a laser displacement sensor on a multi-functional machine tool, which can be used to measure the glossy metal surface of a turbine blade. Through calibration of the zero position vector of the sensor and the direction vector of the laser beam, the 3D coordinates of a measurement point can be calculated, which becomes the key link of the system.[8]

Lee and Shiou developed a novel optical non-contact probe that can inspect the position and orientation of a freeform surface, which comprised a five-laser-beam projector and a CCD. In actual utilization, the probe can be easily integrated on a commercial three-axis platform. Besides, a scheme for calibrating and making measurements using the probe was proposed and verified experimentally.[9] However, in the system, the direction of the laser is fixed to be parallel to the Z axis of the platform, which severely limits the freedom of the system as well as the application scope. Considering the incapability of changing the direction of the non-contact probe continuously according to the fluctuation of a surface to be detected, the system is not competent for measuring parts with complicated structures.

Sun and Li independently developed a four-coordinate measuring system to detect a blade surface in a rapid and accurate way, which was composed of a laser displacement sensor and a four-coordinate measuring body including three vertical coordinates and a rotary table. In the measuring procedure, the measured blade is fixed on the rotary table by a special fixture, which can make the axis of the blade consistent with the Z axis. By moving the laser sensor along the Z axis, characteristic sectionals of the blade at different heights can be measured.[10] However, the sensor was limited to one fixed orientation (the laser beam had to be perpendicular to the Z axis), which practically precluded inspection of complicated targets requiring multi-axis motions and multiple orientations of the laser displacement sensor.

Xie et al. proposed a five-axis laser scanning system integrated with a CMM, a laser displacement sensor, and a pH10 rotary head. In their work, an "equivalent probe" approach was presented for the system verification and an iterative verifying process was adopted to eliminate the verification error caused by the inclination error of the laser sensor.[11–13] However, in the procedure, the laser beam sensor is equivalent to a trigger probe and it needs to keep the length of the laser beam unchanged, which is so difficult to control.