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A novel orientation and position measuring system for large & medium scale precision assembly

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ABSTRACT

In the field of precision assembly of large & medium scale, the orientation and position measurement system is quite demanding. In this paper a novel measuring system, consisting of four motorized stages, a laser rangefinder, an autocollimator and a camera is proposed to assist precision assembly. Through the design of coaxial optical system, the autocollimator is integrated with a laser rangefinder into a collimation rangefinder, which is used for measuring orientation and position synchronously. The laser spot is adopted to guide autocollimation over a large space and assist the camera in finding collimated measurand. The mathematical models and practical calibration methods for measurement are elaborated. The preliminary experimental results agree with the methods currently being used for orientation and position measurement. The measuring method provides an alternative choice for the metrology in precision assembly.

1. Introduction

In the fields of aerospace, automotive industries and scientific instruments, large-scale metrology (LSM) has played a much important role in assisting manufacturing and assembly with the development of optical technology, high-speed electronics and computers [1,2]. Usually an assembly process takes much time of overall production period, which has crucial impact on manufacturing efficiency and product performance of large & medium structures [3]. Nowadays, considerable attention in the area of LSM has been focused on the position as well as orientation measurement, such as satellite assembly and integration of spacecraft components [4].

For large & medium scale position measurement, some commercial instruments have been developed and put into use on the basis of optics [5–9], mechanics, electromagnetics [10], and acoustics [11,12]. Compared with other techniques, optical measurement systems have many advantages, such as large working volume, high resolution and immunity to electromagnetic interferences. Moreover, the measuring principles may be classified into three types: (1) two angles and one length (such as laser radar); (2) multiple angles (such as camera-based triangulation, indoor GPS, and photogrammetry) and (3) multiple lengths (such as multiple laser trackers) [13].

For orientation or angular measurement, optical encoders or gratings are usually used for rotation stages, robots, laser radars and so on. In a small-angle measurement system, typical optical methods such as interferometer [14–16], imaging devices [17] and autocollimator [18,19] are good choices. A ring laser was investigated for dynamic angle measurement, such as the external angle measurement of rotating objects [20]. For high precision angle measurement in large scale space, multiple theodolites are used to aim each other mutually [4], or collimate the optical cube bonded to the measured object, whereas the efficiency is low due to the extra work associated with manual handling operations. A common optical reference was provided to measure separation angles at a large distance with measuring uncertainty about 0.1° [21].

For position and orientation measurement, the laser tracker can be applied to monitor six degrees of robot with high accuracy over large range, whereas it is hard to realize automated measurement because of some time-consuming manual operations, such as transporting the retroreflector to points of interest [22,23]. A 6-DOF tracking method based on a total station with video imaging was given, but its measuring accuracy and efficiency could not meet the industry demand for precision assembly [24,25]. Some measuring systems were designed to measure 6-DOF motion of objects such as rigid bodies, optical elements, whereas their measurements are range limited [26–28]. To fulfill orientation and position measurement, some theodolites are combined with

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other devices such as laser trackers in the process of spacecraft assembly [4]. Obviously more skilled support staff are needed in these kinds of hybrid measuring systems.

However, there are limitations inherent to the commonly used techniques for rigid assembly with precision orientation and position measurement over a large & medium scale. To meet the application demands in spatial precision assembly of several meters with orientation accuracy (at a deviation level of below 2 arcmin) and position accuracy (at a deviation level of below 1 mm), there is an obvious need for a novel orientation and position measuring system (OPMS). In this paper an OPMS based on an autocollimator, a laser rangefinder (LRF), a camera and four motorized stages is designed. Section 2 outlines the system configuration and working principle. In Section 3, the mathematical model of OPMS is established, and both orientation and position geometrical relationships are analyzed. The calibration method of OPMS is stated in Section 4. Section 5 details preliminary experimental tests and results to verify the measuring accuracy. In the end, Section 6 demonstrates some concluding remarks and future work needs to be done.

2. System design

In the building of aerospace instrumentation as well as in aircraft assembly, the orientation measurement technique based on reference cubes mounted to the scientific instruments is regarded as the most accurate method [29]. For discussion purposes, this section will reference the precision measurement of a spacecraft assembly. The system scheme is shown in Fig. 1, and the cubic prism represents the measurand (target). It is the aim of OPMS to obtain the orientation and position information for different measured targets. The OPMS is mainly composed of some precision motorized stages, an autocollimator, a LRF and a camera. The measured equipment is fixed on a 360° rotation stage, and the vertical stage is assembled on the linear stage which can move horizontally. The goniometer stage mounted on vertical stage may rotate vertically. The LRF and autocollimator are integrated into a Collimation Rangefinder (CR), which is the key unit for measuring orientation and position synchronously. The camera installed on CR can monitor the measurement sites, and may be utilized to assist in the optical alignment between the LRF beam focal spot and the center of target for the purpose of quick autocollimation to avoid the tedious manual operations.

A schematic diagram of the optical layout for CR and cubic prism is illustrated in Fig. 2. Laser beam from the laser rangefinder is kept coaxial with the optical axis of the autocollimator via the reflective mirrors I and II. To simplify the optical structure, the parameter values of φ_1 and φ_2 are both set to 45°. In this way, the laser spot coincides with the center of autocollimator reticle. Usually, it is difficult for autocollimator itself to capture target over the areas larger than its field of regard, owing to its limited measuring range. By means of laser spot, the measuring system can search the collimated object automatically. The light reflected by the mirrored surface on the cubic prism returns to the autocollimator, and at the same time the light power received by autocollimator is expected to be maintained at a desired level to ensure the autocollimator being under normal working conditions.

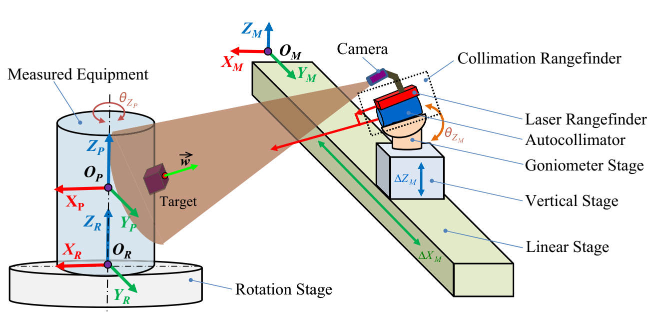

Fig. 1. System scheme for orientation and position measurement.

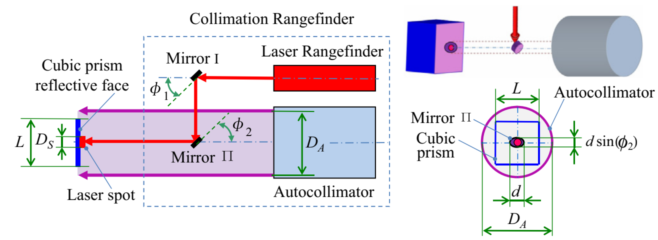

Fig. 2. Optical layout illustration of CR and cubic prism.

As shown in Fig. 2, a fraction of the light power output from autocollimator is blocked by the flat mirror II; therefore, from the theoretical point of view the size of mirror II should be optimally designed in order to realize the minimal loss of autocollimator light power. We assume that the light power for autocollimation is approximately proportional to the reflective surface area; thus the diameter of mirror II should meet the following requirements:

$$\begin{cases} K_A \le \dfrac{K_R\left(L^2 - \frac{\pi d^2}{4}\sin(\varphi_2)\right)}{\pi\left(\frac{D_A}{2}\right)^2} \\ d \ge \dfrac{D_S}{\sin(\varphi_2)} \end{cases} \tag{1}$$

Then rearranging Eq. (1), we can get another expression for the parameter d estimation and decision analysis as follows:

$$\frac{D_S}{\sin(\varphi_2)} \le d \le \sqrt{\left(\frac{4}{\pi\,\sin(\varphi_2)}L^2 - \frac{K_A}{K_R\,\sin(\varphi_2)}{D_A}^2\right)}, \tag{2}$$

where d, D_S, D_A represent the diameter of mirror II, the focal spot size of LRF and the field of view of autocollimator, respectively; L, K_R are the side length and equivalent reflectivity factor of the cubic prism, respectively, and K_A is the minimum coefficient of light power reflected from target necessary to ensure normal autocollimation. Some information of the measured cubic prism, including spatial coordinates (x, y, z) and normal direction, could be obtained through the cooperative control of positioning and measuring modules in the measuring system.

3. Geometric modeling for measurement

The geometric model is established for orientation and position measurement in the Cartesian coordinate system, as shown in Fig. 3. The space coordinate system O_P-$X_PY_PZ_P$ is associated with the measured precision equipment with the origin at its geometric center O_P, where Z_P-axis is aligned with the center axis of the measured equipment. The rotating coordinate O_R-$X_RY_RZ_R$ and measuring coordinate O_M-$X_MY_MZ_M$ are fixed on the rotation stage and linear stage, respectively, and the Z_R and Z_M axes are parallel with the Z_P-axis. The planes $O_RX_RY_R$ and $O_MX_MY_M$ are both horizontal. The location of the geometric center of prism is denoted by C_0, and $\overrightarrow{\mathbf{w_0}}$ represents a normal vector at point C_0 to the reflective face 1, correspondingly $\overrightarrow{\mathbf{w_1'}}$ be a normal vector at point C_1. The main goal of measuring system is to calculate the coordinates of C_0 and the direction of the normal vector $\overrightarrow{\mathbf{w_0}}$.

The measurement process can be summarized in two stages: firstly, obtain the information about the orientation and position of reflective face 1, such as the starting point $T_{M\_w_1'}(X_{M\_w_1'}, Y_{M\_w_1'}, Z_{M\_w'})$ of the normal vector $\overrightarrow{\mathbf{w_1'}}$; secondly, derive the