Improving the accuracy of 3D displacement measurement using ring-shaped laser beam and high resolution CCD

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Abstract

By progress of the computer technology, the mechanisms in which control is conventionally difficult are used widely and increasingly. They are, for example, mechanisms which have two or more stages, a robot arm which have two or more revolutionary joints, a complicated 3D mechanism which contains parallel mechanism and so on. However, in order to perform 3D positioning flexibly, it is necessary to measure the position of the end-effector with high precision and non-contact method. Moreover, highly precise measurement of the position of the end-effector is needed when we calibrate the 3D mechanism. Conventionally, in the measurement of the 3D displacement, it was common to put plural (usually 3) sensors or scales and to measure the 3D displacement. However, in combination of plural sensors or scales, it is difficult to measure flexibly and to calibrate the measurement sensors themselves because of the low freedom of the measurement. Consequently, we propose the novel 3D displacement measurement using optical system [1] that lens focuses are collected in the centre of the sphere, which has been used conventionally for the radius measurement of the sphere [2-3]. In this optical system, high sensitive measurement is achieved in a plane perpendicular to light axis (XY direction), but we need some ideas for the measurement in the direction of light axis (Z direction). And so, we developed the method that the displacement of not only the XY direction but also the Z direction can be measured at the same time, with the single light source, with high precision, by using a ring-shaped laser beam instead of the simple ray. This method has the example used for form measurement as the 1D sensor [4-5], but there are no example used for 3D displacement measurement.

Introduction

Firstly, we constructed the optical system to measure 3D displacement of the target sphere. In the optical system (Fig.1), the laser beam from the light source is expanded with the beam-expander. The expanded laser beam becomes a shape of a ring collimated through the ring-patterned slit. The ring-shaped laser beam bended with the beam-splitter focuses on the centre of the target sphere through the objective lens. The laser is reflected on the sphere surface and incidents to the acceptance of the CCD camera. The ring image on the CCD camera changes according to the displacement of the target sphere. It turned out that 3D displacement of the target sphere is obtained as change of the centre coordinates and the diameter of the ring image on the CCD camera. Secondary, we performed the theoretical analysis and the computational testing of the optical system. As the result, the ring form of the reflected laser beam can be approximated with a circle. The position of the centre of the circle is moving in proportion to the X-axis displacement of the target sphere and the Y-axis displacement of the target sphere, and change of the diameter of the circle is proportional to the Z-axis displacement of a target sphere. And we evaluated the measurement sensitivities and the measurement ranges in various optical settings. And we manufactured the experimental equipment based on the measurement principle for the basic experiments. The system functioned well and we could measure the 3D displacement of the target sphere. The measurement repeatability of the system was achieved of micrometer order. In this report, to improve the measurement repeatability of the system for practical use, we introduced the high resolution CCD image sensor. And, to evaluate the repeatability in the measurement of nanometers displacement of the target sphere, we introduced the piezoelectric stage. The experiments with the new equipment were performed and we analysed the results.

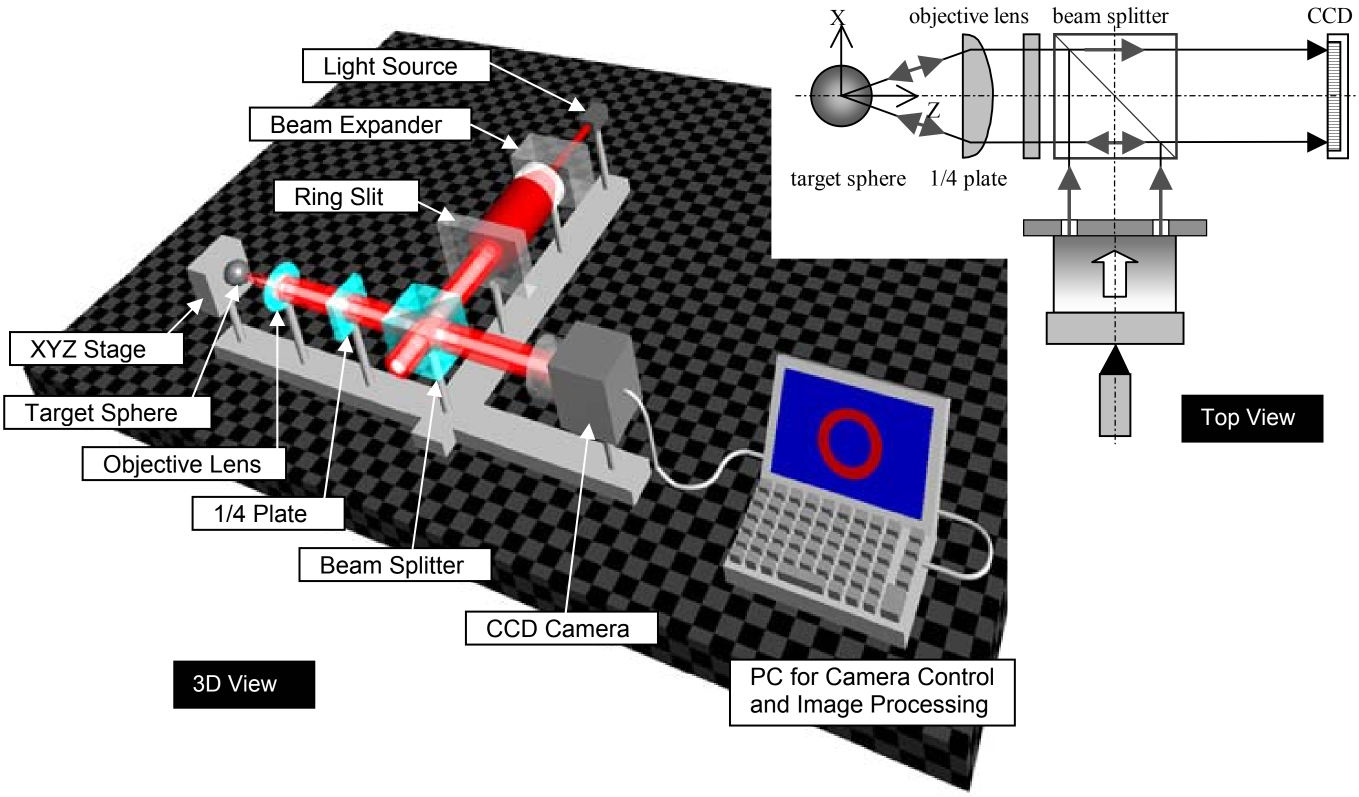

Fig. 1 Optical System and Basic Experimental Equipments

Nanometers Displacement Measurement and Analysis

The experimental set-up is shown in Table.1. The 3D displacement of the target sphere is detected by obtaining the least squares circle of the ring image on CCD. The least squares circle is calculated by the brightness peak positions of the image profiles. The ring image brightness profile obtained in the measurement is shown in Fig.2. In the displacement measurement, the target sphere was displacing by the step of 48nm with the piezoelectric stage. The displacement of the X coordinates of the centre of the ring image corresponding to X-axis displacement of the target sphere is shown in Fig.3. The change of the diameter of the ring image corresponding to Z-axis displacement of the target sphere is shown in Fig.4. The Theoretical measurement resolutions are 17nm in X direction at the measurement range of 0.34mm and 38nm in Z direction at the measurement range of 0.39mm. In the experiments, the measurement repeatability of X direction was 32nm and Z direction was 39nm. The experimental results seemed to be good compared with the theoretical data.

Table 1 Experimental Set-up

Light Source	Laser Diode: Wave Length 635nm
Ring Slit	Cr Evaporated Glass: Inner Diameter 4mm, Outer Diameter 5mm
Objective Lens	Plane Convex Lens: Focal Length 10mm
Target Sphere	Steel Ball: Diameter 10mm
XYZ Stage	Piezoelectric Stage: resolution 2.4nm
CCD Camera	16bit Cooled CCD Camera: 2048 x 2048, 7.4μm x 7.4μm
Distance Lens-CCD	200mm

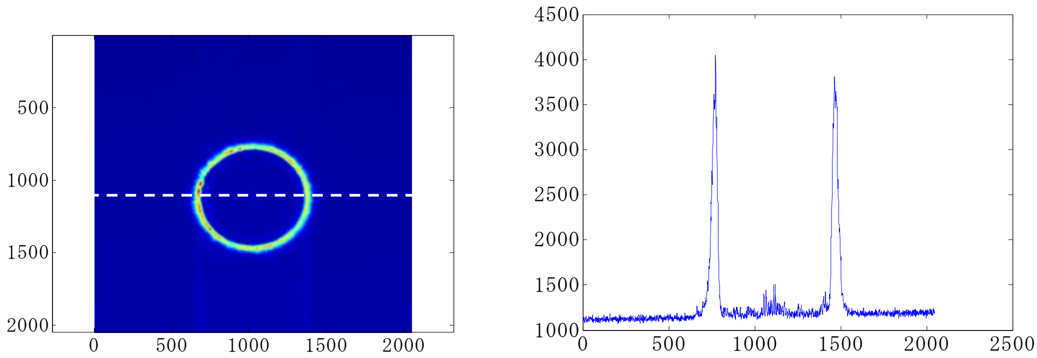

Fig. 2 Ring Image Brightness Profile

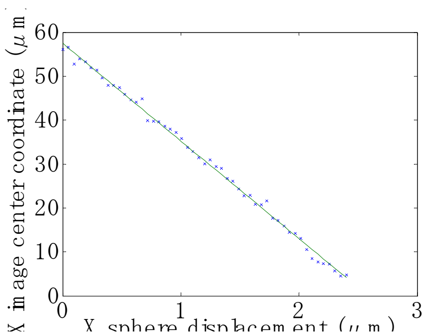

Fig. 3 Relationship between X coordinates of ring image centre and X displacements of target sphere

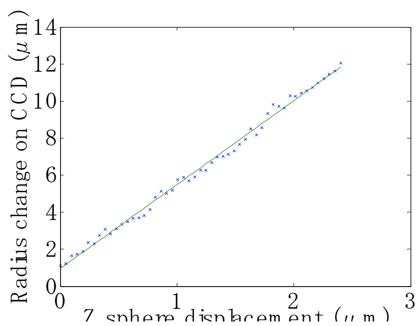

Fig. 4 Relationship between diameter D of ring image and Z displacements zd of target sphere

Conclusions

As the result of the experiment using the improved system and its analysis, it turned out that we could measure the 3D displacement of the target sphere of nanometers order. We think the error factors of the measurement are the alignment errors of the optical devices and the surface and sphericity errors of the steel balls. We measured the displacement at the range of 2.4μm because of the small stroke of the piezoelectric stage. However, actually in the long-range displacement measurement, the linearity of the system cannot be maintained because of the theoretical approximation error, so we must carry out the linearity correction. In conclusion, by using the lens magnification optical system, the high-resolution CCD image sensor and the ring shaped laser beam, we can measure the 3D displacement at the same time, with nanometers resolution, at the millimetres range, with single light source.

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