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Development of the trilateration optical comb tracking system adopting ball lenses as references and targets

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Abstract

A new laser tracker using an optical frequency comb and ball lenses as reference and target is proposed. In our system, a high accuracy long range absolute length measurement based on a pulsed interferometry of an optical comb is used. By using ball lens with refractive index of 2.0 that acts like a retroreflector, it has wider acceptance angle over a conventional retroreflector. The three dimensional position of the target ball lens based on a principal of multi-lateration can be obtained by making use of the distance between target and reference ball lenses. The proposed method only requires the distances among ball lenses while angle information is rendered unnecessary. In this research, the design of the laser tracker is proposed and the preliminary experiment result up to 10 m with standard uncertainty about 1.2 μm is reported.

Laser tracker optical comb ball lens trilateration absolute length measurement

1. Background

Since the development of laser tracker (LT) in 1980s, LT has been widely used in the field of engineering such as in production and assembly of large components of aerospace, calibration of robot motion, evaluation of CMM error, alignment of large scale structures such as a particle accelerator and a telescope [1]. However, there are no LTs available in the market that can achieve sub-micro accuracy (< 1 μm/m) and can perform absolute measurement even though the laser is obstructed during measurement. Therefore, accuracy improvement of a LT is highly demanded in order to achieve higher accuracy of product. The purpose of this research is to develop the LT that achieves the accuracy of 1 μm/m up to 10 m measurement range There are three important factors that influence the overall accuracy of LT, which are ranging technology, target, tracking mechanism.

2. Proposed method

In this research, a new LT is proposed as shown in Fig. 1, which adopts a pulsed interferometry by optical frequency comb for ranging technology, ball lens as a target, and ball lens as reference in tracking mechanism.

2.1. Ranging technology

Conventional methods such as monochromatic interference method, TOF(Time Of Flight) method and light modulation method have been used as ranging technology of LT. In this research, pulsed interferometry by optical frequency comb is used, which can measure absolute distance in long range precisely [2]. It can perform absolute measurement even though the laser is obstructed during measurement. Moreover, pulsed interferometry can detect weak signal by localizing the area of interference.

2.2. Target

Two kinds of retroreflector which are widely used as a target are corner cube and cat's eye [1]. Takatsuji et al. proposed the whole-viewing-angle cat's eye retroreflector which uses high refractive index glass (approximately 2), and is homogeneous, and a perfect sphere [3]. It is used as a target in this research because it has wider acceptance angle. Hence, it can be tracked from almost any orientation. Furthermore, it is easier to be produced since it does not need an axis alignment between two hemispheres nor bonding process.

2.3. Tracking mechanism

With regards to a LT, the reference needs to be constant while in tracking motion. Previously, two types of trackers that use spherical surface as motion mechanism have been proposed: a hemisphere mirror, which is used as a tracking mirror, and high precision polished sphere as reference surface [4, 5].

In the proposed LT, it uses ball lens as reference, which can accept incident beam from any direction. As the advantage of using ball lens, the incident and reflected beams are considered always parallel even in long optical path length (OPL). Even though it has demerit that the intensity of reflected beam is considered weaker compared to the other methods, sufficient interference fringe signal still can be detected due to the high S/N ratio of pulsed interferometry.

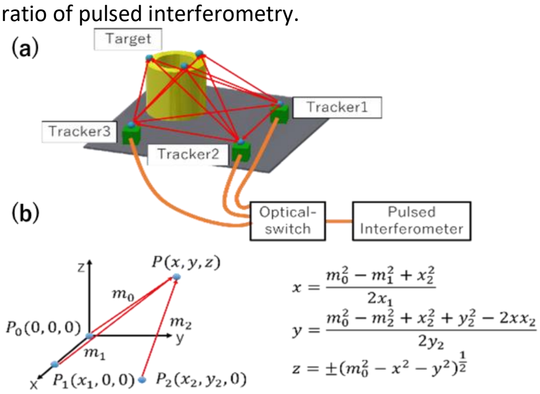

Figure 1. Overview of (a) the proposed laser tracker (b) multi-laterarion

2.4. Overview of proposed tracking system

Fig. 1(a) shows the overview of the proposed tracking system, in which fixed references and targets are composed of ball lenses. Three dimensional position of a target as shown in Fig. 1(b) is calculated following the principal of multi-lateration by measuring the distance between targets and references sitting on trackers (m_0, m_1, m_2) whose relative positions of the trackers (P_0, P_1, P_2) are known. In this system an optical switch is used to measure the distance among ball lenses using one interferometer. Absolute length measurement enables to use switching method so that only one interferometer is required, which leads to the cost reduction.

3. Pulsed Interferometer

Pulsed interferometer is used to realize the absolute length measurement based on the principle of Michelson interferometer as shown in Fig. 2 [2].

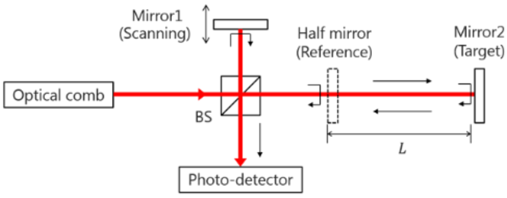

Figure 2. Pulsed interferometer

The laser beam from the optical comb is divided into two beams by a beam splitter (BS). Reference beam is reflected by Mirror1 while measurement beam is reflected by Half mirror and Mirror2. Interference fringes will be detected when the optical path difference (OPD) between reference beam and measurement beam is an integral multiplication of half pulse interval. In this system, two fringes will be detected if Eq. (1) and Eq. (2) are satisfied

$$L_1 = x_1 + i_0 c \,/\, (n f_{\mathrm{rep}}) \qquad (1)$$
$$L_2 = x_2 + i_1 c \,/\, (n f_{\mathrm{rep}}) \qquad (2)$$

where L_1 is OPL of the measurement beam reflected by Half Mirror, L_2 is the OPL of the measurement beam reflected by Mirror2, x_1 and x_2 are OPLs of the reference beam, i_0 and i_1 are integers, c is the speed of light in vacuum, n is the refractive index of air, and f_{rep} is the repetition frequency of optical comb. The length to be measured L is calculated by Eq. (3)

$$L = (L_2 - L_1) / 2 = (ic / n f_{\mathrm{rep}} + x_2 - x_1) / 2 \qquad (3)$$

where i is an integer. By measuring the displacement of Mirror1, $x_2 - x_1$ is obtained so that L can be determined. The realization of the pulsed interferometer is shown in Fig.3 where it is connected to the tracker.

4. Design of the laser tracker

The proposed ball lens based tracker is shown in Fig. 3. The beam from pulsed interferometer coming out through the collimator is directed to reference and target ball lenses by triangle prism. Thereafter, reflected beams are then coupled to single mode fiber and goes back to pulsed interferometer. To obtain parallel light, the ball lens whose refractive index is 1.999 (TAFT65, Ohara) is adopted. The distance between two ball lenses (L) as shown in Fig. 3 is obtained by calculating the total length of two optical paths with some corrections. The unique point of the proposed tracker is that each tracker can measure the distance to other trackers from self-position which is needed for multi-lateration calculation.

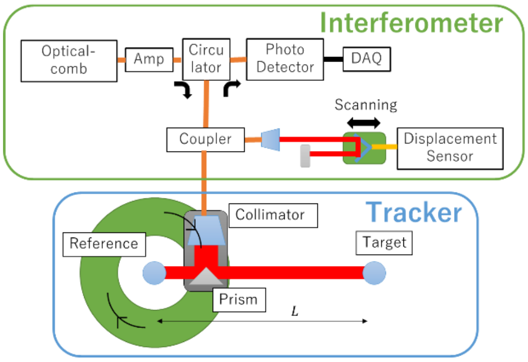

Figure 3. Design of the laser tracking system

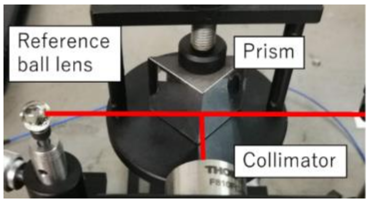

Figure 4. Experimental setups of the laser tracker

5. Experiment

To confirm the proposed method, the preliminary experiment was performed by evaluating the repeatability of the LT. Optical comb (Neoark) is used as light source, of which repetition frequency and central wave length are 58.4 MHz and is 1560 nm respectively. Distance between ball lenses was measured up to 10 m in every 2.5 m. Each point was measured 14 times in 60 seconds in temperature-uncontrolled room (±1℃/h) and the standard deviation was calculated. The result as shown in Fig. 5 indicated that the standard deviation grows along the measurement length by disturbance of air and vibration. Standard deviation at 2.5 and 10 m were 0.4 and 1.2 µm, respectively and it is enough for our purpose.

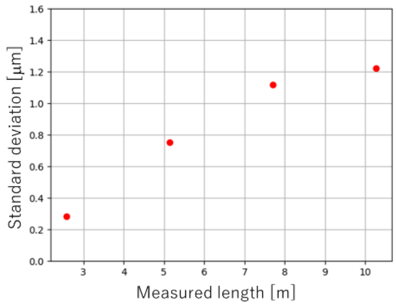

Figure 5. Standard deviation at each distance

6. Summary

The new LT based on pulsed interferometry and ball lenses is proposed, which can measure an absolute position in long range with high precision. The whole-viewing ball lens were used as reference and target. In this report, the tracker design was described and preliminary measurement up to 10 m was performed. Measurement repeatability was approximately 1.2 µm at 10 m which is considered to meet the purpose and the absolute length evaluation will be performed in the near future.

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