Abstract（論 文 の 内 容 の 要 旨）

論文題目　High-Accuracy Verification Method of Coordinate Measuring Machines Using a Single-Mode Fiber Optical-Comb Pulsed Interferometer

（シングルモードファイバー光コムパルス干渉計を用いた三次元座標測定機の高精度検査手法）

氏　　名　スダータム　ウィロート

This research presents a new optical measurement method of Coordinate Measuring Machine, CMM verification based on the temporal coherence interferometry of the optical frequency comb. The absolute-length measurements are successfully implemented by the first combination of a single-mode fiber optical-comb pulsed interferometer and a ball lens target. The required lengths or absolute positions are controlled by a fiber etalon that is used to modify the repetition frequency of an optical frequency comb. The optical frequency comb directly traces through the rubidium frequency standard to the base SI unit, and a ball lens serves as a three-dimensional target of the interferometer. The principle is original and the experiments were done by the author. Specially, the peak detection method of envelope interference fringe and the automatic measurement was developed for practical real-time applications. The proposed measuring technique was compared with the conventional standard step gauge method. The result is that the measurement procedure is simply and less time consumption. It has a high efficiency for the medium-sized to large-sized CMM verification, long-measuring range up to 10 m with a small measurement uncertainty of ~0.26 μm/m (k = 2). In addition, the first complete set of the absolute-length measuring machine has been established. Consequently, this research is not limited for only CMM verification, but also can be applied to other absolute-length measurements in dimensional metrology, which performed as a non-contact measurement. Furthermore, this study provides background knowledge for development of the calibration system using the single-mode fiber optical-comb pulsed interferometers, which is able to identify 21 parametric errors of a CMM based on multi-lateration measurement method. The proposed research is therefore intended to make contributions to the literatures on coordinate metrology, and variety on dimensional metrology.

Standard of acceptance and reverification tests for CMM has been introduced methods to obtain machine performance by comparing with standard lengths. Artifact-based methods, e.g. based on a series of gauge blocks, a step gauge, or a ball plate are limited in their application to small and medium-sized CMMs (measuring volume < 1 m^3). This technique cannot easily be applied to large CMMs, because artifacts cannot be simply up scaled. They become too heavy and hard to handle. Elasticity and thermal behavior of artifacts become critical to maintenance of the gauge accuracy. Beyond artifact tests, optical instruments such as continuous-wave laser interferometers for length measurements are wildly used in dimensional field. The interference patterns are counted continuously during the motion of the measuring mirror. This relative displacement measurement technique is one of the most precise metrological tools. However, it has practical difficulties in the long-range measurement, because the target mirror should be installed for translating from the initial position to the final position continuously without any interruption.

The optical frequency comb is now become a standard for length and frequency measurements. It provides many precise lines of optical frequency and very short-pulse train. Many researchers have studied applications of the optical frequency comb for dimensional metrology, because it directly transfers a high accuracy of the primary standard to working standard lengths. The pulsed laser itself can construct a temporal coherence interference fringe patterns, and these fringes are used as the length standard for practical absolute-length measurements. The distance of constructive interference fringe between pulsed trains can be defined. It is inverse proportion by a repetition frequency of the laser source. Therefore, the repetition frequency becomes a key to control a length standard. Normally, modification the repetition frequency directly inside a laser cavity is difficult, because the laser cavity is almost fixed. In this research, the external repetition rate modification of the C-fiber femtosecond laser is done by a fiber etalon. The repetition frequency of 100 MHz is transferred to a high frequency of 1 GHz that corresponds to the distance of constructive interference fringe of approximately 150 mm. In practice, a high-accurate length of a fiber etalon provides a high accuracy of free spectral range, and a high finesse presents a shaper transmission peaks with lower minimum transmission coefficient. The precise positions of constructive interference fringe relate to the accuracy of free spectral range, and amplitude power of interference fringe is proportional to finesse of an etalon. However, the constructive absolute position of interference fringe of any etalon can be measured by comparing with the known lengths such as standard lengths of gauge blocks or other interferometers. General the constructive interference fringes of a single-mode fiber optical-comb pulsed interferometer are presented in the time domain. For practical absolute-length measurement, the conversion of time to length scale is required for determining the distance of peak-to-peak envelope interference fringes. The accuracy of the conversion factor is associated with the measurement method and accuracy of used instrument. This factor relates to the speed of the scanning device in the scanning arm of interferometer. Therefore, precise motion and a constant speed of a scanning device are required.

This research aims to develop a measuring system for CMM verification, which can be used to measure absolute length in three dimensions by a target. Thus, the sphere target type had been considered. The stylus tip of a CMM will be replaced by a sphere target. Then, the verified lengths are defined by a CMM controller comparing with absolute lengths of interferometer. First, metal balls had been experimented. Two factors affect the measurement; there are sphericity and surface roughness. The sphericity of the target directly affects to optical path difference or accuracy of absolute length in three-dimensional measurements, but it is less significance for one dimension. For the surface roughness of the target, it strongly affects the amplitude power of interference fringe. In application, a rough metal ball with a diameter of approximately 25 mm, and surface roughness of 0.1 μm had been selected as the target of a single-mode fiber optical-comb pulsed interferometer for CMM positioning accuracy measurements. The uncertainty of measurement is mainly caused by repeatability of peak detection. The repeatability of peak positions involves with interference fringes shape that relates to the surface roughness of the target. This target can be applied to measured absolute length up to 1.5 m, which achieves the measurement capability approximately 0.6 μm. By a rough metal ball target, the measuring range is limited due to a poor reflected beam of the target, and if the laser beam is misalignment of $\pm$ 0.2 mm from the center of the target, it may be caused an error of length measurement approximately 1 μm. However, a single-mode fiber optical-comb pulsed interferometer with a rough metal ball target is simply to construct, and this target can be applied only for low-accuracy measurements such as robotic arms, or arm CMMs, which performed as a non-contact absolute-length measurement.

According to measuring range limitation of the rough metal ball target, the ball lens with refractive index of 2 had been studied as the target of interferometer. The total accuracy of the ball lens target depends on the accuracies of both the refractive index of glass material and the spherical fabrication. For one-dimensional length measurements, the sphericity of the ball lens does not affect the optical path length, but it significantly affects three-dimensional lengths measurements. Thus, the optical path error due to the target based on the proposed method can be ignored for CMM diagonal measurements. However, the reflected-beam intensity from the target is rapidly decreased, when the beam located far from the center of the target more than 0.15 mm. The best area on the target for achieving interference fringe is that the reflected-beam power should be sufficiently higher than 70% or around $\pm$ 0.3 mm from the center of target. If laser beam is misalignment of 0.3 mm, it may be caused of the cosine error less than 50 nm. Using a ball lens target, absolute length can be performed up to 10 m, cover the range of medium-sized to large-sized CMM applications. For diagonals CMM measurements, the initial zero positions of both CMM and a single-mode fiber optical-comb pulsed interferometer are set when the order of interference fringe is $m \geq 1$. As a result, the difference indices between the reference plate and the ball lens target are automatically compensated by initial zero position. The proposed measurement method was compared with the standard artifact method for diagonal in space measurements. The experimental results show that the measurement accuracy depends on noise in the interference fringe caused by airflow fluctuations and mechanical vibrations. However, measurement uncertainty is smaller than that of the artifact test method due to less effects of air temperature. In addition, the measurement time of the proposed method is 60% less than that of the artifact-test method because of its shorter start-up time; the proposed method can be used in measurements after 30 minutes system warm-up, while the artifact method requires a waiting period of more than 3 hours to achieve a stabilized gauge temperature for each alignment. Moreover, the alignment procedure is easier in the proposed system because of the compact and convenient optical components. However, the proposed method is a non-contact one, and therefore its CMM verification does not include effects of the CMM probing system.

The results of experimental measurements show that the single-mode fiber optical-comb pulsed interferometer with a ball lens target successfully encourage goals of the thesis. Subsequently, the prototype of absolute-length measuring system and automatic measurement software has been developed. The machine prototype consists of two optical boxes, which are separated. There are a scanning box and a measuring box. Both optical boxes are connected together through a single-mode optical fiber. Due to separated design, a measuring part can be placed for measurement around the working area, while a scanning part can be fixed as a stationary that make the measurement system easily for real applications. In addition, the automatic measurement software was developed based on LabVIEW programming platform, which the absolute length under measurement is directly reported on the computer screen. The precise peak detection function is applied by the measurement software. It precisely detects peak positions, because only peak of each envelope interference fringe is detected. The error of peak position detection is approximately 10 nm. Additionally, the basic performances of a prototype have been confirmed by comparing with a standard fixed length under controlled measurement conditions. The measurement repeatability is approximately 30 nm with resolution of 10 nm, a short term stability is approximately 130 nm and measurement accuracy is approximately $[(0.24)^2 + (0.10 \times 10\text{-}3l)^2]^{1/2}$ μm, where l is the indication length expressed in mm. The absolute-length measuring system is satisfied for CMM verification, and also can be applied for any non-contact absolute-length measurement in dimensional metrology with a high accuracy requirement.