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Automatic Absolute Distance Measurement with One Micrometer Uncertainty Using a Michelson Interferometer

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Abstract—In this paper, we suggest a novel system that is capable of measuring absolute distances with an uncertainty of one micrometer, or better, over a distance of up to 20 meters. This system consists of a Michelson interferometer, a tunable external cavity diode laser, a wavelength meter, a digital camera and a computer. The Michelson interferometer contains a reference arm mirror, a target arm mirror, a coherent light source, a white screen and a beam-splitter. The distance between the beam-splitter and the reference arm is known a priori with one-micrometer accuracy. The distance between the beam-splitter and the required measurement target arm is initially known with only a low precision accuracy of one-millimeter. The distance between the beam-splitter and the target arm is required to be measured with one micrometer uncertainty, or better.

Index Terms— Absolute distance measurement, external cavity tunable diode laser, Fourier fringe analysis, Michelson interferometer, synthetic wavelength.

I. INTRODUCTION

The recent developments in some industrial applications such as robotics, mechanical engineering, and space tracking, have imposed a renewed interest in developing precise instrumentation methods for performing absolute distance measurements [9]. The problem of measuring across several meters of distance with a resolution that is 0.1mm, or better, cannot be addressed by classical techniques such as time of flight, or incremental interferometry [3]. Time of flight techniques are able to measure distances ranging from several meters to several hundreds of meters, or even greater and the expected accuracy for this technique ranges from several tenths of a millimeter to accuracies that are worse than several millimeters [9]. Commercial devices for displacement measurement tend to use incremental interferometry, where it is vital to continuously maintain a line-of-sight between the measuring tool and the measured target. In this method it is necessary to carefully displace a suitable optical component from that fixed position to the final measurement position. Optical misalignment must be avoided during this displacement, or the measuring attempts must be repeated. The problem with this method is that it requires a precise device to move the mirror/reflector, and a counter to keep track of the number of interfering fringes that pass a specific point. If the line of sight is disrupted at any time, the fringe count is lost and the measurement is invalidated.

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From the beginning of 1970s, experiments have been conducted in order to replace incremental laser interferometers [1]. The drawbacks of incremental modes of interferometric measurement can be overcome by employing absolute distance interferometry [5], [7]. Absolute distance interferometry methods are based upon the principles of fractional fringes, a method that had been used in defining the meter as the basic length measurement unit by Benoit [4]. As a result of the development of laser light sources in the 1960s of the last century, absolute distance interferometry saw considerable development in the 1970s [9]. The existence of multiple wavelength lasers with increasing levels of stability has enhanced absolute distance interferometry. The use of multiple wavelengths in laser interferometry to produce an interference fringe effect has made it possible to generate a much longer synthetic wavelength than either of the two individual optical wavelengths that are interfering [6]. The synthetic wavelength that is generated from the two individual laser wavelengths may be calculated as being

$$\lambda_s = \frac{\lambda_1 \lambda_2}{|\lambda_1 - \lambda_2|} \tag{1}$$

The technique of two wavelength interferometry helps in reducing the sensitivity of interferometric measurement tools and thus makes it possible to increase the non-ambiguity range for interferometry [8]. The method described here provides accuracies of a small fraction of synthetic wavelength over distances up to 20 meters.

In this paper, we explain a new synthetic wavelength approach in which a low precision starting guess at the distance to be measured, obtained in any of a variety of low cost ways, is used alongside a convergence algorithm and Fourier transform fringe analysis to perform absolute length interferometry using a very simple experimental set up. This system has been shown so far to deliver accuracies in the order of ±2.8 μm in distances of up to 300 mm and it has the capability to measure over distances of up to 20 m. In common with other synthetic wavelength methods it does not require a continuous line of sight to the target – only two discrete sightings are required.

II. THEORETICAL BACKGROUND

The Michelson interferometer lies at the heart of our measurement system. A block diagram of the Michelson interferometer is shown in Figure 1.

In a Michelson Interferometer light travels from the coherent light source to the beam splitter, which amplitude splits the light beam into two beams of approximately equal intensity. One beam travels to the reference arm, L_r, and the

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other travels to the measurement arm, L_m. The light beams are reflected back to the beam splitter by the two mirrors, M_r and M_m, at the end of each respective arm of the interferometer. Thus the light beams traverse a total distance of $2L_r$ and $2L_m$ respectively. When the two light beams are recombined at the beam splitter (BS), they form an interference pattern, provided that the optical path difference ΔL, given by

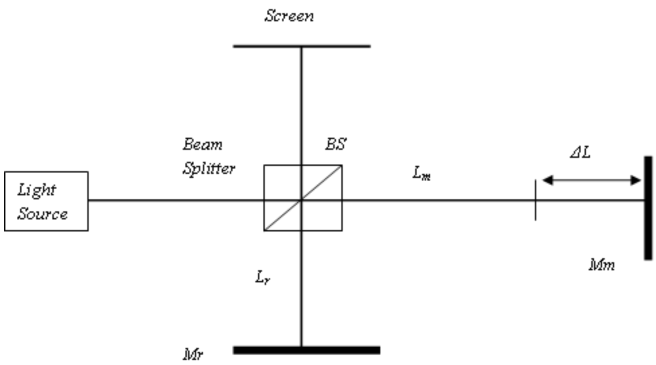

Fig. 1. Michelson interferometer structure.

$$\Delta L=(L_r-L_m) \tag{2}$$

is smaller than the coherence length of the light source. When these two waves meet on the screen they will form a field that is given by:

$$\overline{E} = \overline{E}_r + \overline{E}_m \tag{3}$$

The intensity of this field will be given by $\langle \overline{E}^2 \rangle$ where the angled brackets indicate the "time average". So

$$\langle \overline{E}^2 \rangle = \langle \overline{E}_r^2 \rangle + \langle \overline{E}_m^2 \rangle + 2\langle \overline{E}_r \cdot \overline{E}_m \rangle \tag{4}$$

We are particularly interested in the phase interval between the two waves

$$\delta\phi = \frac{2\pi}{\lambda}\Delta L \tag{5}$$

Where $\delta\phi$ is the phase difference, ΔL is the difference in length between the two arms and λ is the wavelength of the light. A small change in wavelength can be denoted by the term $\delta\lambda$. Where λ_1 and λ_2 are the original and the new wavelengths respectively.

$$\delta\lambda = \lambda_2 - \lambda_1 \tag{6}$$

Provided that ΔL remains the same and that no element of the interferometer has been moved, the total phase change by this wavelength shift may be given by

$$\Delta\phi = \delta\phi_2 - \delta\phi_1 \tag{7}$$

The two wavelengths λ_1 and λ_2 would therefore create a synthetic wavelength, λ_s, assuming $\lambda_2 > \lambda_1$ thus

$$\lambda_s = n\lambda_1 \quad \text{and} \quad \lambda_s = (n-1)\lambda_2 \tag{8}$$

The synthetic wavelength can be determined as

$$\lambda_s = \frac{\lambda_1\lambda_2}{\delta\lambda} \tag{9}$$

The relationship between the synthetic wavelength and the total phase change and path length difference ΔL for that change in wavelength can be defined as follows

$$\Delta\phi = \frac{2\pi\Delta L}{\lambda_s} \tag{10}$$

When the phase shift $\Delta\phi = 2\pi$ then $\lambda_s = \Delta L$ thus a change in ΔL by 2π is equal to the synthetic wavelength λ_s hence the fractional shift can be given by

$$\delta L = \frac{\delta\phi}{2\pi}\lambda_s \tag{11}$$

Where δL is the contribution to ΔL caused by an observable fringe fraction $\delta\varphi$. Equation 8 and Figure 1 are used to accurately determine ΔL. The integer number of synthetic wavelength in the distance ΔL can be defined as being

$$N = \left|\frac{\Delta L}{\lambda_s}\right|_{int} \tag{12}$$

Thus the total phase change involves two parts, namely the integer number of complete cycles of 2π that is equal to N, and also the fractional part of a single synthetic wavelength $\delta\phi$ where $\delta\phi<2\pi$. In other words the total phase change may be expressed as

$$\Delta\phi = 2\pi N + \delta\phi \tag{13}$$

If we could determine the terms in equation (13) then we would know ΔL. The second term can easily be determined experimentally by measurement of the relative fringe shift. Unless we maintain the requirement for a clear line-of-sight and fringe count, the first term cannot be easily determined. The proposed method overcomes this limitation at the cost of needing to know an *a priori* estimate of ΔL with an accuracy of 1 millimeter. To solve these problems, we select the wavelength change $\delta\lambda$ such that the synthetic wavelength λ_s is larger than 2ε, where ε is the uncertainty range. Thus N will have one of only two values; N_1 or N_2 which differ from each other by unity. We can determine these two values of N using

$$N_1 = \left|\frac{\Delta L_{nom}-\varepsilon}{\lambda_s}\right|_{int} \quad \text{and} \quad N_2 = \left|\frac{\Delta L_{nom}+\varepsilon}{\lambda_s}\right|_{int} \tag{14}$$

Where ΔL_{nom} is the estimated value of ΔL and ε is the half range uncertainty in this value. Because of the restriction that $\lambda_s > 2\varepsilon$ only one of these values of ΔL will lie within the *a priori* known tolerance zone of $\pm\varepsilon$ and this will be the answer that we require.

III. THE ALGORITHM

The initial values of the algorithm must be defined; firstly we measure the required distance with a set of extendable calipers and a Vernier height gauge to find ΔL_{nom}, let us say that this is 100 mm and let us also set the error ε to a

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reasonable value, let us say 0.5 mm. The tunable laser is set to the minimum limit of the tunability range, to maximize the possible number of iterations, to a value of let us say λ_1 = 685 nm. Using the wavelength meter the actual wavelength λ_{1m} is measured. The camera then records the first fringe pattern and measures its phase. Then calculate wavelength λ_2 where

$$\lambda_2 = \lambda_1 + \delta\lambda \text{ and } \delta\lambda = \frac{\lambda_1^2}{(\lambda_s - \lambda_1)} \qquad (15)$$

Provided that $\lambda_s > 2\varepsilon$, hence λ_s>1mm, so $\delta\lambda$=0.47nm, therefore λ_2 = 685.47 nm. Then set laser to the new wavelength and grab the second fringe pattern. After this measure the phase shift between the two fringe pattern images by using a Fourier fringe analysis program, here assuming that $\delta\phi$=1.9rads which is less than 2π. The fraction is 0.3 λ_s = 0.3 mm.

From the prior estimation ΔL must lie between either $\Delta L- \varepsilon$ or $\Delta L+ \varepsilon$, i.e. between 99.5 mm and 100.5 mm, so that N_1=99 and N_2=100. So that ΔL_1=99.3mm and ΔL_2=100.3mm. Here ΔL_1 lies outside of the tolerance range and may be disregarded, so we therefore conclude that the measurement of ΔL=100.3 mm.

The process is repeated with increasing accuracy levels for the estimation of ΔL, i.e. by incrementally reducing the error range ε. Then ΔL=100.3±0.25 mm and using a conservative assumption for the error, a more accurate measurement for ΔL can be obtained. The factor limiting this iterative process is the tunability range of the laser light source as this sets the lower boundary for how small a synthetic wavelength λ_s can be produced.

IV. SYSTEM DESCRIPTION

The main parts of the proposed automatic absolute distance measurement system consists of a Michelson interferometer, external cavity diode laser (ECDL) with wavelength controller, monochrome camera, wavelength meter, motion controller and a computer, as is shown in Figure 2. To control the system components custom system software has been developed. This consists of several programs written in the interactive data language IDL to make the measuring system fully automated. The IDL programs are designed to utilize every controllable element accurately. The individual software tasks include moving the target mirror with 0.1 micrometer accuracy, adjusting the tunable laser to the required wavelength, reading the actual wavelength of the laser output via the wavelength meter and acquiring images of the interference fringes using the monochrome camera. To implement the proposed algorithm, various other IDL programs were written; the main program performs calculations to determine the integer part of the measured distance and uses the Fourier transform method to analyze the acquired images to identify the phase shift and define the factional part of the measured distance.

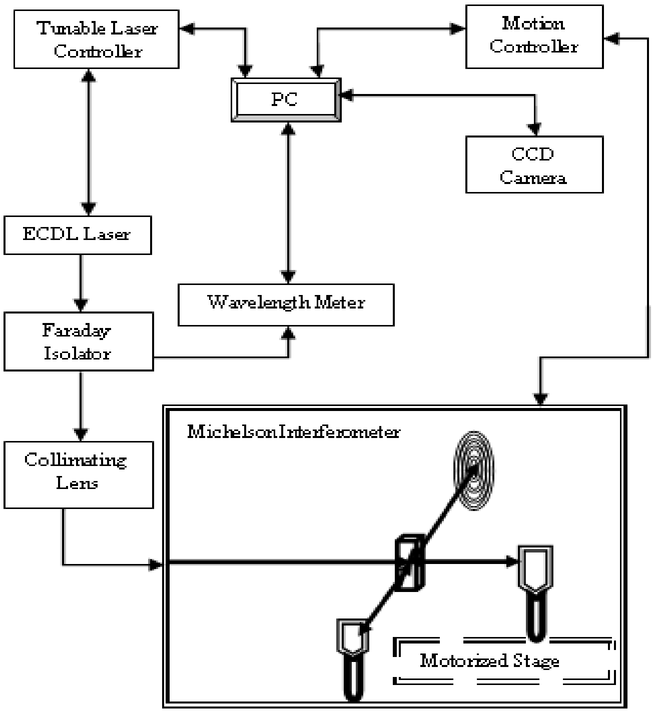

Fig. 2. The block diagram of the measuring system.

System automation helps to reduce the effects of variations in the laser wavelength on measurement accuracy. However, the laser system shows reasonable stability, there are still very small random fluctuations in the wavelengths that are produced by the laser. These fluctuations are 0.1 nanometer approximately. In order to minimize these effects upon the system measurement results the time between reading the wavelength and recording the interference fringe pattern must be minimized. As the system is fully automated the time between these two tasks is only of the order of a few milliseconds. In addition, system automation reduces the overall measurement time, hence the measurement results are recorded under similar conditions of temperature, airflow and any other environmental element. The system is able to implement a single algorithm iteration in less than five seconds. In other words, the total time taken to perform the full iterative algorithm can be less than 20 seconds.

V. MEASUREMNTS

Convergence during the iterative measurements is shown in Figure 3 and Table 1 illustrates a single measurement result for the system. The Michelson interferometer has the following dimensions; L_r = 300 mm L_m = 310 mm so that ΔL = 10 mm by a manual measurement method. The error range ε = 1 mm. However, even when the system begins with different approximate estimations of the measured distance it always converges to the same value within a 1μm deviation range. As the system transits from one iteration to the next it reduces the error range by a factor of 2, and hence the recorded results for the measured distance incrementally approach the real value.

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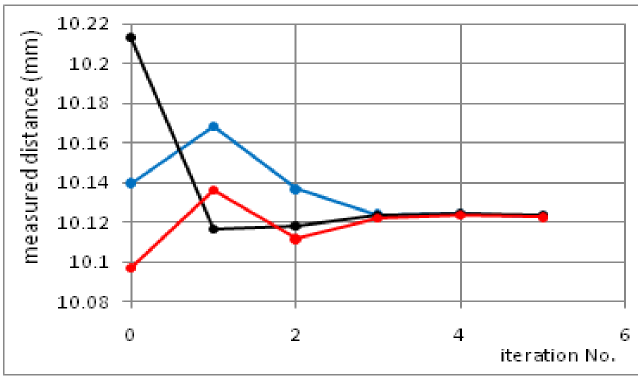

Fig. 3. System convergence for 3 different measurement attempts

TABLE I
CONVERGENCE FOR 3 MEASUREMENT ATTEMPTS

Iteration no.	Measurement-1	Measurment-2	Measurement-3
0	10.1397	10.213	10.0969
1	10.1682	10.1166	101361
2	10.1366	10.1183	101115
3	10124	10.1233	101222
4	10.1244	10.1246	101235
5	10.1232	10.1235	101225

Herein, we set $L_m = 330$ mm so that $\Delta L = 30$ mm. The error range $\varepsilon = 1$ mm. In order to determine the accuracy of the proposed system, the measurement procedure was repeated 300 times. The results for these measurements are shown in Figure 4. The standard deviation for these measurements is less than one micrometer, which is considered here to be the uncertainty of the proposed system. The histogram for these 300 measurements is plotted in Figure 5 and its shape is very close to being Gaussian.

In terms of the accuracy of the measurements, Figures 6 and 7, show the accuracy obtained for the measurement system at various positions of the target. The measured distance here increases from 1 μm to 30 mm. The results that are obtained correspond to the position of the displaced target mirror. The results that are obtained exhibit a slight deviation between the movement of the target mirror and the measured distance. This reflects the degree of accuracy of the system. The maximum recorded deviation was 2.8 μm. The accuracy of the system is better than 2.8 μm.

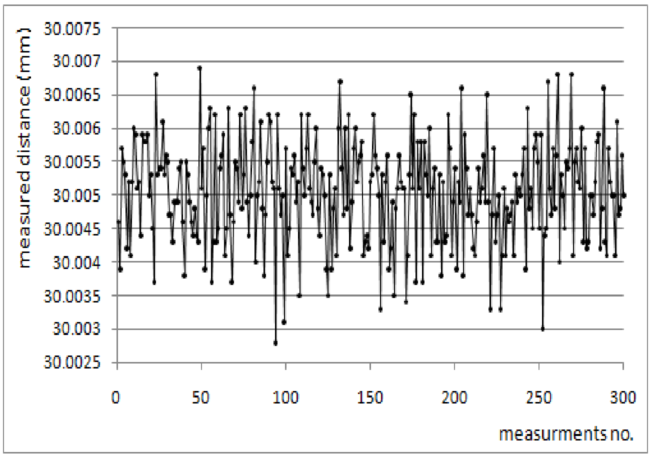

Fig. 4. Results produced by measuring ΔL 300 times.

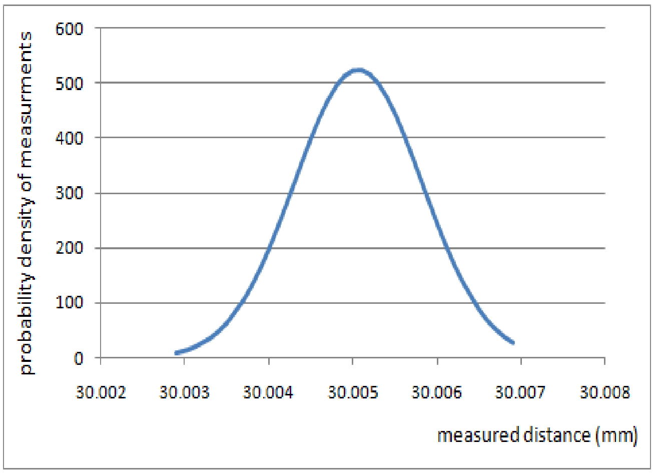

Fig. 5. The histogram for 300 measurements.

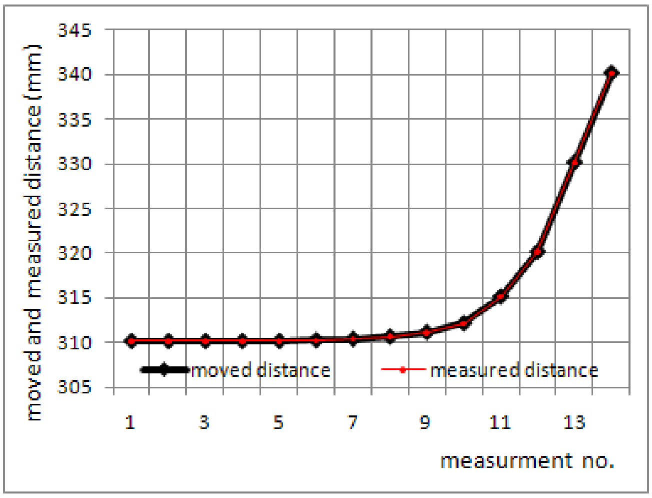

Fig. 6. Target distances and measured distances.

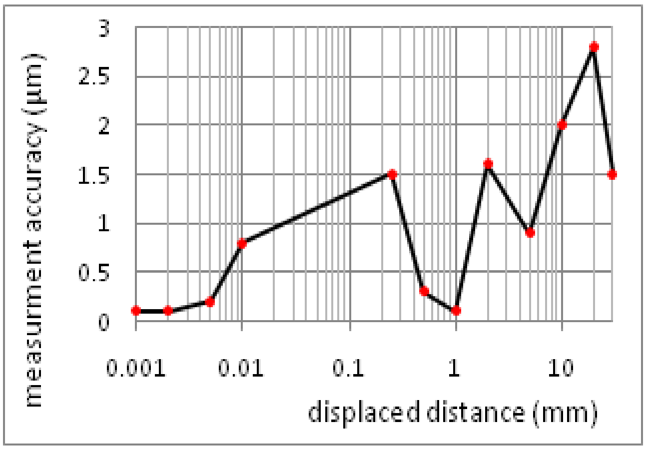

Fig. 7. Accuracy of the measurement system.

VI. CONCLUSIONS

This paper presents a method for performing absolute distance measurements. This method employs a concept known as iterative synthetic wavelengths. In this method, instead of continually sweeping the laser wavelength, a set of discrete wavelengths are used in a heterodyne fashion in order to synthesize a new virtual wavelength, that is usually

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larger than the laser source wavelengths. The experiment employs a Michelson interferometer, a tunable diode laser with tuning range from 680.5 nm to 690 nm, a wavelength meter and a CCD camera. The results for the experiments that were conducted illustrate the system's ability to perform absolute distance measurements with 2.8 micrometer accuracy over distances of up to 20 m, due the fact that the system employs a laser with a 40 m coherence length. The proposed system performance is not immune to external error sources and may be affected by systematic errors that are caused by system components and random environmental factors such as the thermal variations and mechanical vibrations. The absolute accuracy of distance measurement is determined essentially by the characteristics of the laser light source (coherence, stability, power) and also upon the accuracy of the synthetic wavelength calibration [2].

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