Frequency Scanned Interferometry for ILC Tracker Alignment

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In this paper, we report high-precision absolute distance and vibration measurements performed with frequency scanned interferometry using a pair of single-mode optical fibers. Absolute distance was determined by counting the interference fringes produced while scanning the laser frequency. A high-finesse Fabry-Perot interferometer was used to determine frequency changes during scanning. A dual-laser scanning technique was used to cancel drift errors to improve the absolute distance measurement presicion. Under realistic conditions, a precision of 0.16 microns was achieved for absolute distance of 0.41 meters. Numerical simulation of an optical alignment system for a single silicon ladder, cylinder is also presented.

1. Introduction

The motivation for this project is to design a novel optical system for quasi-real time alignment of tracker detector elements used in High Energy Physics (HEP) experiments. A.F. Fox-Murphy *et.al.* from Oxford University reported their design of a frequency scanned interferometer (FSI) for precise alignment of the ATLAS Inner Detector [1, 2]. Given the demonstrated need for improvements in detector performance, we plan to design and prototype an enhanced FSI system to be used for the alignment of tracker elements in the next generation of electron-positron Linear Collider detectors. Current plans for future detectors require a spatial resolution for signals from a tracker detector, such as a silicon microstrip or silicon drift detector, to be approximately 7-10 μm[3]. To achieve this required spatial resolution, the measurement precision of absolute distance changes of tracker elements in one dimension should be on the order of 1 μm. Simultaneous measurements from hundreds of interferometers will be used to determine the 3-dimensional positions of the tracker elements.

The University of Michigan group has constructed several demonstration Frequency Scanned Interferometer (FSI) systems with the laser light transported by air or single-mode optical fiber, using single-fiber and dual-laser scanning techniques for initial feasibility studies. Absolute distance was determined by counting the interference fringes produced while scanning the laser frequency. The main goal of the demonstration systems was to determine the potential accuracy of absolute distance measurements that could be achieved under both controlled and realistic conditions. Secondary goals included estimating the effects of vibrations and studying error sources crucial to the absolute distance accuracy. Two multiple-distance-measurement analysis techniques were developed to improve distance precision and to extract the amplitude and frequency of vibrations. Under laboratory conditions, a measurement precision of $\sim$ 50 nm was achieved for absolute distances ranging from 0.1 meters to 0.7 meters by using the first multiple-distance-measurement technique. The second analysis technique has the capability to measure vibration frequencies ranging from 0.1 Hz to 100 Hz with amplitude as small as a few nanometers, without a *priori* knowledge[4]. The multiple-distance-measurement analysis techniques are well suited for reducing vibration effects and uncertainties from fringe & frequency determination, but do not handle well the drift errors such as from thermal effects.

In this paper, we describe a dual-laser system intended to reduce the drift errors and show some results under realistic conditions. Numerical simulation of an optical alignment system for a single silicon ladder and for cylinders is also presented.

2. Principles

The intensity I of any two-beam interferometer can be expressed as $I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\phi_1 - \phi_2)$, where I_1 and I_2 are the intensities of the two combined beams, and ϕ_1 and ϕ_2 are the phases. Assuming the optical path lengths of the two beams are D_1 and D_2, the phase difference is $\Phi = \phi_1 - \phi_2 = 2\pi|D_1 - D_2|(\nu/c)$, where ν is the optical frequency of the laser beam, and c is the speed of light.

For a fixed path interferometer, as the frequency of the laser is continuously scanned, the optical beams will constructively and destructively interfere, causing "fringes". The number of fringes ΔN is $\Delta N = D\Delta\nu/c$, where D is the optical path difference between the two beams, and $\Delta\nu$ is the scanned frequency range. The optical path difference (OPD for absolute distance between beamsplitter and retroreflector) can be determined by counting interference fringes while scanning the laser frequency.

If small vibration and drift errors $\epsilon(t)$ occur during the laser scanning, then $\Phi(t) = 2\pi \times (D_{true} + \epsilon(t)) \times \nu(t)/c$, $\Delta N = [\Phi(t) - \Phi(t0)]/2\pi = D_{true}\Delta\nu/c + [\epsilon(t)\nu(t)/c - \epsilon(t0)\nu(t0)/c]$, Assuming $\nu(t) \sim \nu(t0) = \nu$, $\Omega = \nu/\Delta\nu$, $\Delta\epsilon = \epsilon(t) - \epsilon(t0)$, the measured distance can be written as,

$$D_{measured} = \Delta N/(\Delta\nu/c) = D_{true} + \Delta\epsilon \times \Omega. \tag{1}$$

3. Dual-Laser Scanning Technique

A dual-laser FSI system was built in order to reduce drift error and slow fluctuations occuring during the laser scan, shown in the top right plot of Figure.1. Two lasers are operating simultaneously, the two laser beams are coupled into one optical fiber but isolated by using two choppers. The principle of the dual-laser technique[2] is shown in the following. For the first laser, the measured distance $D_1 = D_{true} + \Omega_1 \times \Delta\epsilon_1$, and $\Delta\epsilon$ is drift error during the laser scanning. For the second laser, the measured distance $D_2 = D_{true} + \Omega_2 \times \Delta\epsilon_2$. Since the two laser beams travel the same optical path during the same period, the drift errors $\Delta\epsilon_1$ and $\Delta\epsilon_2$ should be very comparable. Under this assumption, the true distance can be extracted using the formula $D_{true} = (D_2 - \rho \times D_1)/(1 - \rho)$, where, $\rho = \Omega_2/\Omega_1$, the ratio of magnification factors from two lasers. If two identical lasers scan the same range in opposite directions simultaneously, then $\rho \simeq -1.0$, and D_{true} can be written as,

$$D_{true} = (D_2 - \rho \times D_1)/(1 - \rho) \simeq (D_2 + D_1)/2.0 \tag{2}$$

The laser beams are isolated by choppers periodically, so only half the fringes are recorded for each laser, degrading the distance measurement precision, as shown in the top and bottom left plots of Figure.1. Missing fringes during chopped intervals for each laser must be recovered through robust interpolation algorithms. Based on our studies, the number of interference fringes in a certain number of Fabry-Perot peaks region is pretty stable. The measured number of fringes is within 0.5 (typically within 0.3) of expected fringes number, which enables us to estimate the number of fringes in the chopper-off slots(laser beam is blocked by the chopper). In order to determine the number of fringes in one chopper-off slot, we need to identify two Fabry-Perot peaks within two adjacent chopper-on slots closest to the chopper-off slot. If the fringe phases at the two Fabry-Perot peaks positions are $I + \Delta I$ and $J + \Delta J$, where I and J are integers, ΔI and ΔJ are fraction of fringes; then the number of true fringes can be determined by minimizing the $|N_{correction} + (J + \Delta J) - (I + \Delta I) - N_{expected-average}|$, where $N_{correction}$ is an integer used to correct the fringe number in the chopper off slot, $N_{expected-average}$ is the expected average number of fringes, based on a full laser scanning sample.

Under realistic conditions with large thermal fluctuations, air flow (large drift errors), 10 sequential dual-laser scans data samples each with open box, with a fan on and then turn off the fan were collected. The two lasers were scanned oppositely with scanning speed of 0.4 nm/s, the scanning time is 25 seconds for one full scan. The measured precision is found to be about ~3-6 microns if we use the fringes of these data samples from only one laser with measured distance of 0.41 meters. If we combine measured distances from two lasers using Eq.(2), then the dual-laser precision is 0.16 microns for open box data and 0.20 microns for open box data with the fan on shown in the bottom right plot of Figure 1.

4. Simulation of Alignment System

Numerical simulation of tracker alignment system has begun. As a first step, we assume the silicon ladder, cylinder (Si disk, TPC or CCD cryostat) are rigid bodies, the off-tracker reference points have rigid supports and their positions are known. The distance resolution is assumed to be 0.5 microns for all lines of sight which is optimistic

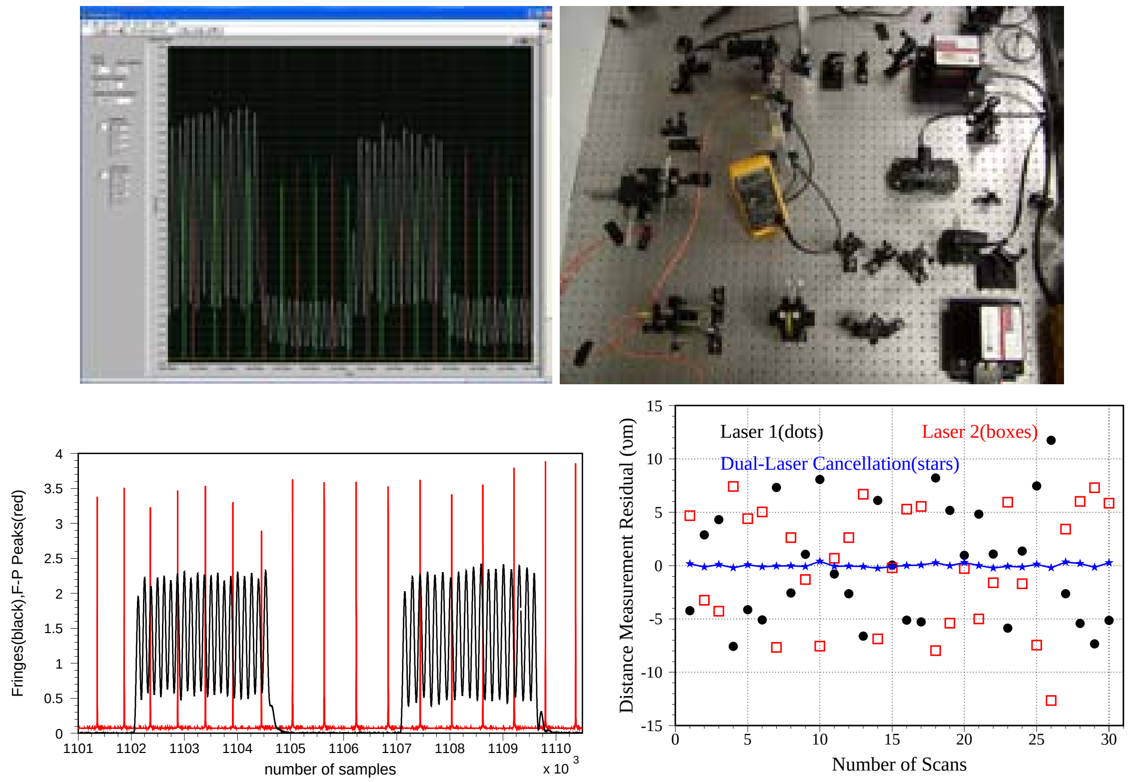

Figure 1: The top left figure shows fringes and Fabry-Perot peaks from dual-laser scanning, the top right figure is the dual-laser system built in the laboratory. The bottom left plot represents the fringes and Fabry-Perot peaks from the first laser with chopper on, the bottom right plot shows distance measurement residuals versus number of scans for dual-laser scanning.

for distance longer than 1 meter, but conservative otherwise. The simulation results under ideal conditions are summarized in Table 1. We will eventually use hundreds of distance measurements along lines of sight to determine tracking component positions, rotations(pitch/roll/yaw) and internal distortions. Thermal expansion, mechnical deformations, systematic uncertainties and possible drifts from reference points etc. will also be considered in the future simulations.

Tracker	No. of Distance	Dimensions(cm)			Position Precisions(μm)			Axis Rotation Precisions (μrad)		
	Measurements	Radius	Half-Length	Width	x	y	z	ψ	θ	ϕ
Single Silicon Ladder	16	20	27	10	0.30	0.30	0.20	0.90	1.40	7.00
Single TCP Cylinder	192	170	270	-	0.08	0.06	0.05	0.02	0.02	0.03
Single CCD Cylinder	96	10	17	-	0.08	0.08	0.17	0.38	0.38	2.77

Table I: Position precisions and axis rotation precisions for tracker alignment system.

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