LONGITUDINAL TRACKING OF DIRECT DRIVE INERTIAL FUSION TARGETS

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Successful ignition of direct drive targets in an IFE power plant requires a reliable system for tracking the location of the target in flight and illuminating it by many separate laser beams with a high degree of precision. As part of a coordinated effort in the High Average Power Laser (HAPL) program, we have developed and tested an interferometric technique for measuring the position and velocity of targets along their axis of motion. The technique involves reflecting light from the moving target and combining it with a reference beam in order to produce interference fringes at a rate corresponding to the movement of the target.

A scaled benchtop experiment has been built and tested to characterize the performance of this technique of axial target tracking. Results are presented here together with recommendations on improvements needed for a full-scale performance demonstration.

I. INTRODUCTION

In direct drive inertial fusion, high power short pulse lasers directly illuminate the surface of a cryogenically cooled D-T target to cause an intense implosion that initiates a thermonuclear burn. This implosion is repeated several times per second within a chamber that recovers excess energy from the fusion reaction for generating electricity. In order for such a nuclear reactor to function, the lasers that illuminate the target must be aimed with very high precision.

This work was performed as one of the HAPL program phase I "proof of principle" experiments in the build-up to an IFE power plant.[1] References 2 and 3 provide an overview of target tracking and engagement; this paper covers solely the fringe counting method of longitudinal tracking, one of several systems needed to precisely illuminate (engage) a fusion target.

II. BACKGROUND

II.A. Direct Drive Tracking Requirements

Current specifications require a <1% out of round spherical target, 4-mm in diameter, coated with highly reflective metal.[1] The injection velocity will be less than 100 m/s and the injection placement precision will be better than ~5 mm. The chamber size is nearly 10 m in radius, and total target tracking accuracy needs to be nominally ±14 μm: 10 μm in the longitudinal axis, and 10 μm in the radial direction, combined in quadrature.

II.B. Longitudinal Tracking Scenarios

Two scenarios for the use of fringe counting are considered. In the first scenario, it is assumed that tracking takes place during the entire path of target travel; *i.e.* to measure absolute distance traveled relative to a crossing sensor. The crossing sensor itself introduces error; a previously demonstrated sensor was capable of ±2.5 μm accuracy.[4]

In the second scenario, fringe counting may be used for the determination of velocity only, over a much shorter distance near target chamber center. This would be enabled by the Glint mechanism outlined in reference 2 that is still in the process of development and characterization. The Glint position measurement provides the engagement system a temporal and spatial reference point from which to locate the target for engagement; the velocity measurement enables proper timing of engagement.

To minimize target heating, the maximum tracking laser radiation fluence is limited to around 2.5 W/cm^2 such that a continuous illuminating beam does not overheat the target over the full 10 m injection distance. If the fringe counting distance is 1 cm, rather than the full 10 m injection distance, the maximum fluence increases to 2.5 kW/cm^2, assuming that the tracking laser is incident on the target for 1000^{th} the amount of time.

II.C. Fringe Counting Method

Fringe counting is performed using a variation of a Michelson interferometer, shown in Fig 1, where the moving leg of the interferometer generates constructive and destructive interference at a detector with frequency $f=2V/\lambda$, when laser wavelength is λ. This can be integrated to obtain the relative position $Z=C\lambda/2$, where C is the number of fringes counted and Z is the longitudinal position. The intensity incident on the detector is $I= I_1 +$

$I_2 + 2\sqrt{I_1 I_2}\cos(2\pi ft)$, where I_1 is reference leg intensity, and I_2 is moving leg intensity. The detector converts this into a voltage that is AC filtered to result in a signal amplitude (peak to peak) of $4\sqrt{I_1 I_2}\,G$, where G is the voltage response of the detector for a given incident light intensity (*i.e.*, Gain).

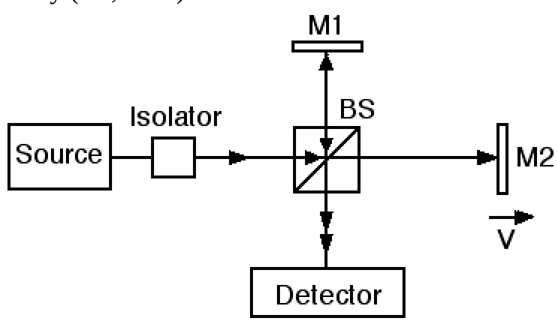

Fig. 1. Schematic of a Michelson interferometer

II.D. Challenges for tracking a moving sphere

The application of interferometry to a moving sphere raises numerous important challenges. These include:

1. Spherical wavefronts reflected off of the target are interfered with a plane reference wave, which leads to complex interference patterns. In addition, the spherical waves are constantly changing as the target moves relative to the detector, both laterally and longitudinally.

2. The precise position of the target cannot be known in advance, and changes in flight. The interferometer must be robust with respect to off-axis deviations of several mm.

3. The high velocity of the target can lead to very high counting rates, above 100 MHz. In our benchtop experiments, we restricted the velocity and used an IR (1.54 µm) telecom laser to keep the frequency low.

4. Limitations in laser intensity due to target heating can lead to severe signal-to-noise problems. In addition, as the target moves, the signal strength varies as $1/R^2$. Therefore, filtering and noise reduction techniques are important for accurate tracking. The second scenario allows for higher laser intensity, reducing this problem.

5. The relatively large distance of target tracking (10 m, corresponding to ~10^7 wavelengths) leads to a very large number of fringes counted. In order to precisely locate the target at the end of its trajectory, the wavelength of the laser must be known to a very high degree of precision. For example, to meet the goal of 10 µm tracking accuracy, the laser wavelength must be known to within 1 part in 10^6. Again, the second scenario reduces this difficulty.

6. Target out of round may have a negative impact on this method of measurement. Fringe counting depends on collecting light reflected from essentially a point on the surface of the target, so if the target has a bulge at one point, it may undermine the measurement. However, if the target is spinning, the spin could average out surface fluctuations and improve fringe counting measurement accuracy.

The main thrust of this work was to characterize and overcome these challenges using optical and electronic techniques, which are discussed below. In particular, here we focus primarily on the accommodation of spherical waves and the techniques we used to improve the signal-to-noise ratio. The difficulty achieving the tracking requirements may be significantly reduced in the second scenario, in which the target is tracked over a much shorter axial distance; however, this scenario is dependent on a functioning glint mechanism. Also, any optically-based tracking mechanism will be severely complicated by any ambient chamber gas; not only is target motion less predictable, but also changes in index of refraction can impact tracking accuracy.

III. TRACKING SYSTEM TECHNIQUES

III.A. Modifications for a spherical reflector

Unlike the flat reflector in Figure 1, a spherical target reflects nearly perfect spherical wavefronts that then need to interfere with a flat reference wavefront. This creates a ringed interference pattern that tends to cancel out the amplitude variations at a detector surface (see Fig. 2). This problem may be most easily overcome by detecting only the central spot of the interference pattern.

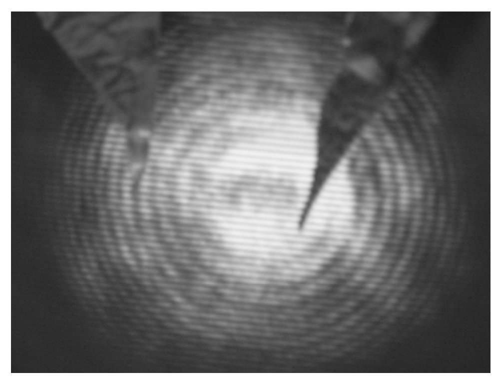

Fig. 2. Interference of spherical and plane wavefronts

The radius of n^{th} light to dark ring is described by

$$\rho_n \cong \sqrt{n\lambda Z}. \qquad (1)$$

In order to obtain the largest amplitude signal, the diameter of the detector (or aperture in front of the detector) should not exceed the first fringe radius ρ_1 for a given distance from detector to spherical target (defined as Z). In addition, the detector should be located as close to the center of the fringe pattern as possible.

While it is important that the photodetector be placed within the central fringe spot, it is also important that the detector receive as much light as possible. If the central fringe spot is larger than the detector, signal power is wasted; optimally, the central fringe radius would be matched to the detector diameter. Since this is not normally the case, an iris is placed before a lens that then focuses the light onto a detector.

This can also be achieved by placing the detector between a lens and the lens focal point such that the fringe radius is matched to the detector at that location (see Fig 3). This method is more challenging due to difficulty locating the ideal detector position.

For both methods, the maximum target offset for a given target-to-lens distance Z is approximately the first fringe radius (eq 1). One demonstration showed that when the offset nears twice the first fringe radius, signal amplitude drops by half. At Z =10 m, this lateral robustness is about 8 mm; a value within the accuracy constraints of the injector.

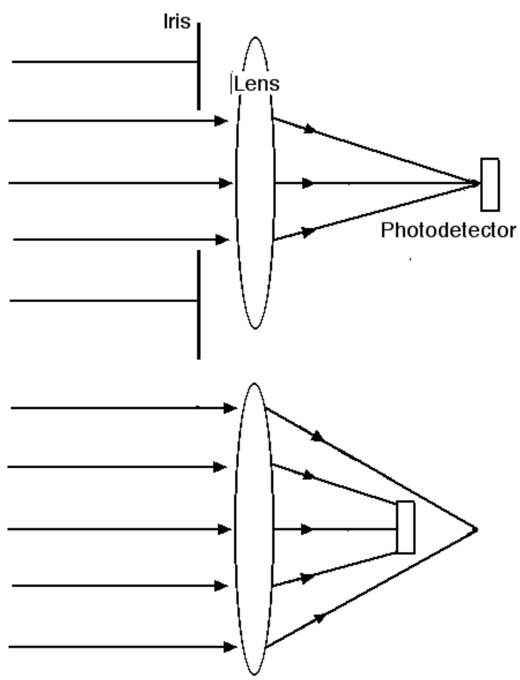

Fig. 3: Two methods of matching the central fringe radius to the detector diameter.

The fringe radius is constantly changing, so a set iris diameter is picked to optimize intensity over the course of measurement. This is less than ideal for the first scenario; for the second scenario, the iris is matched to the target location at which the measurement takes place (i.e. the glint location), yet again easing a technical challenge of longitudinal tracking.

For the first scenario, more advanced ideas were considered, such as feedback-controlled irises, reference leg wave-front feedback control, and LCD irises, however these mechanisms may be unnecessary if the second scenario works.

III.B. Signal-to-noise improvement techniques

Reference 3 concludes that a low-powered laser, ~0.2 W, would be sufficient to obtain ~20 photoelectrons per fringe; this in turn should be enough to track targets. In practice, those photoelectrons may be buried in noise. It is certain that any method that can be employed to increase signal to noise ratio will benefit this highly sensitive method of tracking, and is worth consideration.

One such method is to add a second beam splitter to the interferometer and use a balanced photodetector or other signal subtraction method (Fig. 4). This is intended to remove laser-based or ambient noise and DC signal components. This method has not been fully refined in the laboratory as of this writing, but has the potential to decrease noise greatly.

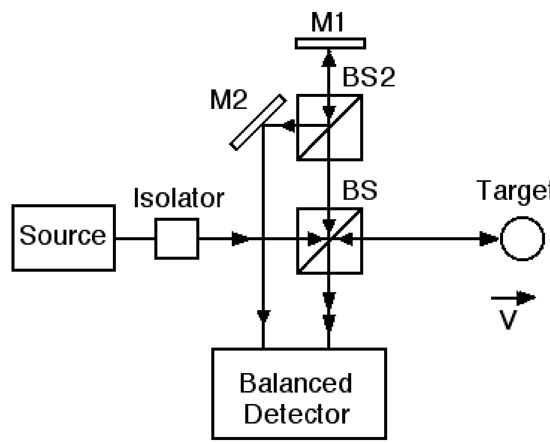

Fig. 4. Second beam splitter and balanced photodetector allows reduction of laser and ambient noise, while also acting as an A/C filter.

A number of electronic techniques are available to find the signal within the noise: frequency filtering and amplification are the most obvious. Ideally, a lock-in amplifier could pick out a narrow, pre-selected bandwidth to amplify. However, the target will most likely be injected vertically, such that the frequency will vary from start to finish as gravity accelerates the target.

For scenario one, it may be possible to use a chirped lock-in frequency that approximates the frequency shift of the target – the lock-in frequency would shift according to a time evolution of target velocity. For scenario two, the lock-in frequency could be approximately matched to the velocity of the target at the desired point of measurement. Or, the lock-in frequency could be chirped cyclically, leading to discrete target velocity measurements over the course of target travel. The lock-in amplifier itself could even serve as a means of measuring the target velocity. Much work needs to be done to test these ideas.

III.C. Laser stability considerations

For scenario one, wavelength must be constant to 1 part in 10^6 (*e.g.*, 1 pm for 1 μm light). A Fabry-Perot wave locker can enable 1 in 10^5 stability, however 10 times that is needed. This may require the use of a precision wave-meter to measure and feedback wave-length to calibrate measurements in real-time.

For the second scenario, in order to predict the position to 10 μm after 10 cm of travel, the velocity needs to be known to approximately one part in 10^4, or 1 cm/s for V=100 m/s. This assumes the glint and velocity measurements are performed 10 cm before chamber center. This reduces wavelength precision requirements to about 1 in 10^4 (not including any other errors in velocity measurement), which is readily attainable.

IV. EXPERIMENTAL STUDIES

IV.A. Experimental apparatus

Initial tests of this technique were performed using a hand-operated micrometer. A 4-mm steel sphere was mounted on a stalk and translated 1 mm ± 3 μm.

Following those tests, we assembled the experimental apparatus shown schematically in Figure 5. Steel spheres were held by a suction needle at the top of a tower and then individually released and tracked using the modified Michelson interferometer described above. In this case, there was no independent technique available to verify the prediction, so only quality and reproducibility of the observations could be studied.

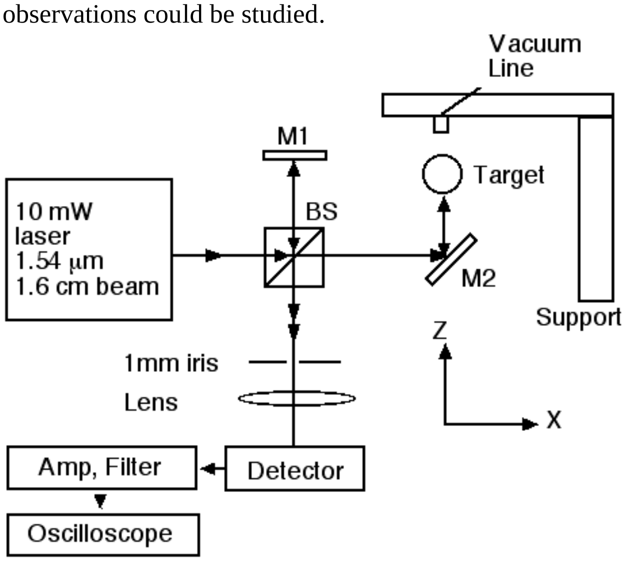

Fig. 5: Sketch of experimental setup. Distance from target to iris was about 30 cm.

The reference wave was mixed with the scattered spherical wave, sent through an iris, a focusing lens and finally into a photodetector. This signal was filtered, amplified and then sent to either an oscilloscope or a data acquisition board with a counter.

IV.B. Results

Fig. 6 shows a histogram of the results from a series of experiments using a hand-operated micrometer. After several independent measurements, the number of data points having a given deviation from 1 mm is plotted as a function of the amount of deviation. The standard deviation of the translation measurement was ~3 μm, within the uncertainty in the micrometer. The apparent tendency to err on the side of greater distances, rather than lower distances, is due to spurious counts caused by vibrations.

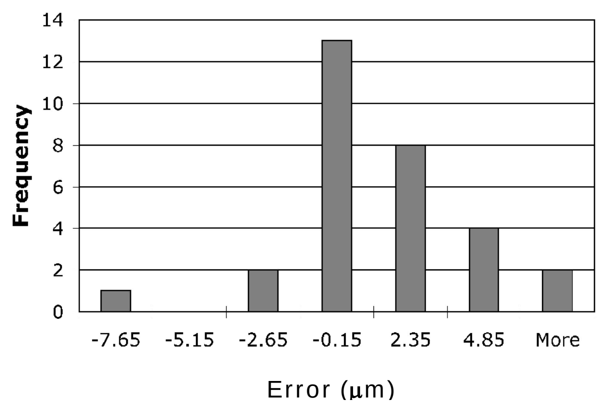

Fig. 6: Fringe count error histogram.

Fig. 7 shows an oscilloscope trace resulting from the dropping of a steel target from a vacuum chuck. The short duration of the signal is a consequence of the large level of signal filtering necessary to remove high-frequency noise.

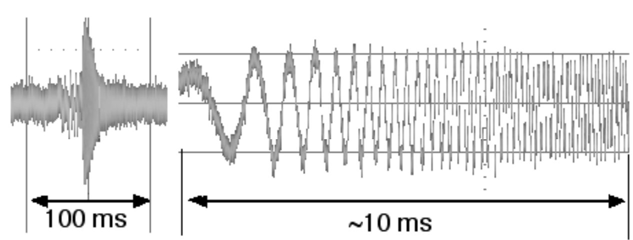

Fig. 7: Signal from short range ball bearing drop test. Signal at right is expanded signal at left; range of tracking was limited by bandpass cutoff to about 10 kHz.

V. CONCLUSIONS

The Michelson interferometer is a simple, precise tool for measuring position and velocity. Its use for inertial fusion as a means of tracking targets is complicated by a number of factors, such as speed, distance, and the spherical nature of the target. Our initial testing has demonstrated the feasibility of this technique for stationary and low-speed sphere-drop tests. Although its robustness is a concern, further efforts to improve the optical design and reduce noise may enable the use of fringe counting in a full-scale IFE power plant. The scenario in which only velocity is measured near chamber center will be much easier to implement.

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