Two-photon dual-comb LiDAR for industrial applications

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Abstract

Common industrial optical metrology techniques are interferometry-based and therefore limited to short-range measurements of displacement, rather than absolute distance. Since such techniques rely on fringe counting to measure larger distances, they are vulnerable to any interruption of the beam during the measurement, which would require the measurement to be terminated and restarted. Our technique, two-photon dual-comb LiDAR (2phDCL) offers an alternative to interferometry which is capable of rapid, absolute distance measurements over long ranges (>1m) and is not inhibited by beam blocking.

Our previous demonstrations were performed with compact, eye-safe Er:fibre lasers and achieved distance measurements with tens-of-µm single-shot precisions, and hundreds-of-nm precisions within two seconds of averaging. We have since developed 2phDCL to enable simultaneous ranging to multiple targets and found no degradation in measurement performance. We extended this capability to provide simultaneous distance measurements to three points on a target object, allowing simultaneous acquisition of range and pose.

Given the impressive measurement precisions, the ability to perform multiple measurements simultaneously, and the immunity to beam blocking, we believe 2phDCL has the potential to become the optical metrology technique of choice in certain applications. The technique could immediately offer advantages to existing machines in terms of faster calibration, and we anticipate applications in the real-time tracking of moving components to enable in-process verification of machine paths.

1 Introduction

Industrial optical metrology tools are typically based on either interferometry or LiDAR – light detecting and ranging. Interferometry involves analysing the changing phase of a laser interference pattern to determine a target's displacement. Interferometry offers nanometre resolutions since the measurement is made on the scale of the laser wavelength. It is therefore the optical metrology tool most commonly used when high resolution is required. Though atmospheric compensation for air dispersion effects is required for nanometre accuracy over long distances. Unfortunately, interferometry is limited to measurements of displacement from a user-defined zero-point, rather than measurements of absolute distance. Furthermore, the measurement requires uninterrupted monitoring of the beam; if the beam is blocked at any point, the measurement is terminated and must start again. Conversely, LiDAR can measure absolute distances over long ranges (>1m). However the timing response of state-of-the-art electronics limits the resolution to many millimetres, at best. With the contrasting limitations of interferometry and LiDAR, there is a gap in the market for an industrial optical metrology tool capable of absolute distance measurements with few-µm resolutions.

Dual-comb ranging (DCR) combines the concepts behind interferometry and LiDAR to benefit from the advantages of both. A 'probe' comb samples the distance to be measured, generating reflections from reference and target optics. The time delay between these reflections constitutes a time-of-flight (ToF) measurement of the distance between the two optics. In dual-comb techniques, a second comb, the 'local oscillator (LO)' coherently gates the 'probe' reflections such that interferograms are collected when conventional one-photon detection is used. The gating with the LO means the information is magnified by a factor of $f_{rep} / \Delta f_{rep}$. So, despite being limited to the same state-of-the-art detectors, high resolution measurements become possible. In some demonstrations of DCR, the time-of-flight measurement is averaged until the precision drops below $\lambda/4$ (where λ is the wavelength of the laser), at which point analysing the phase of the interferograms provides nanometre resolution [1]. However, most demonstrations suffice with the time-of-flight measurement since nanometre resolution measurements would require atmospheric compensation and this is excessive for many applications.

Publications on DCR prove the technique has the potential to bridge the performance gap between interferometry and LiDAR [1-5]. However, the technique typically requires digitization at >100 MSa/s and post-processing of the data. This, coupled with the requirement for stabilised frequency combs, has meant DCR has remained, for the most part, in research labs. To overcome this, we developed two-photon dual-comb LiDAR (2phDCL) as a simplified variation on DCR [6-8]. In our technique, we gate the probe reflections with the LO pulses incoherently and utilise two-photon absorption (TPA) to directly detect intensity cross-correlations between the pulses. The carrier-free nature of the cross-correlations allows them to be conditioned with simple electronics to act as triggers for an inexpensive microcontroller. The microcontroller is programmed to count its internal clock cycles, saving the count and restarting when each new cross-correlation pulse is detected. In this way, the timing gaps between cross-correlations are measured with a timing resolution of 1.67 ns. The raw data takes the form of a stream of integers to the serial port, significantly reducing the data burden associated with dual-comb techniques and enabling real-time measurements. Despite the simplifications made, an Allan deviation of ranging data showed no degradation in measurement precision when exchanging our high-speed digitizer for our inexpensive microcontroller. We demonstrated single-shot precisions of tens-of-micrometres; with averaging precisions reached sub-100 nm within 3 s.

In these conference proceedings, we present a first look at new data demonstrating ranging to multiple targets simultaneously. An Allan deviation shows measurements to three targets retain comparable precision to single-target measurements. We extend this approach to enable simultaneous measurements of distance, pitch, and yaw as an application of the multi-target ranging.

2 Methods

Figure 1 shows a typical measurement set-up. The probe comb emits pulses which pass through a quarter-wave and half-wave plate to give the pulses *p*-polarisation, such that they are transmitted at the polarising beam splitter (PBS1), following which, a quarter-wave plate gives the pulses circular polarisation. A 70:30 (T:R) beam splitter (BS) gives a 30% reflection to act as a reference (R) for the ranging measurement. The transmitted beam hits a diffractive optical element (DOE) and splits into three beams in a single plane. Each beam reflects off a target retroreflector (T1-3). The reference and target reflections return through the quarter-wave plate, giving them *s*-polarisations such that they are reflected at PBS1 and PBS2. Simultaneously, pulses from the LO comb pass through a quarter-wave and half-wave plate and become *p*-polarised, such that they are transmitted through PBS2. Thus, the probe reflections and the LO pulses meet at PBS2 with opposite polarisations and cannot optically interfere. Tight focussing onto a silicon avalanche photodetector (Si APD) induces TPA. The detected signal is low pass filtered at $\sim f_{rep}/2$ to remove the laser pulse repetition frequencies, resulting in a train of four cross-correlations – one for the reference and one for each of the three targets. This signal is amplified and passed through a Schmitt trigger to convert the cross-correlations to 3.3V square trigger pulses to be sent to the microcontroller (Teensy 4.0).

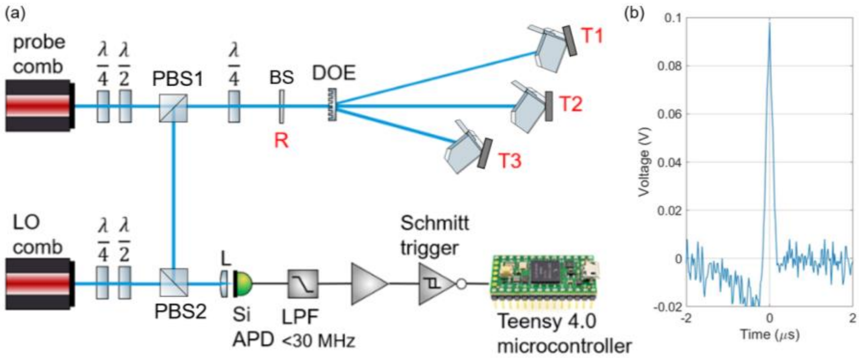

Figure 1: (a) A typical measurement set-up. PBS: polarising beam splitter; BS: beam splitter; DOE: diffractive optical element; APD: avalanche photodetector; LPF: low pass filter. (b) A single intensity cross-correlation.

The probe and LO combs were based on modelocked Er-doped fibre lasers with Er-doped fibre amplifiers. The RF and optical spectra of the combs are presented in Fig. 2. The RF spectra shows the repetition frequencies of the probe and LO combs were 78.816 MHz and 78.815 MHz, respectively, however the LO was tuneable over ~20 kHz. Figure 2(b) shows the optical spectra of the probe and LO combs which were centred at 1555 nm and 1552 nm, with bandwidths of 6.8 nm and 5.6 nm, respectively. During ranging, the combs' repetition frequencies were locked to stable RF sources with hardware-based feedback loops to piezos inside the cavities. Details of the combs and the locking are provided in [8].

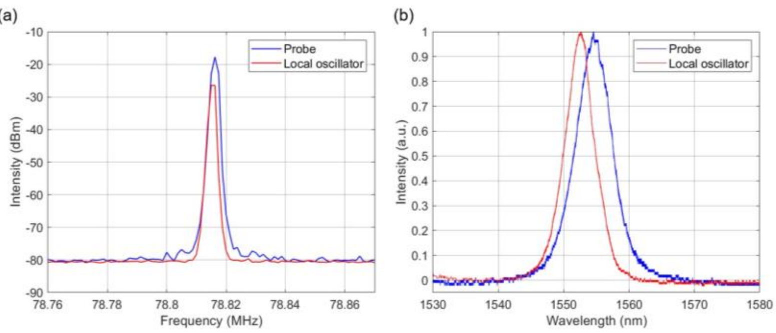

Figure 2: (a) The RF spectra of the combs. (b) The optical spectra of the combs.

Figure 3(a) gives an example of the optical cross-correlations detected by the Si APD and low-pass filtered to remove the pulse trains. The figure is annotated to label the timing delays $\tau_1 - \tau_4$, where τ_1 is the timing gap between the reference and the first target; τ_2 and τ_3 are the timing gaps between the three target reflections; and τ_4 is the gap between the third target and the next reference.

Figure 3(b) shows the raw data plotted in Matlab. The annotations on Fig. 3(a) are colour coded to the values in Fig. 3(b).

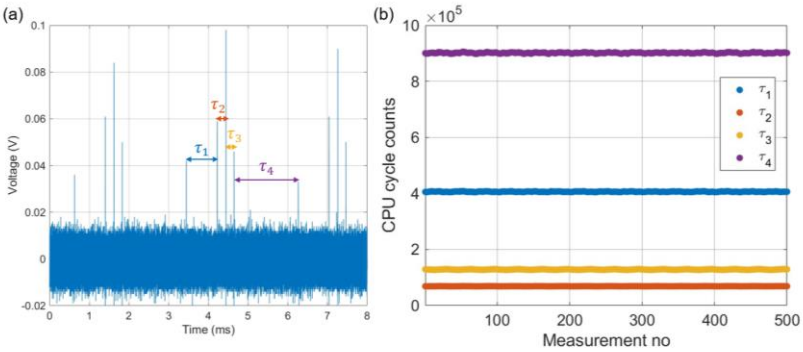

Figure 3: (a) Train of optical cross-correlations annotated to highlight the timing gaps, $\tau_1 - \tau_4$. (b) Raw data.

The raw data, $\tau_{1\text{-}4}$ gives the timing gaps as a count of internal clock cycles. To convert the values to time measurements, they must be multiplied by $1/\tau_{CPU}$, where τ_{CPU} is the CPU speed. Our microcontroller runs at 600 MHz, giving us an equivalent timing resolution of 1.67 ns. Distances, d_i to the targets are calculated by:

$$d_i = \frac{v_g}{2f_{rep,pr}} \frac{\sum_{j=1}^{i} \tau_j}{\tau_1 + \tau_2 + \tau_3 + \tau_4} \ ,$$

where v_g is the group velocity of the pulses and $f_{rep,pr}$ is the repetition rate of the probe comb.

3 Results

3.1 Measurement precision for simultaneous ranging to multiple targets

Data was collected for the simultaneous ranging to three retroreflectors at distances of 30.02 cm, 33.11 cm, and 36.76 cm. During measurements, the repetition rates of the probe and LO combs were locked to enforce a Δf_{rep} value of ~1 kHz. The Allan deviation in Fig. 4 reveals how measurement precision improves with averaging.

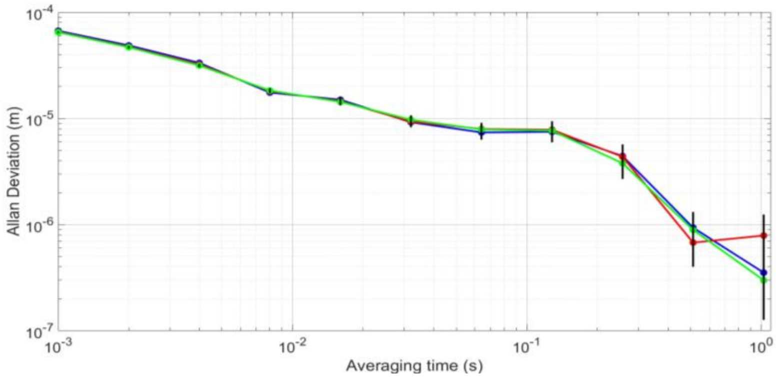

Figure 4: Allan deviation of data ranging to three targets simultaneously. Sub-µm precisions are recorded in 500 ms.

Figure 4 shows the measurements have a single-shot precision of ~67 µm. With averaging, sub-µm precisions are achieved in 500 ms. The Allan deviation is comparable to our previously published data for single-target measurements [5-8].

3.2 Simultaneous ranging to multiple dynamic targets

To demonstrate ranging to moving targets, the target retroreflectors were mounted onto loudspeakers driven by signal generators. Figure 5 shows a photograph of one of the loudspeakers with a retroreflector attached to the front surface.

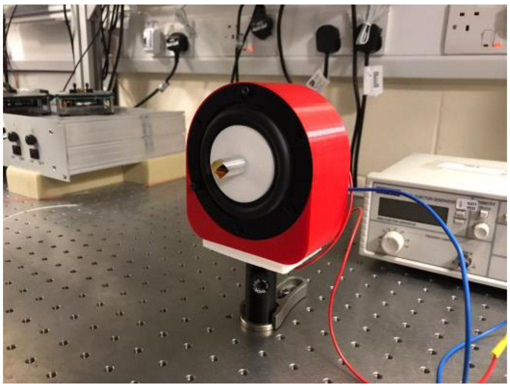

Figure 5: Moving targets were created by mounting retroreflectors on the surface of loudspeakers driven by signal generators.

Figure 6 shows ranging to the three retroreflectors while they were driven by triangular, sinusoidal and square waveforms at 1 Hz. During measurements, the repetition rates of the combs were locked to enforce a Δf_{rep} value of ~1 kHz, meaning a measurement is collected every 1 ms. The data shown in blue is collected without averaging; the data shown in red is collected with 10 ms of averaging.

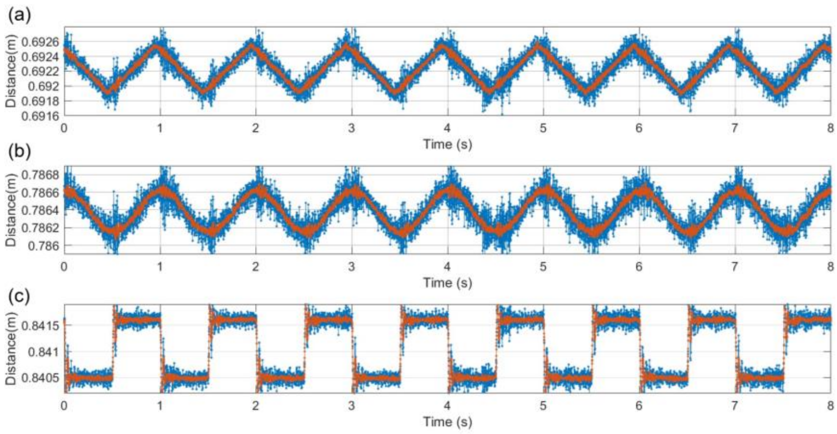

Figure 6: Simultaneously collected ranging data for triangular, sinusoidal and square motion at 1 Hz.

The disturbances in the motion in Figs. 1(a)-(b) temporally align with the motion of the square waveform. We repeated the experiment without collecting data on the square-moving target and found the disturbances were still present in the triangular and sinusoidal data. This confirmed that the disturbances were genuine vibrations caused by the sudden acceleration and deceleration of the square motion.

3.3 Simultaneous position and pose measurements

To demonstrate an application of this multi-target ranging, we performed an experiment with simultaneous measurements of distance, pitch, and yaw. The experimental set-up shown in Fig. 1 was adapted to allow ranging to three points on a target. The DOE was rotated so that the three diverging output beams lay in a plane oriented diagonally at 45° to the optical table; silver mirrors were placed in the beam paths to configure them to propagate in parallel and in a rotated L-shaped orientation, as shown in Fig. 7(a). The centre beam provided the absolute ranging to the target, while the other two beams provided additional ranging to allow calculations of pitch and yaw. To ensure returns from all three beams, a mount was 3D printed to hold three retroreflectors in a L-shaped orientation. Figure 7(b) shows the Autocad model of the mount. The 3D printed mount was placed in an optics mount with built-in picomotors. The mount was controlled remotely by a motion controller.

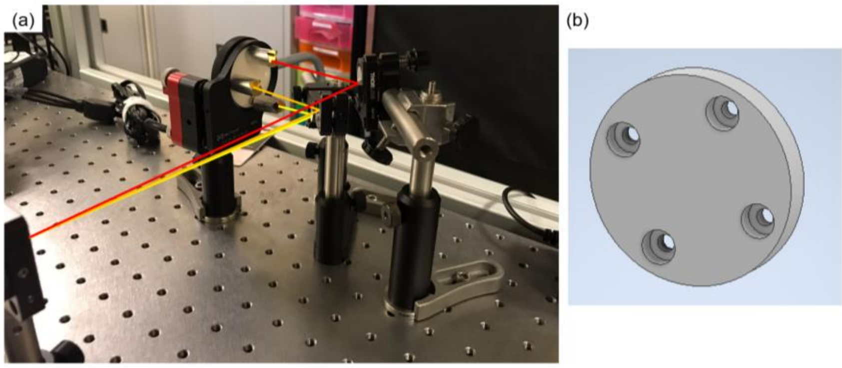

Figure 7. (a) Experimental configuration with annotations showing the beam paths. Mirrors were used to reconfigure the beam paths into a L-shaped orientation and each beam hits a retroreflector. (b) Autocad model of the 3D printed mount to hold retroreflectors in an L-shape.

The mount was controllable in three axes, however only one axis (bottom left) was translated for this experiment. Ranging data were collected for every 200 steps of picomotor translation, where each step is equivalent to ~30 nm of translation. The repetition rates of the probe and LO comb were locked to enforce a Δf_{rep} value of ~1 kHz. The distance to the centre retroreflector is considered the absolute distance to the target. The distances to the top and bottom retroreflectors differ due to the extra path length introduced when reconfiguring the beam paths. The path length between the centre and bottom retroreflectors was similar so the bottom retroreflector was placed on a washer to provide sufficient separation. Ranging to the top and bottom retroreflectors allowed measurements of the pitch and yaw of the target. Figure 8 illustrates how the ranging data to the three targets were processed in Matlab to create a surface which allowed calculation of pitch and yaw. We obtained pitch and yaw angles relative to the initial retroreflector position by subtracting the initial time-of-flight distances from all subsequent values, allowing measurement of the change in pitch and yaw from this nominal 0° position.

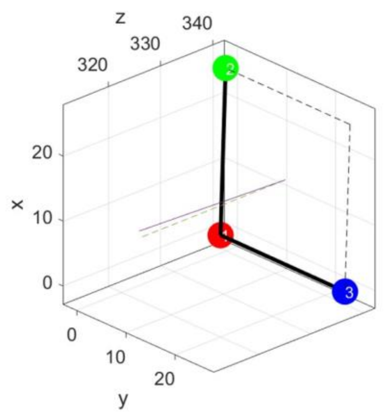

Figure 8: Matlab processing of the data.

Figure 9 shows the pitch and yaw values as a function of axis translation. The translated axis was positioned in the top left corner (behind the green point), thus we see an increase for the pitch (angle between red and green points) in Fig. 9(a). The yaw (angle between red and blue points) increases in very small amounts as seen in Fig. 9(b).

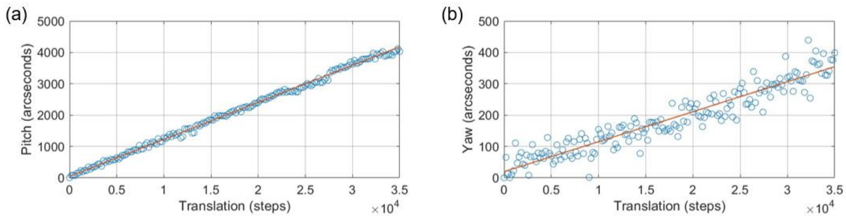

Figure 9: (a) Pitch measurement as a function of motor translation. (b) Yaw measurement as a function of motor translation.

4 Conclusion

We have presented recently acquired data demonstrating 2phDCL for simultaneous ranging to multiple targets. By performing an Allan deviation of data ranging to stationary targets, we have shown single-shot precisions of 67 µm, with sub-µm precisions being achieved in 500 ms. We have demonstrated simultaneous ranging to three dynamic targets, driven by triangular, sinusoidal and square waveforms at 1 Hz frequencies. Finally, we demonstrated simultaneous measurements of distance, pitch, and yaw. The preliminary data presented here show exciting new applications of 2phDCL. We anticipate publication of a more comprehensive study in due course.

References

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