Multi-Tone Continuous Wave Lidar in Simultaneous Ranging and Velocimetry

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Abstract: We demonstrate simultaneous ranging and velocimetry measurements by using multi-tone continuous wave Lidar. We show >95% agreement with conventional time-of-flight Lidar technique in ranging and ±0.8cm/s accuracy in velocity measurements.

1. Introduction

Lidar systems are being vastly used in various applications such as oceanography, topography, and self-driving cars that create the demand for simultaneous ranging and velocimetry [1]. The most conventional method for ranging via a Lidar is the pulse time-of-flight (PToF) technique that inherently lacks the capability of performing velocimetry without applying any form of complex post processing. On the other hand, amplitude (AMCW), and frequency modulated continuous wave (FMCW) Lidars can acquire the speed information while performing ranging by utilizing the Doppler frequency shifts [2,3]. However, these methods rely on frequency, amplitude or phase sweeping to compute the distance of a desired target. To eliminate the necessity of any type of sweeping to achieve ranging, a new technique is developed with a single CW laser modulated by multiple RF tones, namely multi-tone continuous wave (MTCW) Lidar. MTCW ranging is previously analyzed and tested with stationary targets [4,5], however the technique has not been evaluated with a moving target. In this work, we demonstrate the simultaneous ranging and velocimetry capability of the MTCW Lidar via analytical models and experimental results. The experiments yield the target's range with >80% reliability, while the target is moving with a speed of 8cm/s.

2. Working Principle

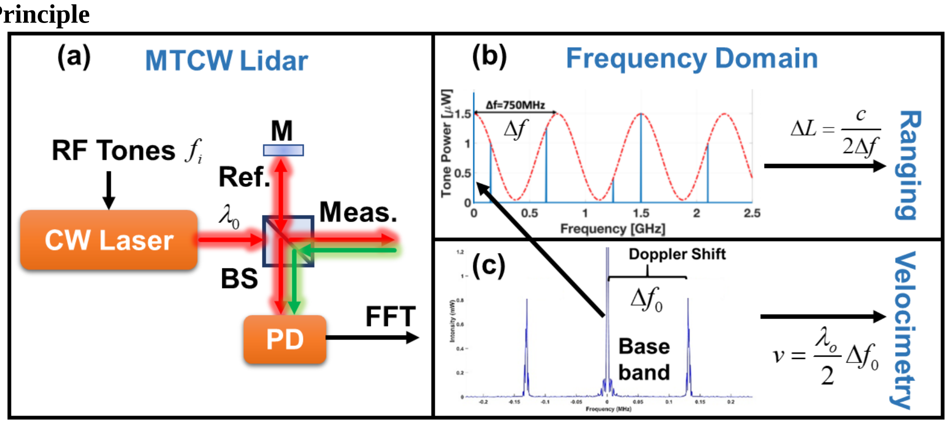

Fig. 1 (a) MTCW Lidar configuration, (b) ranging and (c) velocimetry data extraction in frequency domain.

In MTCW Lidar configuration, a CW laser is modulated by multiple fixed RF tones via a Mach-Zehnder modulator (MZM), as illustrated in Fig.1(a). The modulated CW light is then split into two through a beam splitter (BS) and one arm is kept as the local oscillator to realize interferometric coherent detection. The convolution of the measurement arm with the local oscillator converts the phase accumulation due to path differences into amplitude variations over each preselected RF tone. For ranging, the frequency of the sinusoidal fitting to the acquired RF tone powers will yield the path difference of two arms as $\Delta L = c/2\Delta f$, which is shown in Fig.1(b). By considering the phase difference $\Delta\phi$ as $\Delta\phi = (4\pi/c)\Delta L f_i$, and computing the frequency difference of the two consecutive peaks of the fit as $(4\pi/c)\Delta L(f_2 - f_1) = 2\pi$, it is possible to relate the measurement length with the frequency of sine fitting, where ΔL is the path difference between two arms, c is the speed of light, Δf is the frequency of the fit, and f_i is the i^{th} modulation tone frequency.

The velocimetry is performed by employing the photonic Doppler velocimetry (PDV) approach, where the measurement arm realizes a Doppler shift due to the speed of the target as $v = \lambda_0 \Delta f_0 / 2$, where v is the speed of the target, λ_o is the optical carrier wavelength and Δf_o is the Doppler shift at the central frequency as shown in Fig.1(c). By introducing these Doppler shifts to the measurement arm, it is possible to formalize the photocurrent generated by a P-I-N photodiode, I_{PD}, after interference as in Eq.(1), where $I_{PD,ave}$ is the average photocurrent due to sum of all self-beating components, A_o is the amplitude of the electric field, R is the responsivity of the detector, $\alpha_{ref,meas}$ are the attenuation coefficients, m is the modulation depth and $L_{meas,ref}$ are the distances travelled by the light in each arm.

$$
\begin{aligned}
I_{PD} = I_{PD,ave} &+ \frac{1}{4} R A_0^2 \alpha_{ref}\alpha_{meas}\cos(\Delta f_0 t + \Delta f_0 \frac{L_{meas}}{c}) - \frac{1}{4} R m A_0^2 \sum_{i=1}^{N} \\
&\left\{
\begin{array}{l}
\alpha_{ref}^2 \cos\left(2\pi f_i t + 4\pi f_i \frac{L_{ref}}{c}\right) + \alpha_{meas}^2 \cos\left(2\pi f_i t + 4\pi f_i \frac{L_{meas}}{c}\right) \\
+\frac{1}{2}\alpha_{ref}\alpha_{meas}\left(\cos\left[\left(2\pi f_i + \Delta f_0\right)t + 4\pi f_i \frac{L_{ref}}{c} + \Delta f_0 \frac{L_{meas}}{c}\right] + \cos\left[\left(2\pi f_i - \Delta f_0\right)t + 4\pi f_i \frac{L_{ref}}{c} - \Delta f_0 \frac{L_{meas}}{c}\right]\right) \\
+\frac{1}{2}\alpha_{ref}\alpha_{meas}\left(\cos\left[\left(2\pi f_i + \Delta f_0\right)t + \left(4\pi f_i + \Delta f_0\right)\frac{L_{meas}}{c}\right] + \cos\left[\left(2\pi f_i - \Delta f_0\right)t + \left(4\pi f_i - \Delta f_0\right)\frac{L_{meas}}{c}\right]\right) \\
-\frac{1}{4} m \alpha_{ref}\alpha_{meas}\left(\cos\left[\Delta f_0 t + 2\pi f_i \frac{2\Delta L}{c} + \Delta f_0 \frac{L_{meas}}{c}\right] + \cos\left[\Delta f_0 t - 2\pi f_i \frac{2\Delta L}{c} + \Delta f_0 \frac{L_{meas}}{c}\right]\right)
\end{array}
\right\}
\end{aligned} \quad (1)
$$

3. Experimental Results

A testbench is built by placing a target mirror on a motorized translational stage that is facing the MTCW Lidar. 6 carefully selected RF tones modulate the CW laser, and the experiment is performed while the target is moving with a constant speed. Fig.6(a) illustrates the results of 15 different distance measurements while the target is passing over a predetermined location over the stage that is ~109cm away from the Lidar. The acquired range deviations are <±2cm due to the fitting mismatches and the altering position of the target. Fig.6(b) shows the R-squared (R^2), a statistical fitting measure, of each sine fit that indicates the reliability and stability of the results with a lowest value of 0.88. The amplitude variations caused by the Doppler shifts over the measured RF tones have lower impacts, since the possible distortions didn't alter the goodness of the fits. Moreover, Fig.6(c) represents the measured speed of the target at the corresponding distance with the PDV methodology. The measured speed is ~8cm/s with an accuracy of ±0.8cm/s, which depends on the frequency resolution based on the time window and the sampling rate.

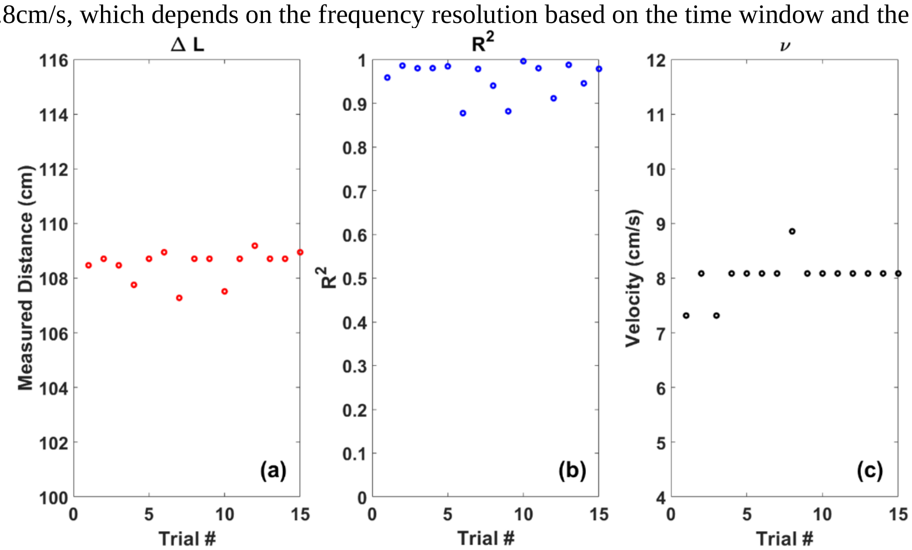

Fig. 2 Simultaneous ranging and velocimetry results for 15 trials while the target is moving with $v = 8$ cm/s. (a) Ranging, (b) corresponding R^2 of the sine fitting, and (c) the measured velocity at the corresponding instance.

4. Conclusion

In this work, the theoretical model of the simultaneous ranging and velocimetry of the MTCW Lidar is developed. The system is demonstrated in the experimental domain with a moving target. The ranging exhibits >80% stability, while the target is in motion with a measured speed of 8.0cm/s with ±0.8cm/s velocity resolution.

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5. References

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