3D Coherent Lidar Imaging Without Coherence Length Limitation

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ABSTRACT

This paper introduces a transformative approach to 3D lidar imaging through the Multi-Tone Continuous Wave (MTCW) coherent lidar system. Addressing coherence length constraints in coherent continuous wave (CW) lidar systems. We present a method utilizing static RF modulation frequencies to achieve 3D imaging. Our system demonstrates the capability to measure distances up to 11km, surpassing the 950m coherence length of the laser. This approach has far-reaching implications for applications requiring extended ranging capabilities, marking a significant evolution in coherent lidar technology. The study concludes by highlighting the potential impact on various fields, including autonomous navigation and remote sensing, thereby paving the way for enhanced spatial awareness in diverse applications.

Keywords: Lidar, Coherent Lidar, Remote Sensing, 3D Imaging, Continuous Wave Lidar, Spatial Awareness

1. INTRODUCTION

To meet the needs of diverse applications, the search for new approaches in light detection and ranging has been a growing area of interest [1]. Implementation of coherent CW lidar systems in this regard for ranging, velocimetry, and imaging has produced successful results [2]. The majority of coherent CW lidars work by combining a local oscillator with the phase-shifted echo signal to determine the target's range by sweeping the frequency or phase of a light source. Their inherent sensitivity as a result of coherent detection makes them ideal candidates for applications with low levels of expected optical power such as space-based or ultra-long-distance applications. However, overcoming fundamentals limitations such as frequency and phase sweeping requirements and finite laser coherence length, necessitate new approaches [3,4].

In this paper, we present the imaging capabilities of the Phase Based Multi-Tone Continuous Wave (PB-MTCW) coherent lidar, without coherence length limitations, and the need for any form of phase or frequency sweeping. By utilizing static RF modulation frequencies for amplitude modulation through an electro-optic modulator, MTCW coherent lidar generates the target distance by self-referencing the phase and frequency differences between each modulation tone. The impact of coherence length requirements that necessitate the use of ultra-narrow linewidth requirements for long-distance CW lidars are mitigated by the novel algorithm that mixes the RF sidebands, removing the impact of laser phase noise or other sources of common noise [5–8] that leads to decoherence and range limitations or range ambiguity. We demonstrate that the MTCW method can accurately produce 3D images of targets at a distance ranging from 50m to 11km (limited by the equipment) regardless of the laser coherence length of 950m with a distance resolution of ~2cm and <10pW received optical power levels.

2. METHODOLOGY

Figure 1 below shows the dual aperture lidar system configuration. First, a 50/50 fiber coupler splits the 1550nm CW laser into two arms. A Mach-Zehnder modulator (MZM) is placed on one arm, while the unmodulated arm remains as the local oscillator. The MZM receives a total number of N RF modulation frequencies with a distinct frequency of ω_i, phase-locked to a common clock. To achieve long-distance transmission, the modulated light is sent through a 7608m long fiber, corresponding to an equivalent 11.4km free space propagation distance. Finally, at the output of the fiber spool, the light is amplified through an EDFA to achieve a transmission power of 200 mW and coupled into free space by the transmitter (Tx) collimator. Then, the echo signal returning from the target surface is collected by the receiver (Rx) collimator. Finally, both local oscillator and Rx signals are combined using a 50/50 fiber coupler before the balanced photodetector. During short-distance measurements, the fiber spool is removed from the system while the rest is left unchanged. After coupling into fiber by the Rx collimator, the return power is measured as sub nW.

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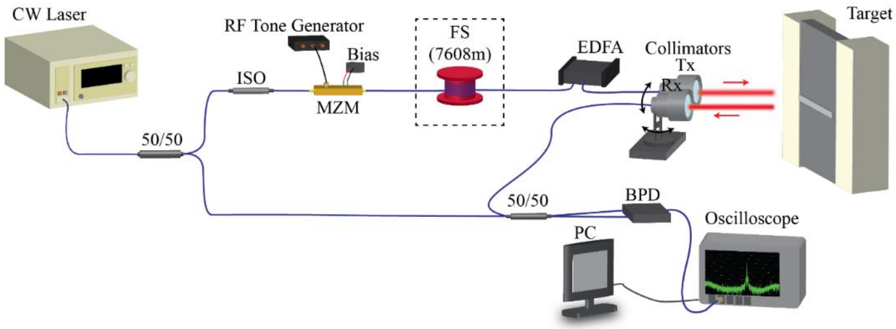

Figure 1. Schematic of PB-MTCW lidar system.

Waveform extraction of a single RF tone is achieved through bandpass filtering near the tone frequencies during post-processing. Subsequently, each of the filtered tones are digitally mixed with a copy of the signal. The cross-beating components convey the phase and frequency information of the echo signal; the self-beating terms will fade due to substantial scattering losses. Amplitude fluctuations over RF tones will be observed because of the laser phase noise, optical carrier phase, and frequency-synthesizer phase noise. Our previously demonstrated approach generates noise-free intermediate frequencies through RF mixing the i^{th} and j^{th} modulation tones $(i \neq j)$ which can be formulated as $A_iA_j\left(cos\Delta\omega_{i,j} \mp \Delta\phi_{i,j}\right)$, where terms $\Delta\phi_{i,j}$ and $\Delta\omega_{i,j}$ represent the phase and frequency of the tones. Then using $L_m = \left(2\pi n + \Delta\phi_{i,j}\right)c/\Delta\omega_{i,j}$ the target distance information can be extracted. Finally, using the relative phase changes obtained from multiple tones a triangulation operation is performed for the exact L_m value [6,7]. After measurements, the recorded range data is matched with pixel locations in an n by m matrix revealing target dimensions in Cartesian coordinates. Then, through coordinate system conversion, pixel locations and the ranging data is obtained as $R = (r, \theta, \phi)$. Once the new coordinate system is constructed, our processing algorithm generates the raw 3D point cloud images. Lastly, to enhance the visual appearance, a series of low pass filters are applied without any effect on measurement results.

3. RESULTS

A prototype based on the schematic shown in Figure 1 is built using a laser operating at 1550nm with 100kHz linewidth that is equivalent to 950m coherence length. Four RF modulation tones are used during experiments to extract distance information of two different targets that have been scanned at distances below 50m and beyond 10km.

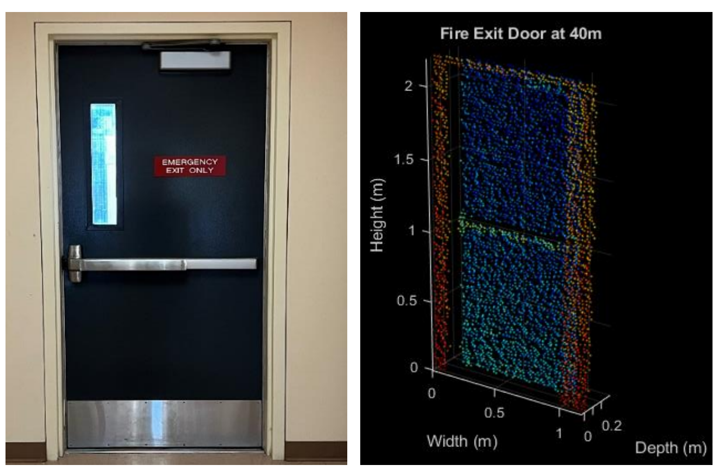

Figure 2. (a) Fire exit door and door frame at 40m distance as the target. (b) 3D Point cloud image of the fire exit door at 40m.

As the first target, a fire exit door located at the end of a hallway was scanned by placing the lidar system 40m away from it. Measurements were performed by recording single shot data at every 2.54cm along a 116cmx218cm target area, resulting in ~4000 pixels in total. Figure 2(a) shows the actual target and the 3D point cloud image was shown as shown in Figure 2(b). The target depth including the closest and the furthermost surfaces was measured as ~25cm. The received optical power as an echo from target surfaces was also measured to be <10pW. Imaging results show different surfaces with thickness values ranging from 2.5cm to 10cm on the target such as the handle and the stopper were resolved at their respective positions, revealing a resolution <3cm from 40m free space distance. In addition, the ranging precision analysis for this scan scenario was determined to be σ = ~1.94cm after standard deviation calculation along target surfaces.

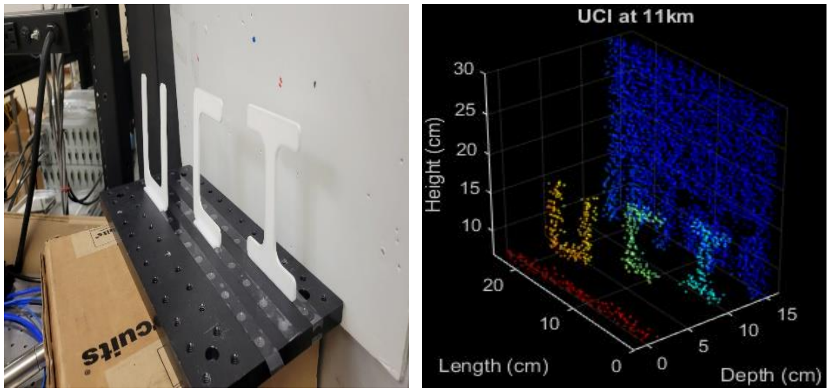

Figure 3. (a) Fire exit door and door frame at 40m distance as the target. (b) 3D Point cloud image of the fire exit door at 40m.

Second, 3D printed U, C, and I letters were placed 3m away from the lidar apertures were scanned with the letter I 5cm further than the background while letters C and U were placed ~2.5 cm further with respect to the previous letter finally having U at exactly 3m away (free-space) from the lidar aperture with the addition of a 7608km fiber spool to the system, resulting in ~11.4 km light propagation equivalent in free space. Measurements were performed by recording single shot data at each 0.5 cm along a 30x30cm target area resulting in 3600 pixels in total. The total target depth was set to be ~15cm. The received optical power from target surfaces was measured to be again <10pW. Figure 3(a) shows the actual target and Figure 3(b) shows the generated 3D point cloud image with an imaging resolution of <3cm at ~11.4km which is approximately 12 times the laser coherence length as proposed. Finally, the accuracy was determined as σ = ~1.25cm by calculating the standard deviation of the data points along each target surfaces. The presented results were scaled to have the closest target surfaces relative to the lidar system as the zero point in ranging to indicate target features and imaging resolution of ~2.5cm. The average <2cm ranging error manifested itself as the noise in images.

4. CONCLUSION

Overall, we demonstrate the multi-point ranging results of MTCW coherent lidar point cloud images of targets at distances <50m and >12x larger than the coherence length of the laser without using any sort of phase, frequency, or amplitude sweeping. Results from different target configurations and further analysis will be presented in detail.

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