Coherent LiDAR Prototype Based on 2D MEMS Mirror Scanning

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Abstract: We present a new coherent LiDAR prototype with two-dimensional micro-electro-mechanical-system scanning and walk-off mitigation capability. We address the linearization challenge of the FMCW transmitter, the scan-capture-synchronization and provide point-clouds of two distinct objects.

1. Introduction

LiDAR (Light Detection and Ranging) is a sensor technology commonly used in remote sensing, and the advancement of advanced driver assistance systems (ADAS). Most applications require LiDAR to be eye-safe, have long range, ideally fit into a small form factor, while being resource-efficient and cost-effective. Especially coherent LiDAR concepts have gained momentum because of their long reach and built-in mitigation of interference. One coherent technology that prevailed is frequency modulated continuous wave (FMCW) [1] [2]. It is based on a triangular frequency-modulated optical carrier, where the linearity of this modulation relates directly to the range and accuracy of the sensor. A description of the FMCW method we use can be found in [3].

Previous demonstrations of FMCW ranging show various system concepts. For example, the generation of the frequency modulation is either realized by external modulation [4] or direct modulation of a laser. For the latter case, which is used here, additional current predistortion is necessary to obtain a linear frequency modulation. Also, different mechanisms for scanning were proposed. The combination of beam steering and coherent LiDAR proves to be especially challenging due to the walk-off effect. This effect describes the problem of capturing the returning light with the optical aperture due to the continuous motion of the mirrors [5]. To our best knowledge, we show the first prototype of a fiber-based directly modulated FMCW LiDAR with two-dimensional quasi-static micro-electro-mechanical-system (MEMS) mirror scanning with reduced walk-off, which is potentially a low-cost, lightweight, long-range LiDAR solution.

2. Setup

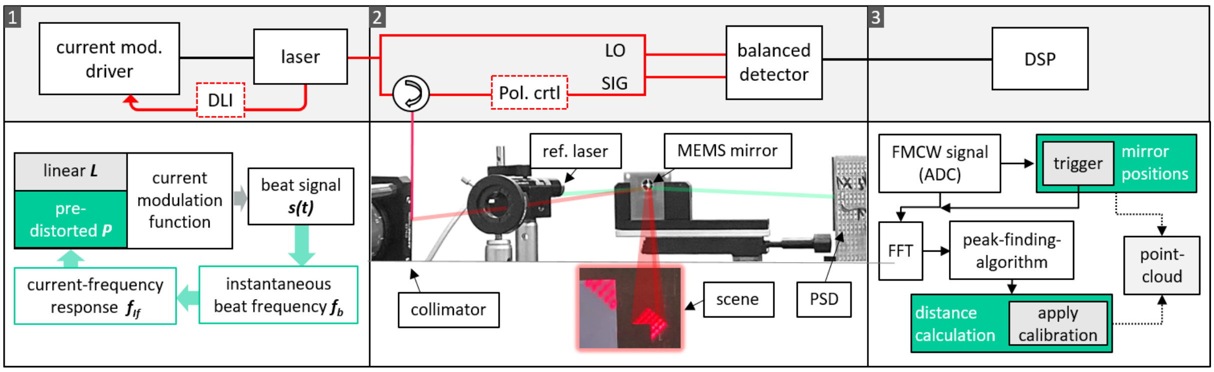

Fig. 1. Coherent LiDAR prototype with 2D MEMS mirror scanning, divided into three blocks: (1) linearization of the transmitter, (2) scanning of the scene and (3) scan-capture synchronization.

Our prototype operates at 1550 nm which allows higher eye-safe power (here around 10 dB m) compared to wavelengths around 900 nm [6]. It also allows the use of standard telecom components for the transmitter and receiver, as well as fiber-based optics for the sensor head. The theoretical axial resolution of our prototype is

$\Delta R = 15\,\text{cm}$ with a precision limit of $\sigma_R = 6\,\text{cm}$ [7]. A range of 60 m was confirmed experimentally with a signal-to-noise ratio (SNR) of around 20 dB. Fig. 1 shows the building blocks of our prototype:

1. The transmitters frequency modulation has a bandwidth of $f_B = 1\,\text{GHz}$ over a period of $T = 16\,\mu\text{s}$. The modulation is linearized by an auxiliary delay line interferometer (DLI), similar to the method in [8] [9]. However, we use an offline script to find a fully analytical (polynomial) description of the current modulation function that linearizes the frequency modulation, which is the predistortion P. The calculation starts at the beat signal $s(t)$ of the DLI, where we use a Hilbert Transform to obtain the instantaneous beat frequency $f_b(t)$, then fit this beat frequency curve with a polynomial function and integrate to get the current-frequency response $f_{If}(t)$ of the laser. In the last step, the difference of the desired linear modulation to the obtained $f_{If}(t)$ results in the predistortion P.

2. Scanning is realized as a monostatic setup based on our 2D quasi-static MEMS mirror [10] [11] (diameter: 2 mm) providing directional illumination of the scene and simultaneously capturing the return signal, which gets recombined with the local oscillator before reaching the balanced photodetector. In contrast to customary resonant MEMS mirrors, which scan the scene continuously, our MEMS mirror scans the field-of-view (FOV) in two dimensions in a quasi-static manner. This means the mirror is able to hold positions along a predefined path, avoiding the problematic walk-off effect of scanning LiDARs. The motion of the mirror is monitored simultaneously with a green laser and a position sensitive detector (PSD).

3. The construction of the point-cloud is done offline in post-processing with our scan-capture synchronization method: We create a software trigger of the event where the mirror reached its hold position based on the PSD signal and induce the capturing and fast-fourier-transforming (FFT) of the FMCW beat signal consequently. Then, a peak-finding-algorithm determines the distance d of the scanner to the object while subtracting the calibration length. This method maps the scanning angles to the distances of the object and hence creates the point-cloud.

3. Results

In this section we show the point-clouds obtained by scanning a corner edge of paper in front of a screen, as highlighted in Fig. 1 and described in section 2. The distances obtained by our LiDAR prototype d are compared to the actual distance D of the object with the use of the root-mean-square-error $RMSE$.

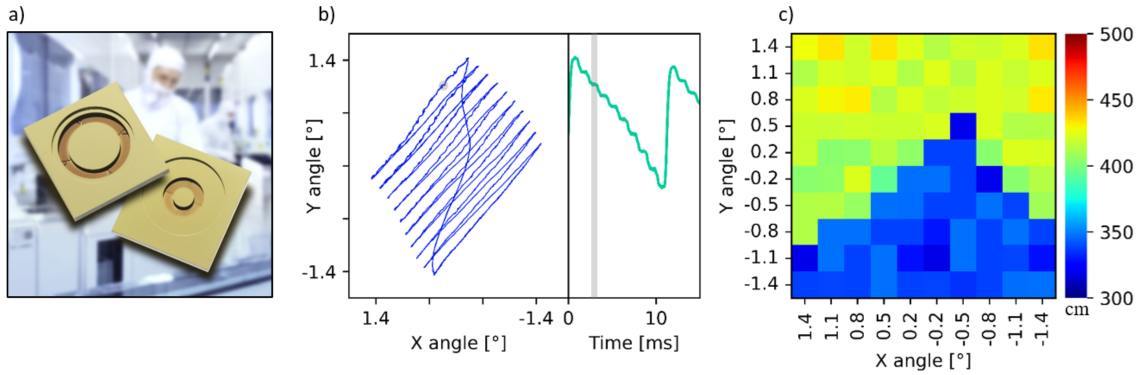

Fig. 2. a) Illustration of our quasi-static MEMS [3] [10] b) Trace of mirror movement in X and Y direction (PSD signal) and section of Y-PSD signal with one hold position marked grey c) Point-cloud shows the corner edge of a paper in front of a screen, scanned with a speed of $t_{ptp} = 1\,\text{ms}$.

The predefined scanning path of our test included 10 by 10 hold and scan positions within a FOV of around 2.8°. The extent of the total scan angle is owed to the peak voltage of the driving signal, which was set to 40 V for this measurement. A FOV up to 10° could be achieved with higher voltage [10]. The point-to-point scanning speed, e.g., the time between two consecutive hold positions, t_{ptp} was chosen as 1 ms, although the mirrors theoretical limit is in the region of several hundred µs [3]. Fig. 2 c) shows the point-cloud visualized as a heat map. The corner edge ($D_c \approx 335\,\text{cm}$) is clearly visible in front of the screen ($D_s \approx 415\,\text{cm}$). The average obtained distance for the corner is $d_c = 338.7\,\text{cm}$ and for the screen it is $d_s = 417.8\,\text{cm}$, resulting in an $RMSE = 8.9\,\text{cm}$.

3.1. Effect of Predistortion

Fig. 3 a) shows how the predistortion affects the FMCW spectrum measured in the DLI with a reference beat frequency of $f_{ref} = 2.1\,\text{MHz}$. The predistortion reduced the full-width-half-max (FMWH) linewidth from 160 kHz to 50 kHz. The inset also shows that the temporal variation of the beat frequency $f_b(t)$ is reduced and approaches f_{ref} (marked as a dashed line). We repeated a scan of the corner edge with non-predistorted and predistorted current modulation. Here, the FOV was increased to 4.5° by adjusting the mirrors driving signal peak voltage to 60 V and the objects were placed closer to the scanner ($D_c \approx 160$ cm, $D_s \approx 210$ cm). Fig. 3 b) and c) show the effect of the predistortion in regards to the point-cloud output. The first observation is the reduction of inconclusive measurements due to the predistortion. Furthermore, in the non-predistorted case, the average obtained distance for the corner and screen is $d_c = 232$ cm and $d_s = 293$ cm with an $RMSE = 80.9$ cm. The accuracy is improved for the predistorted case, which is $d_c = 161$ cm for the corner and $d_s = 207$ cm for the screen, resulting in an $RMSE = 7.6$ cm. This 10 fold reduction of the range error ($RMSE$) can directly be linked to the applied predistortion and allows a significantly greater precision of our LiDAR prototype.

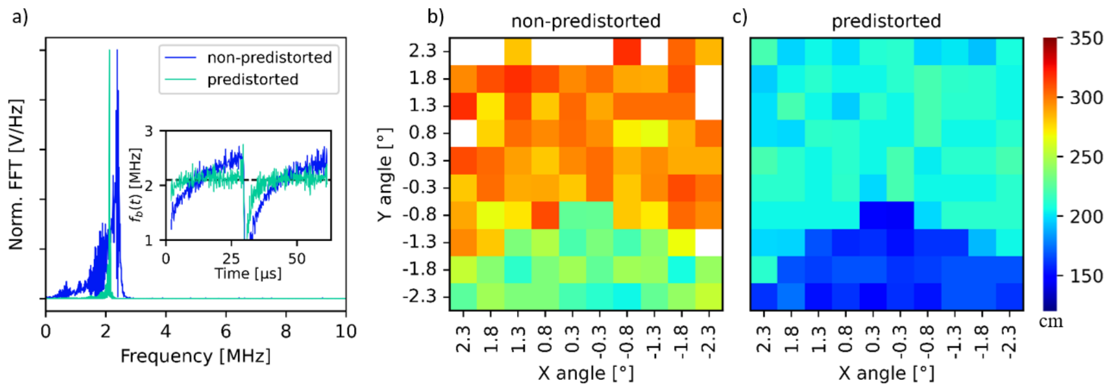

Fig. 3. Comparison of predistorted and non-predistorted results. a) DLI beat frequency spectrum, inset: temporal variation of instantaneous beat frequency over the duration of $2T$. b)-c) Point-cloud with linear b) and predistorted c) current modulation. Corner edge of a paper in front of a screen scanned with a scanning speed of $t_{ptp} = 1.6$ ms. Inconclusive measurements shown in white.

4. Discussion and Outlook

We show our system concept of a new coherent (FMCW) LiDAR prototype with 2D MEMS mirror scanning. Therefore, we utilize a newly developed quasi-static MEMS mirror to mitigate the walk-off effect and show point-clouds generated from a 10 by 10 point scan with a scanning speed of 1 ms. We show that our predistortion method reduced the range error 10 fold, which highlights its importance for the LiDAR prototypes accuracy. Future work entails the increase of scanning speed along with real-time implementation on FPGA and demonstrating point-clouds at longer ranges and increased FOVs.

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