Range Resolution Improvement in FMCW Radar Through VCO's Nonlinearity Compensation

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***Abstract*—In order to achieve good range resolution and accuracy on frequency-modulated continuous-wave (FMCW) radars, highly linear chirps are necessary. Voltage-controlled oscillators (VCOs) present nonlinearities in their tuning curve. Then, once VCOs are a fundamental building block in many continuous-wave radar systems, these nonlinearities translate into negative effects in terms of range resolution performance. A common approach to generating linear tuning curves is to connect the system VCO to a phase-locked loop (PLL). Although, PLLs increase the system complexity and cost. This work presents a way to improve the range resolution in a portable and low-cost C-band FMCW radar system. The radar VCO is driven by a microcontroller that applies a customized waveform developed to compensate for the nonlinear behavior to achieve such results.**

***Index Terms*—frequency-modulated continuous-wave (FMCW) radar, nonlinearity compensation, range resolution improvement, voltage-controlled oscillator (VCO).**

I. Introduction

Frequency-modulated continuous-wave (FMCW) radars have the advantage of accurate range measurements while maintaining characteristics common to other continuous-wave (CW) radars like high sensitivity, simple structure, and low transmitted power. Also, compared to camera-based sensors, microwave radars provide better glass detection capabilities and do not rely on light [1].

Previous work presented a portable FMCW radar system for short-range localization and vital sign tracking [1]. Another work shown improvements in range measurements accuracy and detectability of FMCW radars through transmitter output frequency linearization [5].

In this work, portability and low-cost were achieved by implementing building blocks based on simpler components and a microcontroller. Besides it, sensors based on radar systems are in increasing demand due to their usage in the automotive industry, which has been promoting radar systems implementations costing significantly less [4].

Besides the advantages, previous works have shown performance degradation introduced by nonlinearities from the system components themselves or from an external control system on FMCW radars [1] - [4]. The range accuracy may be achieved if the system has a high signal-to-noise ratio (SNR), low phase noise, and high-frequency ramp linearity [2]. Also, to achieve a good range resolution, good frequency sweep linearity is required. So, systems with RF sources affected by nonlinearities in the tuning frequency curve must be compensated to obtain high-performance results implementing FMCW radars [3]. Moreover, systems based on free-running voltage-controlled oscillators (VCOs) typically present a progressive decrease in the frequency output slope in response to the same stimuli as long as the stimuli progressively increase [4]. This nonlinearity effect degrades FMCW systems the most as the target range increases, which was previously demonstrated through simulations [1]. Phase-locked loops (PLLs) may be implemented to successfully produce a linear chirp. Even though, PLL implementations have drawbacks like increased cost and complexity when compared to free-running VCO implementations [1].

In this work, an FMCW radar system VCO is characterized, has its behavior modeled by a fourth-order polynomial, and then is submitted to measurements while fed by a microcontroller containing a waveform developed to compensate for the nonlinearities. These measurements are expected to obtain range resolution improvement when compared to the same system fed by a standard sawtooth waveform. In section II, the basic theory regarding FMCW range detection and range resolution is presented, the FMCW range detection degrading is demonstrated in simulation, the VCO characteristic tuning curve modeling is given, and also the process to obtain a waveform capable of compensating for the nonlinearities is shown. In section III, the measurements taken implementing the proposed system are exhibited, showing the results of a compensated and of an uncompensated waveform. Finally, in section IV, the results obtained are summarized in a conclusion.

II. Theory

A. FMCW Range Detection

The range detection may be obtained in FMCW radar systems transmitting a linear FM signal, called chirp, and comparing the transmitted signal with the received signal, which can be modeled as a delayed version of the transmitted signal. Applying both transmitted and received signals to a mixer, the instantaneous frequency difference between the two signals can be obtained. This difference is proportional to the range of the target that reflected the transmitted signal. The Fig. 1 illustrates this process.

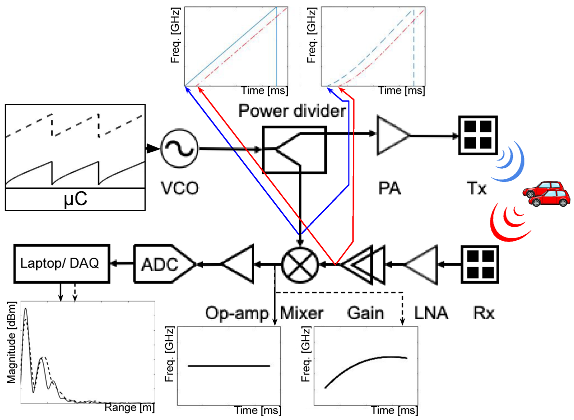

Fig. 1. Graphical representation of the range detection in a generic FMCW radar system driven by a nonlinear VCO.

B. Range Resolution

The range resolution is the minimum range difference in which a radar system can detect and distinguish between two targets. An equation that describes the range resolution in the ideal case is shown in (1), where c is the speed of light and BW is the bandwidth [3].

$$\Delta R = \frac{c}{2BW} \tag{1}$$

Even though, in real systems, the actual range resolution depends on other factors such as the transit time and losses in the data processing. These factors introduce a reduction in the effective processed bandwidth. Therefore, a degradation when compared with the ideal case may be observed.

C. VCO Tuning Curve Compensation

In order to synthesize the chirp, a VCO may be implemented. Ideally, if a linear ramp is applied to the tuning voltage terminal of the VCO, its output is a sinusoidal signal with its instantaneous frequency changing proportionally to the applied voltage. Unfortunately, practical VCOs present nonlinearities that may distort the output signal expected behavior.

In this work, a compensation method was implemented to produce a more linear chirp. The method consists of, in the first moment, characterizing or obtaining the VCO tuning curve. Then a polynomial curve fitting is applied, where the lowest order polynomial that models the VCO properly is chosen. Finally, the voltages that must be applied to provide a linear output may be found by looking for which set of voltage values the desired set of frequency values in a progressive sequence are obtained. The Fig. 2 shows the tuning curve polynomial obtained characterizing the radar VCO. The measured values were taken by applying a controlled voltage source output to the VCO input and measuring the output frequency with a spectrum analyzer.

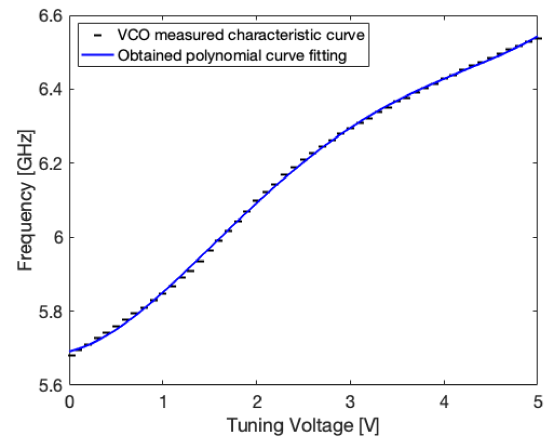

Fig. 2. Tuning curve of the characterized VCO and its obtained polynomial fitted curve.

A mathematical representation of the obtained polynomial is given in (2), where V_{ctrl} is the control voltage applied to the VCO input and f is the VCO output frequency. A set of control voltages corresponding to a set of desired frequencies may be obtained by substituting this set of frequencies in (2). For each element in this set of polynomials, the roots will correspond to tuning voltage values that translate into the desired frequencies.

$$\begin{aligned} f(V_{ctrl}) = 0.003592V_{ctrl}^4 - 0.004142V_{ctrl}^3 \\ + 0.1399V_{ctrl}^2 + 0.05745V_{ctrl} + 5.691 \end{aligned} \tag{2}$$

D. Range Detection Under Nonlinearities

In order to verify the nonlinearities effects concerning the range detection, a simulation was implemented. In this simulation, an ideal chirp and a waveform consisting of a sinusoidal signal with its frequency modulated by the polynomial exhibited in (2) were applied to a target located 1.5 m apart from the radar. In both cases, the initial and the final frequencies were the same. The range map for both cases, the chirps' instantaneous frequencies, and baseband samples are shown in Fig. 3.

Comparing the cases depicted in Fig. 3(a), there is a slight increase in terms of amplitude in the ideal case. Although, the most expressible result is the sharpening of the peak located at the target range. This result indicates that a compensated waveform with instantaneous frequency closer to an ideal ramp may provide increased range resolution, once two targets located at slightly different ranges can be resolved in two separated peaks at shorter distances. Thus, making multiple targets detection achievable at shorter distances.

III. Measurements

The 5.8 GHz radar printed circuit board (PCB) was mounted on a tripod and supplied by a portable USB charger. Due to the antennas' limitations, its operating range is constrained between 5.7 GHz and 6.1 GHz. The radar system VCO was

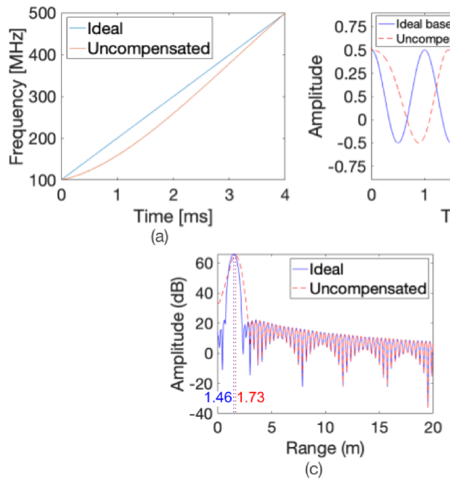

Fig. 3. (a) Transmitted chirps' instantaneous frequency. (b) Time-domain baseband signals. (c) Range map simulation comparing ideal and uncompensated chirps with a target placed 1.5 m distant.

fed by a Texas Instruments MSP430FR2355 microcontroller mounted on the same tripod. The microcontroller has a 12-bit digital-to-analog converter (DAC) and was programmed to provide output a conventional sawtooth waveform with 2 V amplitude at 250 Hz on its analog. Also, when a switch button is pressed, the microcontroller provides a waveform developed to compensate for the VCO's nonlinearities, constrained in the same amplitude and frequency values as the sawtooth waveform. Taking Fig. 2 as a reference, the 2 V amplitude is converted into 400 MHz bandwidth starting around 5.7 GHz and ending around 6.1 GHz, ideally providing a 0.375 m of range resolution. Fig. 4 shows the experiments' setup. One corner reflector was placed 1.1 m apart from the radar antennas, and a second corner reflector was placed 1.6 m distant from the same antennas.

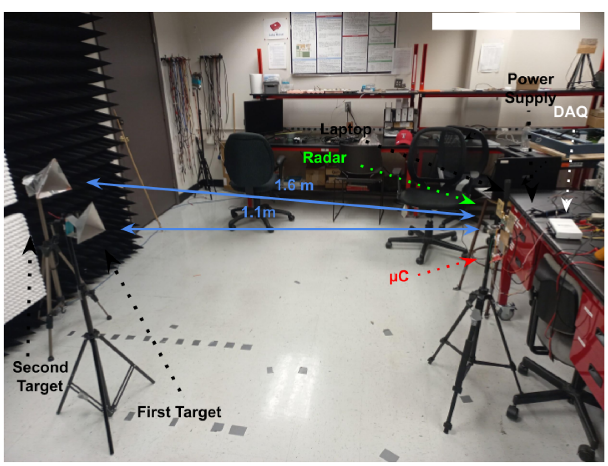

Fig. 4. Range resolution evaluation experiments' setup

To validate the range resolution improvement hypothesis, both waveforms were applied to the radar system with targets in the same conditions. After the measurements applying both waveforms, the separation between the targets was increased, moving the second target away from the radar. Starting with the first target at 1.1 m and the second target at 1.6 m, the second target was displaced at 0.1 m steps away from the radar antennas. Then, 10 s samplings of the baseband signals from the radar were recorded and processed. The results are shown in Fig. 5, where the plots in the top represent the results taken from compensated chirp, and the plots in the bottom represent the results taken from the conventional sawtooth.

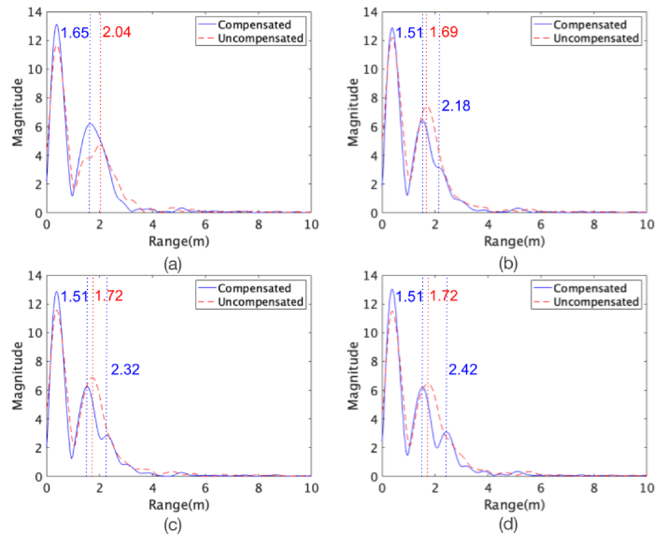

Fig. 5. Range maps with the first target placed 1.1 m away from the antennas and the second target placed at (a) 1.6 m. (b) 1.7 m. (c) 1.8 m. (d) 1.9 m.

IV. Conclusion

A 5.8 GHz radar VCO was characterized, and it had its behavior modeled by a fourth-order polynomial. From this polynomial, a set of values were extracted to perform compensation in the VCO's nonlinearities. Also, the degrading effects of nonlinearities were verified by simulation. Finally, based on the results in Fig. 5, the implemented technique improved the range resolution through a low-cost and portable system. These results show that the threshold value for which two targets can be detected happened at a smaller separation when the customized waveform was applied.

Acknowledgment

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