Design and Implementation of FMCW Radar Using the Raspberry Pi Single Board Computer

Husain Ali[1], and Ergun Erçelebi[1]

[1]Gaziantep University, Gaziantep, Turkey
eng.husain.ali@gmail.com, ercelebi@gantep.edu.tr

Abstract

Frequency Modulated Continuous Wave (FMCW) radar measures the target's range and velocity by emitting a continuous wave, frequency modulated by a sawtooth or triangular function. With this technology, many advantages can be achieved compared to that of the pulse radar. This paper presents a complete design and implementation of a 6 GHz FMCW radar system using the Raspberry Pi single board computer as a signal processing platform. The proposed system consists of 6 GHz RF front-end architecture with analog to digital interface. To improve the linearity of generated FM chirps, a closed loop fractional-N frequency synthesizer is used along with VCO. The baseband signal is applied to a high pass filter to equalize signal before digital interface stage. Target measures like range and velocity will be extracted at the signal processing stage which implemented on Raspberry Pi single board computer.

1. Introduction

FMCW radar was originally developed for radar altimeters for aircraft in the mid 1930's. Today, FMCW is useful in applications where wide-band high resolution time-of-flight measurements must be made with low-power transmitters. Applications include automotive radar, short-range imaging, and many others [3]. FMCW radar have many advantages compared to the pulse radar such as: reducing the transmitted power, ability to measure target range and its relative velocity simultaneously, and ability to perform signal processing after mixing at a low frequency range, which considerably simplifying the processing circuits [2].

FMCW radars can measure the target's velocity and range. This type of radars sends out continuous microwave signal, frequency modulated with low frequency waveform, e.g. a sawtooth shape. The distance information of the target can be obtained through spectrum analysis by identifying a target (or beat) signal.

This paper introduces a practical design and implementation of FMCW radar system based on the Raspberry Pi single board computer.

2. FMCW Radar Structure

The block diagram on Fig. 1 shows the structure of a typical FMCW radar system. It consists of a RF transceiver, an intermediate frequency (IF) module, a modulating signal generator and a digital signal processor.

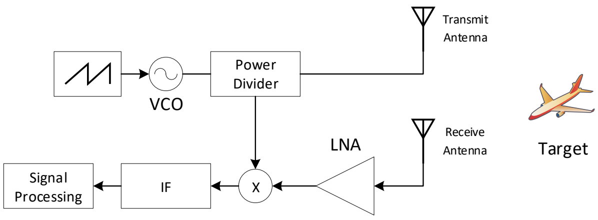

Fig. 1. Typical FMCW Radar block diagram

Voltage-controlled oscillator (VCO) is the key component of the FMCW radar, it acts as the source of microwave signal. The frequency modulated signal can be generated by applying a sawtooth signal to the tuning input of VCO. This signal is amplified and transmitted with the antenna, it reflects from the target to a receive antenna.

Target's rage can be resolved by calculating the frequency difference between the received signal and the transmitted signal, which increases with delay, and the delay is linearly proportional to the range.

This process can be performed by mixing the echo with a copy of transmitted signal to produce a beat signal which is linearly proportional to the target range after demodulation.

In sawtooth form, high speed ramp waveform with increasing slope and bandwidth makes Doppler frequency negligible, thus, sawtooth chirp modulation can only measure the target's range but not its velocity. Fig. 2 shows the transmitted and received ramp signals [4].

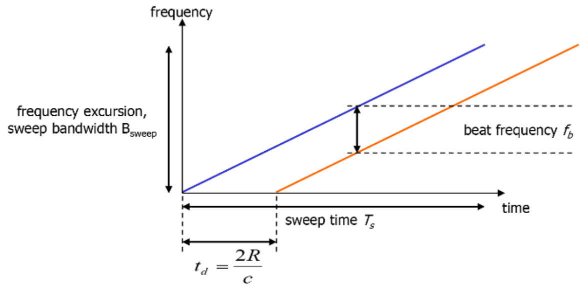

Fig. 2. Sawtooth modulated chirp

The delay between transmitted and received signals is given by [4]:

$$t_d = \frac{2R}{C} \quad (1)$$

Where R is the target range and c is the free-space speed of light. The beat frequency is given by [4]:

$$fb = \frac{B_{sweep}}{T_s}\, t_d \tag{2}$$

Where B_{sweep} is the total frequency deviation of the chirp signal, and T_s is the sweep time or chirp period. The target range is thus found from the following equation [4]

$$R = \frac{cT_s}{2B_{sweep}}\, f_b \tag{3}$$

For moving targets, measuring velocity requires a triangular wave chirp modulation as shown in Fig. 3 [4].

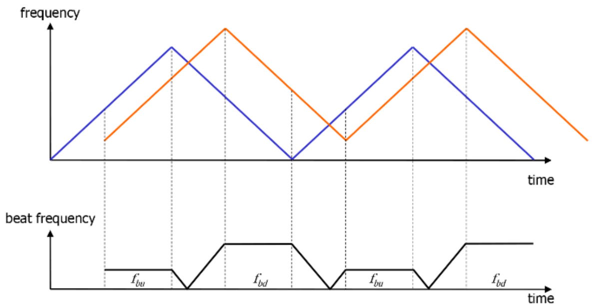

Fig. 3. Triangular modulated chirp

A moving target generates Doppler frequency shift. Beat frequency components due to range and Doppler frequency shift are given by [4]:

$$f_b = \frac{T_{sweep}}{T_s} . \frac{2R}{c} \tag{4}$$

$$f_d = \frac{2v_r}{\lambda} \tag{5}$$

Doppler and Beat frequencies are superimposed as [4]:

$$f_{bu} = f_b - f_d \tag{6}$$

$$f_{bd} = f_b + f_d \tag{7}$$

So range and radial velocity can be obtained as [4]:

$$R = \frac{cT_S}{4B_{sweep}}(f_{bd} + f_{bu}) \tag{8}$$

$$v_r = \frac{\lambda}{4}(f_{bd} - f_{bu}) \tag{9}$$

3. RF Front End

The block diagram of proposed system is shown in Fig. 4 and its specifications are listed in Table 1.

We selected the well-known VCO chip HMC431 which have integrated resonators, negative resistance devices, varactor diodes, and buffer amplifiers. It's phase noise performance is excellent over temperature, shock, vibration and process due to the oscillator's monolithic structure. It's frequency range is 5.5-6.1 GHz and output power is 2 dBm typical from a 3V supply voltage.

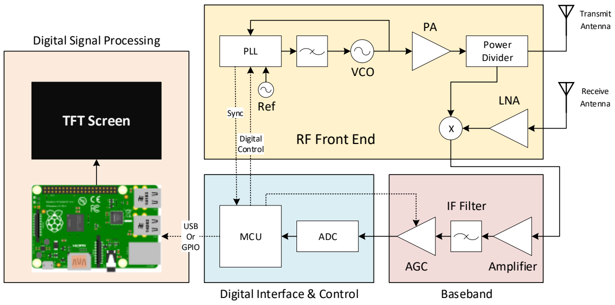

Fig. 4. Proposed FMCW radar system block diagram

Table 1. Proposed FMCW Radar specification

Maximum Bandwidth	400 Mhz
Sweep period	20 ms
IF frequency	10kHz - 1MHz
Tuning signal	Triangular/Sawtooth
Transmitted power	20 dBm
Antenna Gain	23 dBi
Beam width (Azimuth/elevation)	12°/12°
Maximum range	500m

The main problem of VCO is that it uses an exponential converter, which is extremely temperature sensitive. It consequently exhibits a drifting oscillation frequency when the operation temperature changes, so when a linear ramp is applied as a tuning voltage, it generates non-linear frequency sweep, which lead to non-constant mixing tone at the baseband and affects the range resolution negatively. Fig. 4 illustrates the VCO's nonlinearity.

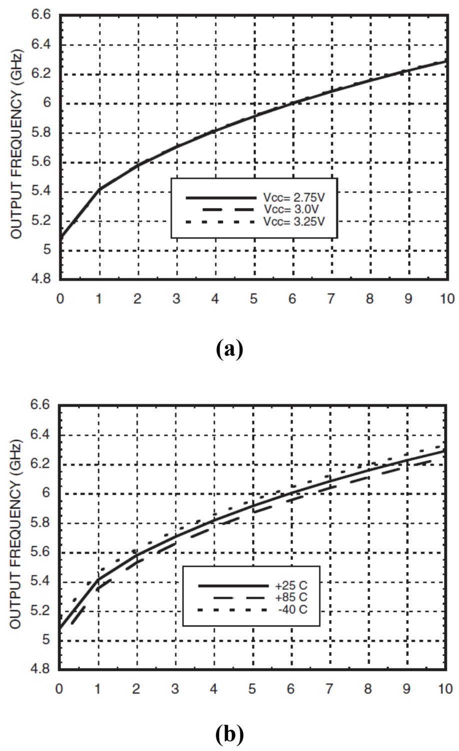

Fig. 5. Frequency vs. Tuning Voltage, (a) Fixed Temperature T= 25°C (b) Fixed Supply Vcc= +3V.

To solve this problem, we used a fractional-N frequency synthesizer with direct modulation and waveform generation capability. It depends on a phase locked loop (PLL) with a frequency divider and a feedback loop, which can adjust VCO tuning voltage. A linear sweep can be generated by sweeping the divider value in small fractional steps.

The selected fractional-N frequency synthesizer was ADF4158. It is designed especially for radars and it can be programmed to generate various waveforms in the frequency domain, for example, sawtooth and triangular waveforms. It also features cycle slip reduction circuitry, which leads to faster lock times, without the need for modifications to the loop filter. Controlling all on-chip registers is performed via a simple 3-wire interface. A temperature compensated crystal oscillator generates the 30 MHz reference frequency. A bridged-T attenuator is used to implement the feedback loop.

A linear power amplifier with 4.9 to 5.9 GHz frequency range is used to amplify the VCO's output signal with gain of 30dB. The amplified signal then passes via coupler and propagate toward the target with transmitter antenna.

To provide down converting stage with the local oscillator signal, a 15dB coupler is designed. We choose the ADL5801 high linearity, doubly balanced, active mixer core with integrated LO buffer amplifier.

Selected antenna is TL-ANT5823B from TP-Link with gain of 23dBi and beam width of 12°. This antenna is commonly used in outdoor Wi-Fi applications and have a suitable bandwidth for our radar application.

4. Baseband

The function of baseband stage is to equalize the IF signal to be ready for A/D conversion. A key challenge in baseband is the difference in power levels of reflected signal from multiple targets. Targets close to radar reflects higher power than the farther target.

First, a low pass filter is implemented to remove high frequency noise. An active high pass filter with 40dB/decade slope is then used to equalize the signals from far apart targets which results in a same amplitude for different targets. Finally, an automatic gain controller (AGC) adjusts the signal amplitude to be ready for A/D conversion.

5. Digital Interface and Signal Processing

Digital interface and control board consists of a high-speed microcontroller connected with differential A/D converter. The microcontroller controls the frequency synthesizer, the A/D converter, AGC, RF power amplifier, and mixer. It also performs the digital interface with signal processing computer via USB or GPIO. As the frequency synthesizer is controlled by microcontroller, the chirp modulation waveform and period can be adjusted according to user's needs. The maximum frequency output of down converter is 1MHz, thus a sampling rate of 10Msps is selected. Clock signal of ADC is provided by microcontroller, and transfers the digital data to microcontroller via parallel port which will send data packets to Raspberry Pi via USB or GPIO.

Baseband processor plays a dominant role among all other radar components. Besides the linearity and noise suppression of the RF/analog front end, the performance of an FMCW radar is largely affected by the efficiency of the baseband processor [5].

Two Fast Fourier Transform processing are used to detect range and velocity. The first FFT processing of each single chirp extracts mainly target range information. Next, the Doppler frequency is obtained by the second FFT processing, using the discrete data in each range-bin over the PRI (Pulse Repetition Interval). In this approach, since the clutter falls into range-bins with zero-Doppler, stationary targets including clutter can be easily suppressed [6].

To perform FFT processing, we used the library GPU_FFT which exploits the BCM2835 SoC V3D hardware to deliver ten times the performance that is possible on the 700 MHz ARM.

GPU_FFT uses single-precision floating point for data and twiddle factors, so it does not compete on accuracy with double-precision libraries; however, the relative root-mean-square (rms) error for a 2048-point transform is less than one part per million.

The library runs on dedicated 3D hardware in the BCM2835 SoC, and communication between ARM and GPU adds 100µs of latency [7].

6. Conclusion

In this paper, we developed a 6 GHz FMCW radar system with capability of detecting both range and velocity. The chirp generation is implemented by digital-controlled frequency synthesizer which enables the user to adjust chirp waveform and period. Signal processing is performed by a Raspberry Pi single board computer exploiting its SoC V3D hardware to implement FFT processing in real time. Results are displayed on a TFT screen also in real time.

References

[1] M. Skolnik, "Radar Handbook", McGraw-Hill, 2008.

[2] I. V. Komarov, S. M. Smolskiy, "Fundamentals of Short Range FM Radar", Artech House Publishers, 2003.

[3] G. L. Charvat, "Small and Short-Range Radar Systems", CRC Press, 2014.

[4] T. Otto, "Principle of FMCW radars", Remote Sensing of the Environment, Delf University of Technology.

[5] C. T. Leondes and D. D. Rivers, "Frequency Domain Interpolation", IEEE Trans. Aerospace and Electronic Systems, Vol. AES-13, no. 3, pp. 323-327, May 1977.

[6] Y. T. Hwang, Y. C. Chen, C. R. Hong, Y. T. Pei, C. H. Chang and J. C. Huang, "Design and FPGA implementation of a FMCW radar baseband processor," *2012 IEEE Asia Pacific Conference on Circuits and Systems*, Kaohsiung, 2012, pp. 392-395.

[6] E. Upton. (2014, Jan, 30). *Accelerating Fourier transforms using the GPU*, Available: http://www.raspberrypi.org.