Accuracy Analysis of FM Chirp in GNU Radio-based FMCW Radar for Multiple Target Detection

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***Abstract*—In this paper, different waveforms of frequency modulation (FM) chirp are investigated to analyze the accuracy of GNU radio-based frequency-modulated continuous wave (FMCW) radar for multiple target detection. The 3 waveforms used for the investigation as FM chirp are sinusoidal, triangular, and sawtooth waveforms. The analysis is performed by use of GNU radio referred as an open source software-define-radio project. There are 2 methods employed for the detection process; the first is real-condition simulation method and the second is USRP-based implementation method. In the analysis, some targets in different ranges are characterized using both methods to determine the accuracy of target range. By using FFT (Fast Fourier Transform) function from Matlab® to obtain the result in frequency domain, both methods show that the triangular waveform has the highest average accuracy, i.e. 95.73% for the 1st method and 99.75% for the 2nd method. The sawtooth waveform has the lower average accuracy than the triangular, i.e. 94.93 for the 1st method and 98.33% for the 2nd method, whilst the sinusoidal waveform has the lowest average accuracy, i.e. 92.60% for the 1st method and 98.59% for the 2nd method. From the result, it shows that the USRP-based implementation method has better average accuracy than the real-condition simulation method.**

***Keywords*—frequency modulated continuous wave (FMCW); FM chirp; GNU radio; multiple target detection**

I. Introduction

The radar system usually utilizes some modulated waveforms and directive antennas to transmit electromagnetic energy into specific volume of target in space to detect the range of targets [1]. In general, radars are often classified by the types of waveform used for their modulation, or sometimes by their operating frequency. Considering the waveform types, radars can be categorized as continuous wave (CW) radars or pulse radars (PR). CW radars are those continuously emit electromagnetic energy and usually use separated transmit and receive antenna systems. In other hand, pulse radars are those periodically transmit high power electromagnetic energy in pulsed form and sometimes use single antenna system in their operation. In CW radars, frequency- or phase-modulated waveforms can be applied to achieve much wider operating bandwidths or to increase the accuracy of target detection. The waveform modulation that is commonly used in CW radar is linear frequency modulation (LFM).

Basically, pulse radars are generated by use of magnetron or klystron which requires high power energy. Therefore, some scientists and engineers involved in radar research community have proposed another type of radar categorized as CW radar namely frequency-modulated continuous-wave (FMCW) radar [2]-[4]. One of advantages of this radar type can be realized in low power as well as low cost. In recent time, the radar has been gaining popularity due to the fact of emerging technologies in solid state microwave transmitter and of very fast digital circuits [2]. Moreover, the radar has provided a convenient method to increase the signal-t-noise ratio and to reduce the complexity of system power level [3].

In this paper, the FMCW radar with FM chirp is applied for analyzing the accuracy of multiple target detection. The FMCW radar is implemented based on GNU radio known as an open source software-define-radio project. The GNU radio itself has been widely applied to implement very sophisticated, yet low cost software-defined- radio [5]-[6]. Three different waveforms of FM chirp are applied for the analysis, i.e. sinusoidal, triangular, and sawtooth waveforms. The frequency of FM chirp is swept linearly for triangular and sawtooth waveform, and non-linearly across the pulse width for sinusoidal waveform. The matched filer bandwidth is employed proportionally to the sweep bandwidth and is independent of the pulse width. Two methods, i.e. real-condition simulation and USRP-based implementation, are introduced to investigate how the accuracy of characterization in target detection can be obtained. Some discussion related to the characterization result and its analysis will be pointed out.

II. Overview of FMCW Radar and System Design

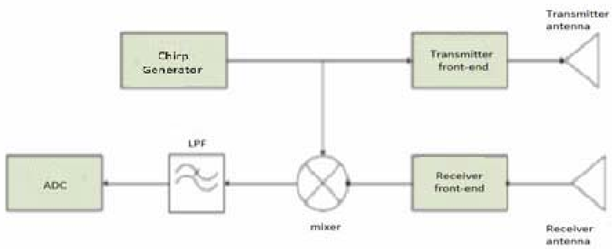

Fig. 1. Block diagram of basic FMCW radar system

Fig. 1 shows the block diagram of a basic FMCW radar system consists of chirp generator as signal source for the transmitter and for the mixer input of receiver as well. The transmitted FMCW signal is radiated by transmitter antenna into specific targets and the reflected signal from some targets

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is then received by receiver antenna to be processed to obtain the property of targets. The FMCW signal commonly defined as chirp can be from many different kinds of signal waveform type. As the FMCW radar is one of the CW radar types, typically it uses linear frequency modulation (LFM) waveform as indicated in Fig. 2. In this work, linear waveform type such as triangular or sawtooth waveform and non-linear type of frequency modulation waveform will be used for the analysis.

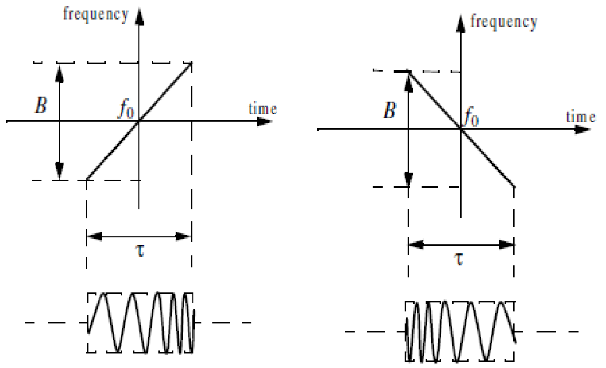

Fig. 2. Typical LFM waveform; up-chirp (left) and down-chirp (right)

The FMCW waveform itself is a result carrier signal that is frequency-modulated by a periodic signal $m(t)$. A FM chirp signal $f(t)$ can be written in (1),

$$f(t) = f_o + f_c \tag{1}$$

where f_o is initial frequency, f_c is chirp rate ($f_c = B/T$), B and T are bandwidth and time duration of chirp, respectively. Prior performing the system design, parameters of design are set as tabulated in Table 1.

TABLE I. DESIGN PARAMETERS OF FMCW RADAR

Parameters	Signal waveform
Sweep frequency of FM chirp	1kHz
Sample rate of FM chirp	6 Megasample/second
Carrier frequency of signal source	1.5MHz
Bandwidth of signal source	750kHz
Delay of signal source	100, 250, and 1000 sample

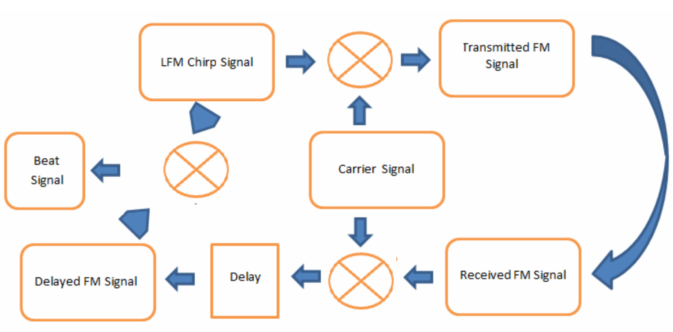

Fig. 3. Block diagram of real-condition simulation method

There are 2 methods employed for the detection process; the first is real-condition simulation method and the second is USRP-based implementation method. The block diagram of 1st method, i.e. real-condition simulation method, and its implementation based on GNU radio are illustrated in Figs. 3 and 4, respectively. It shows in Fig. 3 that the LFM chirp signal is mixed with the carrier signal to be transmitted by the transmitter, in the same time the signal is also mixed with the delayed FM signal to obtain the beat signal.

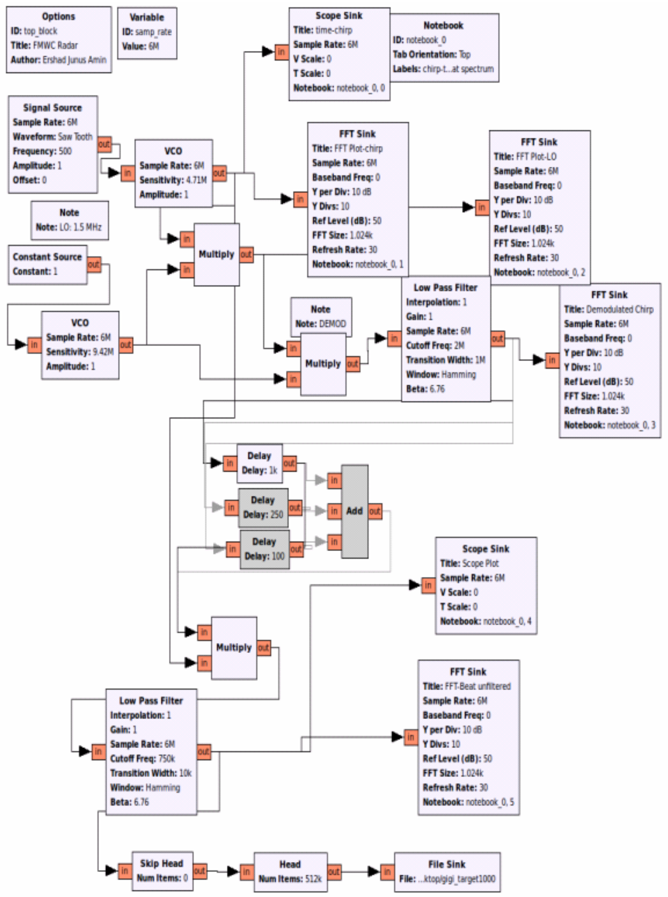

Fig. 4. Implementation of 1st method based on GNU radio

Furthermore, Figs. 5 and 6 show the block diagram of 2nd method, i.e. USRP-based implementation method and its implementation based on GNU radio. In contrast with the 1st method, the transmitted FM signal is obtained from coltage controlled oscillator (VCO) as chirp modulation which is modulated by baseband signal.

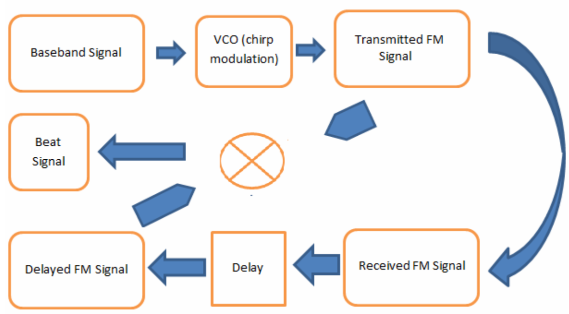

Fig. 5. Block diagram of USRP-based implementation method

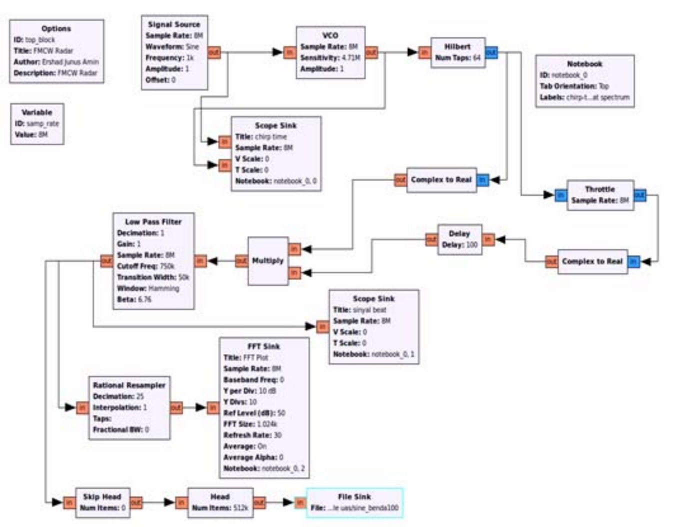

Fig. 6. Implementation of 2nd method based on GNU Radio

III. Result and Discussion

Since the sample rate is 6Msps, hence 1 sample equal to 166ps, the conversion of 100, 250 and 1000 sample then equal to 16.67μs, 41.67μs, and 166.7μs, respectively. The distance of the target an be calculated using (2),

$$R = distance = \frac{c.\Delta t}{2} \tag{2}$$

where c and Δt are speed of light in vacumm and time delay, respectively. Therefore, the distances of target for 3 different samples based on theoretical approach equal to 2.5km, 6.25km, and 25km, respectively. To obtain the distance of target from beat frequency in triangular, sawtooth, and sinusoidal waveforms, equations expressed in (3), (4), and (5) are applied, respectively.

$$R = \frac{f_b.c}{4.f_m.\Delta f} \tag{3}$$

$$R = \frac{f_b.c}{2.f_m.\Delta f} \tag{4}$$

$$R = \frac{f_b.c}{12.f_m.\Delta f} \tag{5}$$

Figs. 7, 8, and 9 depict the beat signal of sinusoidal waveform, beat frequency, and target distance for 3 different targets obtained from the real-condition simulation method. The comparisons between the theoretical approach and each waveform of FM chirp for 3 different targets are summarized in Table 2, 3, and 4 for triangular, sinusoidal, and sawtooth waveform, respectively. From the results, it shows that the triangular waveform of FM chirp has highest average accuracy among 2 other waveforms. It also shows that the higher time step, the higher accuracy is obtained. This is possibly due to the consistency of triangular waveform which only has equal up-chirp and down-chirp modulation timing, while the average accuracy of sawtooth waveform which only has up-chirp modulation is lower than the triangular one. The lowest average accuracy result is sinusoidal waveform, since this waveform is considered as non-linear frequency modulation which may lead to generate bigger error compare to LFM model, i.e. triangular and sawtooth waveforms.

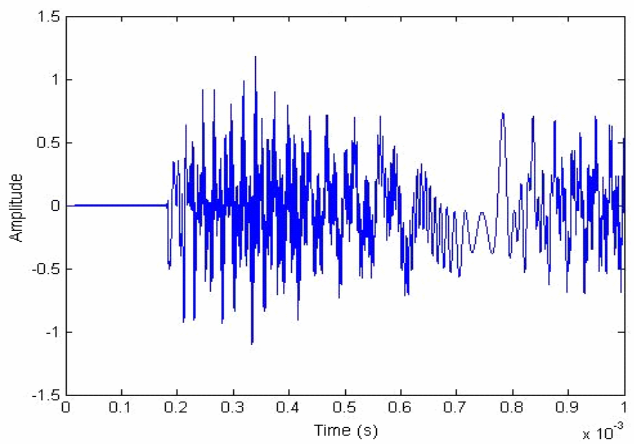

Fig. 7. Beat signal of sinusoidal waveform obtained from 1st method

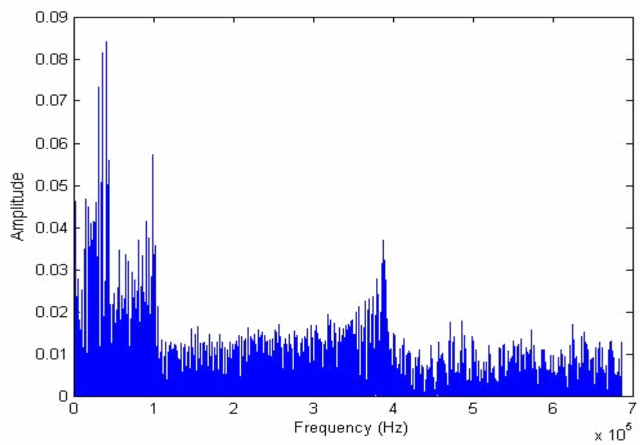

Fig. 8. Beat Frequency of sinusoidal waveform obtained from 1st method

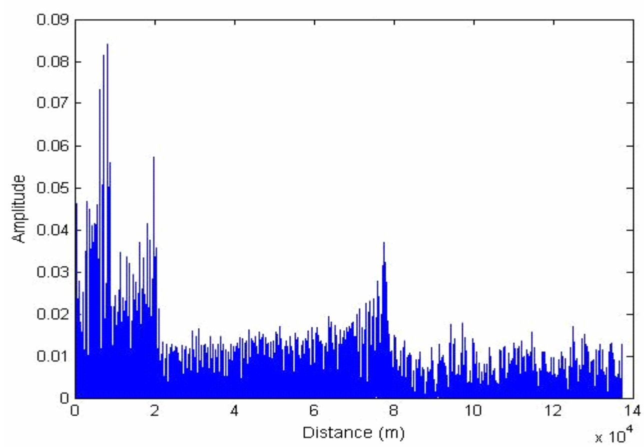

Fig. 9. Distance of 3 different targets using sinusoidal waveform of FM chirp from 1st method (based on triangular waveform for distance detection)

TABLE II. COMPARISON OF THEORETICAL APPROACH AND TRIANGULAR WAVEFORM OF FM CHIRP USING 1ST METHOD

Time step	Distance based on theoretical approach (km)	Distance based on GNU radio implementation	Accuracy (%)
1000	25.00	25.20	99.20
250	6.25	6.50	96.00
100	2.50	2.70	92.00

TABLE III. COMPARISON OF THEORETICAL APPROACH AND SINUSOIDAL WAVEFORM OF FM CHIRP USING 1ST METHOD

Time step	Distance based on theoretical approach (km)	Distance based on GNU radio implementation	Accuracy (%)
1000	25.00	25.87	96.52
250	6.25	6.67	93.28
100	2.50	2.80	88.00

TABLE IV. COMPARISON OF THEORETICAL APPROACH AND SAWTOOTH WAVEFORM OF FM CHIRP USING 1ST METHOD

Time step	Distance based on theoretical approach (km)	Distance based on GNU radio implementation	Accuracy (%)
1000	25.00	25.20	99.20
250	6.25	6.40	97.60
100	2.50	2.80	88.00

Moreover, by using the 2nd method, i.e. USRP-based implementation method, the beat signal of sinusoidal waveform, beat frequency, and target distance for 3 different targets are depicted in Figs. 10, 11, and 12, respectively. While the comparisons between the theoretical approach and each waveform of FM chirp for 3 different targets are summarized in Table 5, 6, and 7 for triangular, sinusoidal, and sawtooth waveform, respectively. Similar to the 1st method, the triangular waveform has the highest average accuracy compared to 2 other waveforms. As listed in Table 5 the accuracy of target detection using triangular waveform form time step of 1000 is up 99.99%. In addition, it shows that the 2nd method has better accuracy than the previous one. This is due to efficiency issue of the 2nd method compared to the 1st method, whereby the waveform signal has no need conversion process since all the processes have been conducted in the baseband frequency signal.

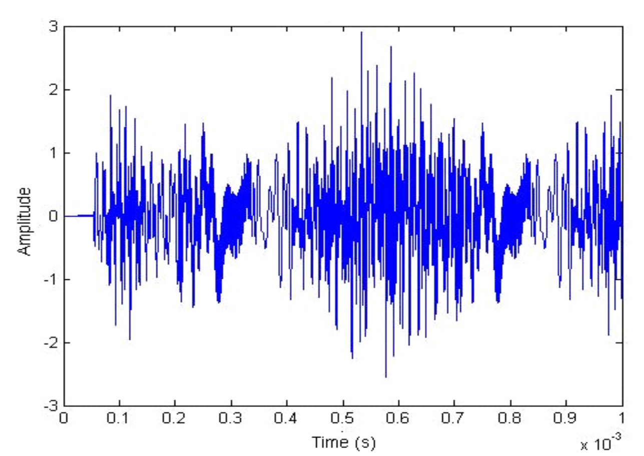

Fig. 10. Beat signal of sinusoidal waveform obtained from 2nd method

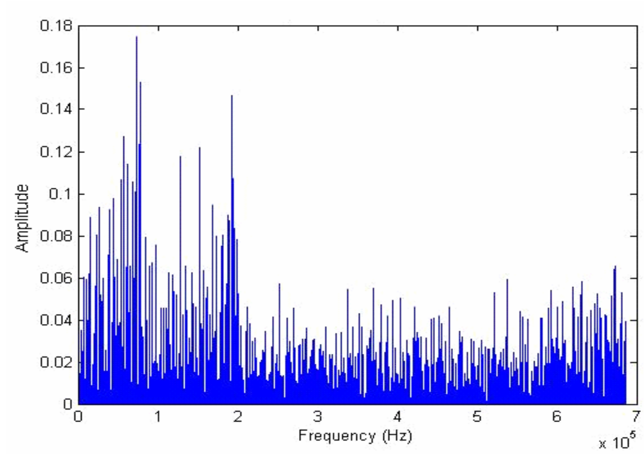

Fig. 11. Beat Frequency of sinusoidal waveform obtained from 2nd method

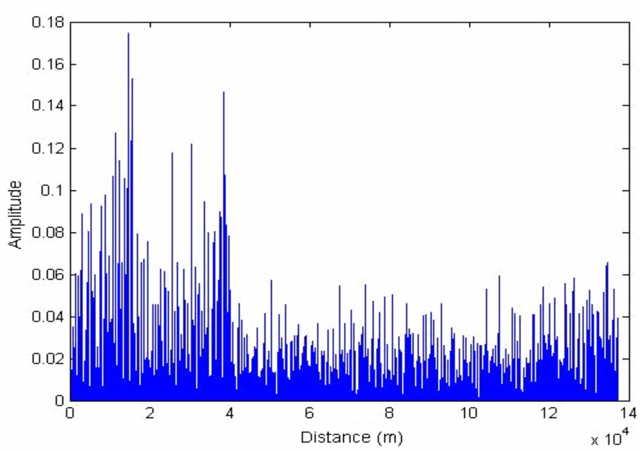

Fig. 12. Distance of 3 different targets using sinusoidal waveform of FM chirp from 1st method (based on triangular waveform for distance detection)

TABLE V. COMPARISON OF THEORETICAL APPROACH AND TRIANGULAR WAVEFORM OF FM CHIRP USING 2ND METHOD

Time step	Distance based on theoretical approach (km)	Distance based on GNU radio implementation	Accuracy (%)
1000	25.00	24.99	99.99
250	6.25	6.21	99.26
100	2.50	2.49	99.99

TABLE VI. COMPARISON OF THEORETICAL APPROACH AND SINUSOIDAL WAVEFORM OF FM CHIRP USING 2ND METHOD

Time step	Distance based on theoretical approach (km)	Distance based on GNU radio implementation	Accuracy (%)
1000	25.00	25.53	98.85
250	6.25	6.33	98.24
100	2.50	2.47	98.68

TABLE VII. COMPARISON OF THEORETICAL APPROACH AND SAWTOOTH WAVEFORM OF FM CHIRP USING 2ND METHOD

Time step	Distance based on theoretical approach (km)	Distance based on GNU radio implementation	Accuracy (%)
1000	25.00	25.00	100.00
250	6.25	6.18	98.89
100	2.50	2.60	96.00

IV. CONCLUSION

The accuracy analysis of FM chirp in GNU radio-based FMCW radar for 3 different targets detection has been investigated using 3 different waveforms and compared with the theoretical approach. The 3 different waveforms used for the investigation were sinusoidal, triangular, and sawtooth waveforms in 2 different methods, i.e. real-condition simulation method and USRP-based implementation method. The characterization for some distances detection has been carried out by using carrier frequency of signal source of 1.5MHz with 6Msps sample rate. The result shows that the 2nd method, i.e. USRP-based implementation method, has had better average accuracy than the 1st method in which the highest, lower and lowest average accuracy are triangular, sawtooth and sinusoidal waveforms, respectively.

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