A High-Resolution Short-Range X-Band FMCW Radar System for Ranging Applications

Phat T. Nguyen, Vinh Truong Nhat and Cuong P.M. Huynh
Department of Telecommunication Engineering
Ho Chi Minh City University of Technology
Ho Chi Minh City, Vietnam
tanphatnguyen9x@gmail.com, truongnhatvinh@gmail.com, hpmcuong@hcmut.edu.vn

***Abstract* — A Frequency - Modulated Continuous - Wave (FMCW) radar system is built to measure the distance to target in range of 1 – 4.5m with high accuracy. A method of range resolution enhancement using Gaussian window and Gaussian interpolation is proposed, simulated and implemented. The simulated results show that FMCW radar systems with Gaussian interpolation method implemented provide measurement errors smaller than 1mm, which is 500 times less than those of conventional systems. The proposed resolution enhancement algorithm is implemented on the designed FMCW radar system. The experiment results show that the designed radar system exhibits the maximum error less than 3mm in range of 1 - 4.5m. Methods to overcome the non-idea characteristics of the radar system is also proposed and implemented.**

Keywords* — *FMCW; radar; Gaussian; window; interpolation.

I. INTRODUCTION

Accurate measurement systems are in high demand due to their broad applications in many fields such as: motion sensor for automated systems, speed and range measurement for industrial uses and traffic control, automobile collision warning systems that measure the distance to other vehicles and obstacles to avoid collision, level-sensing gauge that uses non-contacting measurement method to determine the level and volume of volatile, explosive or high-temperature liquid… [1]. To build these systems, many approaches have been proposed, which expose their own advantages and disadvantages. Ultrasound systems provide high resolution but are sensitive to the measurement conditions (temperature, noise…). Video-camera systems have low cost and high flexibility but need large computation for real-time high-precision applications. Laser systems provide high accuracy but have bad performance when measuring badly-reflective targets [2]. One preferred system is radar (Radio Detection And Ranging) that uses radio waves to detect range and velocity of remote objects. The use of microwave propagation, which is less affected by temperature and environment, makes it possible for radar systems to provide stable and precise results in severe measurement conditions [3].

Radar systems transmit RF-pulses or continuous waves to sound the targets. Pulse radar systems emit RF-pulses and then receive reflected RF-pulses from which the target information is extracted. On the other hand, FMCW radar systems transmit a continuous wave frequency-modulated by a low-frequency sawtooth waveform. The frequency difference between transmitted and received signals is used to determine the target range and velocity. While pulse radar systems are complex and require high power sources to detect targets accurately, the FMCW ones are usually simpler and need lower power. Some benefits such as quick updating of measurement, stability in many conditions… make FMCW radar systems more suitable in many applications, especially in ranging [4].

One important parameter of FMCW radar is the range resolution which is inversely proportional to the bandwidth of swept frequencies [5]. Improving the range resolution means increasing the bandwidth of the whole system, particularly RF front-end blocks, which leads to more complexity in hardware design. Another solution is using more effective signal processing algorithms. Many FMCW radars with signal processing algorithms are proposed. A real-time X-band FMCW radar using rectangular window and Fast Fourier Transform (FFT) offers accuracy of 10cm [6]. Another system, which uses Yule-Walker autoregressive method [1] to estimate the spectrum, can achieve a resolution less than 5mm but requires 4096-points FFT calculation and an additional autocorrelation filter. This complicates the whole system design as well as requires large computation. Another system with a resolution of 1mm presented in [7] uses both frequency and phase information for more exact results. However, the hardware design is challenging due to the requirements of high linearity RF front-end blocks. In addition, many high accurate measurement systems using the FMCW radar principle are developed and commercialized. Two of the most precise systems are the level meters DR7000 of Drexelbrook [8] and Reflex VG7 of Paab Tekno Trading [9]. Either of them offers accuracy up to 3mm by using microwave signal of 26GHz and large bandwidth of 2GHz. In this paper, an interpolation algorithm, which enhances range resolution while maintaining computation complexity, is proposed, simulated and implemented on an X-band FMCW radar system, which is based on SiversIMA's transceiver RS3400X [10]. The whole radar system is packaged and optimized to achieve the measurement accuracy up to 3mm in range of 1 – 4.5m.

This paper is organized as follows: section II presents the operating principle of FMCW radar, section III proposes some resolution enhancement methods and their simulated results, section IV presents the radar system and measurement results, and section V is the conclusion.

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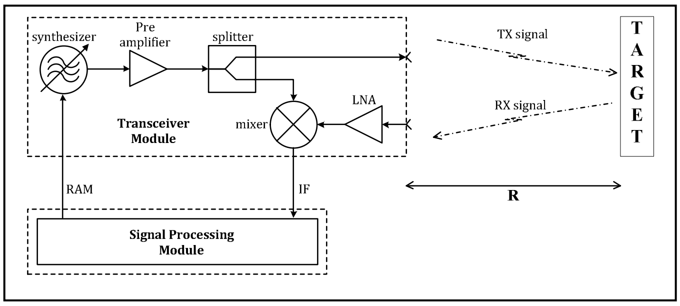


Fig. 1. FMCW Radar System.

II. FMCW Radar Operating Principle

A. FMCW Radar operating principle

Figure 1 shows the architecture of an FMCW radar system, which contains transceiver and signal processing modules. Transceiver module transmits and receives microwave signals, and produces an IF signal carrying information of target (distance and velocity). Signal processing module uses information in IF signal to compute measurement results of range and velocity.

Transceiver module, which consists of a synthesizer, power amplifier, low noise amplifier and mixer, transmits continuous signal whose frequency changes with time, usually in a linear sweep across a set of bandwidth [4]. The reflected signal from target is amplified and mixed with a reference signal (split from transmitted one), which generates an IF signal. The frequency f_{IF} of this IF signal is proportional to the round trip time of the travelling signal from radar system to target:

$$f_{IF} = \frac{BW}{T} \cdot \frac{2R}{c} \tag{1}$$

where R is the distance of target, c is the velocity of microwave signal propagating in free space, BW is bandwidth of sweep frequency, and T is time for frequency of transmitting signal to be swept over the bandwidth.

In the signal processing module, the IF signal is converted to digital one and then is processed using FFT, from which the frequency f_{IF} is determined. The IF frequency is determined corresponding to the maximum spectrum peak in frequency domain. Determining exact value of f_{IF} is vitally important to range resolution of radar system because the frequency resolution, after applying FFT on a time-limited signal *T,* equals to *1/T* [4]. Therefore, range resolution is limited by:

$$\Delta R = \Delta f \cdot \frac{cT}{2BW} = \frac{1}{T} \cdot \frac{cT}{2BW} = \frac{c}{2BW} \tag{2}$$

This equation indicates that range resolution is limited by the sweep bandwidth of radar system.

B. Transceiver RS3400X

In linear FMCW radar, it is difficult to design a wideband system where frequency is swept linearly on the whole bandwidth. A preferred choice is building a system where the frequency sweep is generated by a discrete set of frequencies. In this case, characteristics of the IF signal phase are used instead of frequency [4]. The RS3400X transceiver used in this work is designed to operate on this principle.

In this phase measurement method, the transmitted and received signals always have the same frequency at sampling time but the phase of received one is delayed by the amount of time which is proportional to round trip travelling time of signal from radar to target. The phase difference is defined by:

$$s = \cos(\phi) = \cos\left(2\pi \frac{2R}{\lambda}\right) = \cos\left(2\pi f_{RF} \frac{2R}{c}\right) \tag{3}$$

where f_{RF} is the frequency of RF signal and λ is the electrical wavelength of the RF signal. f_{RF} is increased step by step over the bandwidth *(BW)*, from f_{RF_0} to $f_{RF_0} + BW$. The above equation can be rewritten as:

$$s(n) = \cos\left(2\pi (f_{RF_0} + \frac{n}{N-1} BW) \frac{2R}{c}\right) \tag{4}$$

where N is the number of frequency points and n indicates each unique measurement, $n = 0, 1, \ldots, N-1$.

Applying FFT to *s(n)*; the cosine function is defined by:

$$S(m) = \frac{1}{2}\left[\delta\left(m - \frac{2R.BW}{c}\right) + \delta\left(m + \frac{2R.BW}{c}\right)\right] \tag{5}$$

With positive value of m, the first term on the right hand side has a peak at $m = 2R.BW / c$, where m is the position at which the maximum spectrum peak is located. Therefore, the ranging function is defined by:

$$R = m \frac{c}{2BW} \tag{6}$$

In two schemes of sweep frequency (linear and stepped), range resolution is the same and equals to $c / (2BW)$.

With parameters of RS3400X, which are set as follows: $f_{RF} = 9250 - 10750MHz$, $BW = 1500$ MHz, $N = 1024$, the range resolution of this transceiver equals to 10cm. Thus, if there are more than one target in range of 10cm, FFT of IF signal has one peak instead of many peaks in range of measurement. In other words, the FMCW radar system can detect only one target in this case.

III. Resolution Enhancement Methods

A. FFT, Windowing and Spectrum Interpolation

The desired signal frequency f_{IF}, hence the location of target, is determined by applying a window function and then an FFT on the discrete-time IF signal. The desired range is derived from the maximum peak of discrete spectrum in frequency domain. For this reason, the range resolution of FMCW radar is proportional to frequency resolution of FFT calculation. To improve the accuracy of determining signal frequency, some methods such as zero-padding and interpolation are proposed. In the zero-padding method, zeros are added to signal in time domain before applying FFT to increase the frequency resolution. Therefore, the system accuracy increases when more zeros are padded but it becomes less attractive (because of large computation) if so many zeros are added for very high accuracy. Another solution is using means of interpolation to construct signal spectrum from a discrete set of spectrum peak after performing FFT.

The conventional method is to extract the desired frequency information by applying a rectangular window and FFT on the time-limited signal, and then finding the maximum peaks of resulting signal spectrum. This method can only offer the exact result if the desired frequency is k (where k is an integer number) times larger than FFT frequency resolution. In this case, the main lobe of signal spectrum exactly represents the desired frequency. In contrast, if desired frequency is not k times larger than FFT frequency resolution, two spectrum peaks may appear in both sides of actual desired frequency peak, resulting in a false measurement result. For more accurate frequency determination, interpolation algorithms along with other types of windows are used. Applying the FFT on the IF signal with the use of Hann and Gaussian windows results in the spectrum with wide main lobes, which contain more than two spectrum peaks, facilitating the accurate interpolation. In the following part, the interpolation method using Lagrange interpolation and Gaussian interpolation with several types of windows are presented and compared.

1) Lagrange interpolation

An n^{th} degree Lagrange interpolation method uses n^{th} degree interpolating function *p(x)* which passes through all specified *n+1* discrete points of exact function *f(x)* [12]:

$$p(x_j) = f(x_j),\ j = 1, 2 \dots n, n+1 \tag{7}$$

The value of any point x between x_1 and x_{N+1} can be interpolated from *N+1* known ones and given by:

$$p(x) = \sum_{j=1}^{n+1} f(x_j) l_j(x) \tag{8}$$

where $l_j(x)$ is the Lagrange polynomial defined by:

$$l_j(x) = \frac{\prod_{k=1,k\neq j}^{n+1}(x - x_k)}{\prod_{k=1,k\neq j}^{n+1}(x_j - x_k)} \tag{9}$$

In case $n = 2$, 2nd degree Lagrange interpolation is:

$$p(x) = a(x - x_o)^2 + p_o \tag{10}$$

Translate (10) into range form:

$$Y = a\left(R - R_o\right)^2 + Y_o \tag{11}$$

where R_0 is the exact distance, Y is the value of spectrum peak corresponding to distance $R, Y_o = Y(R_o)$. The interpolated exact distance R_0 is defined by:

$$R_o = R_2 + \frac{Y_3 - Y_1}{2\left[2Y_2 - Y_1 - Y_3\right]}\Delta R \tag{12}$$

where Y_2 is the value of maximum peak, Y_1, Y_3 are values on the left and right of the maximum peak, R_2 is the distance corresponding to the maximum peak, and ΔR is range resolution.

2) Gaussian interpolation

Gaussian interpolation uses Gaussian function which is given by:

$$f(x) = a.e^{-\frac{(x-b)^2}{2c^2}} + d \tag{13}$$

$f(\infty) \rightarrow 0$ in spectrum leads to $d = 0$, (13) is rewritten as:

$$f(x) = a.e^{-\frac{(x-b)^2}{2c^2}} = e^{A(x-x_o)^2 + K_o} \tag{14}$$

Take logarithm of both sides of (14):

$$\ln\left[f(x)\right] = A(x - x_o)^2 + K_o \tag{15}$$

This is a common form of 2nd degree Lagrange interpolation:

$$\ln\left[Y\right] = A(R - R_o)^2 + K_o \tag{16}$$

where Y is the value of discrete spectrum peak corresponding to R and R_0 is the exact distance. The interpolated exact distance R_0 is defined by:

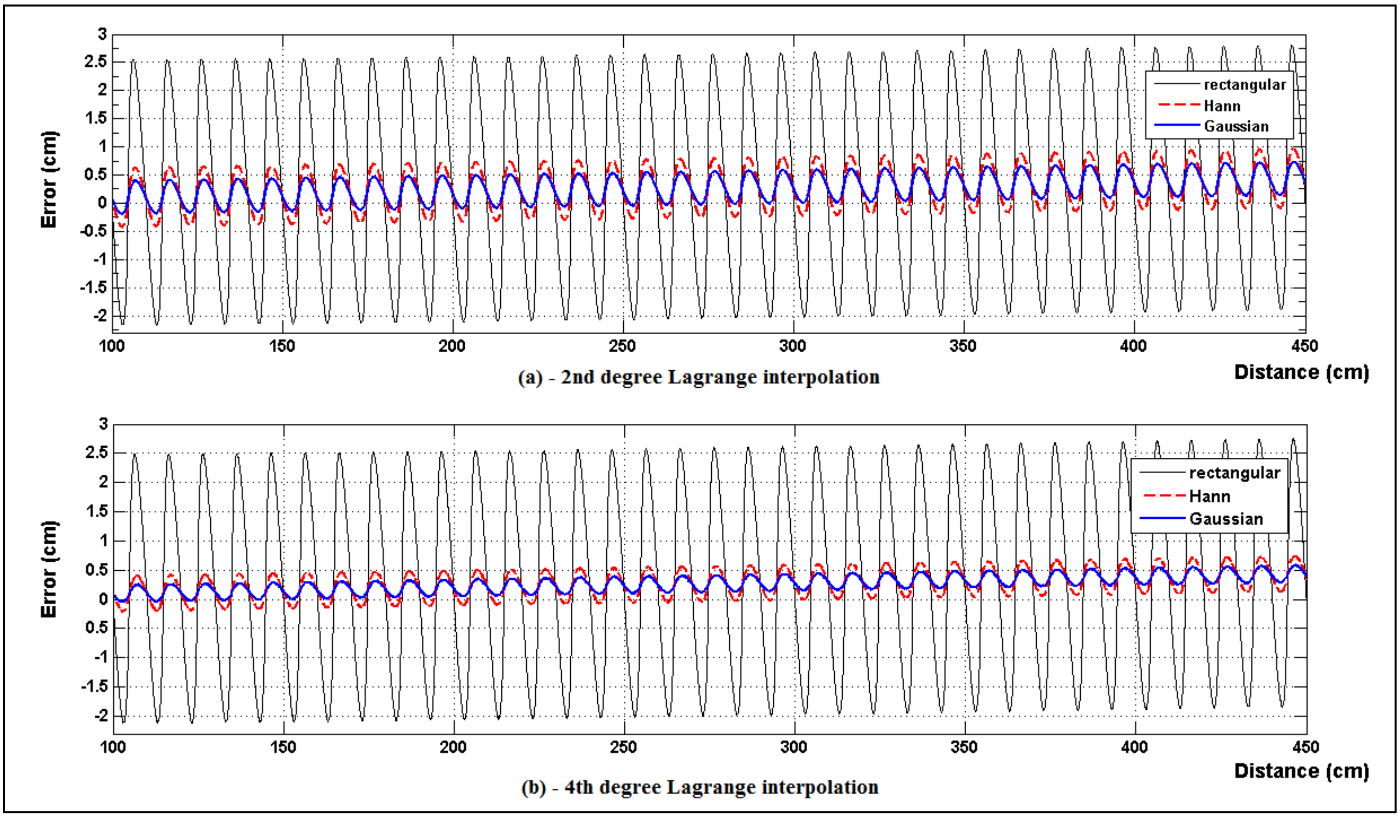


Fig. 2. Simulated error of 2nd (a) and 4th (b) degree Lagrange interpolation.

$$R_o = R_2 + \frac{\ln(Y_3) - \ln(Y_1)}{2\left[2\ln(Y_2) - \ln(Y_1) - \ln(Y_3)\right]} \Delta R \qquad (17)$$

where Y_2 is the value of maximum peak, Y_1, Y_3 are values on the left and right of the maximum peak, R_2 is the distance corresponding to the maximum peak, and ΔR is range resolution.

B. Simulated Results

In this part, simulated results of 2nd, 4th degree Lagrange interpolation and Gaussian interpolation with various types of windows are shown and compared with each other. The aim is to find the most effective interpolation method to implement on the designed FMCW radar system. Parameters for the simulation are the real parameters of the transceiver RS3400X and are used in the following parts: $BW = 1500$ *MHz*, $N = 1024$.

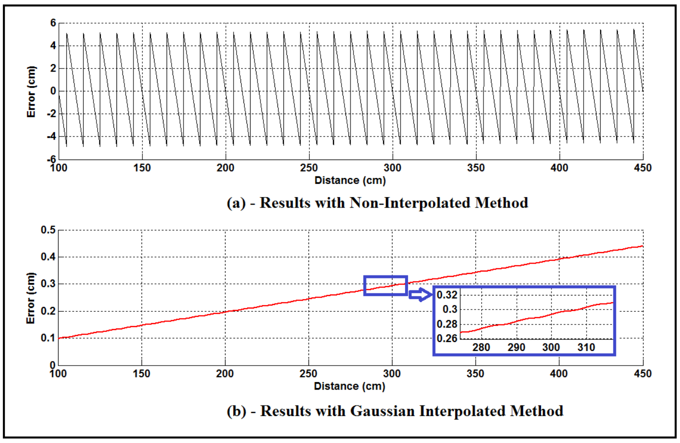
1) Lagrange interpolation

Figure 2(a) demonstrates the 2nd degree Lagrange interpolation with a variety types of windows. The use of stepped frequency instead of continuous one increases the error corresponding to target range. This error becomes severe when target is far. However, it can easily be eliminated by compensation. After being eliminated, the maximum errors when using rectangular, Hann and Gaussian windows are repeated periodically, about 23.6mm, 5.3mm, and 3mm respectively. The error when using Gaussian window is enhanced about 16 times compared to non-interpolated case.

Figure 2(b) shows the 4th degree Lagrange interpolation with various types of windows. Maximum error with rectangular window is about 23mm, a little smaller than that of 2nd degree Lagrange interpolation. However, with Hann and Gaussian windows, the results are improved considerably. Maximum errors of Hann and Gaussian windows are about 3.1mm and 1.5mm, respectively. With 4th degree Lagrange interpolation using Gaussian window, the error is enhanced about 2 times when compared to that of 2nd degree Lagrange interpolation, over 30 times when compared to non-interpolated case.

2) Gaussian interpolation

In order to compare with Lagrange interpolation, Gaussian interpolation using Gaussian window is simulated with the same parameters. Figure 3(a) and Figure 3(b) show the simulated results of conventional method and Gaussian interpolation method, respectively. The errors vary according to target range and repeat every inherent range resolution of 10cm. The error equals to zero when the target location is a multiple value of inherent range resolution. The non-interpolated method produces maximum error when the target is located right in the center of the two spectrum peaks, while the proposed one gives a zero error at this location. Moreover, the error ripple of interpolated method is over 500 times smaller than that of non-interpolated method, which means the proposed method significantly enhances the range resolution. Very small errors are obtained thanks to the similarity of the curve passing FFT results and the curve of Gaussian interpolation.



(a) - Results with Non-Interpolated Method

(b) - Results with Gaussian Interpolated Method

Fig. 3. Simulated errors of conventional and Gaussian interpolated method.

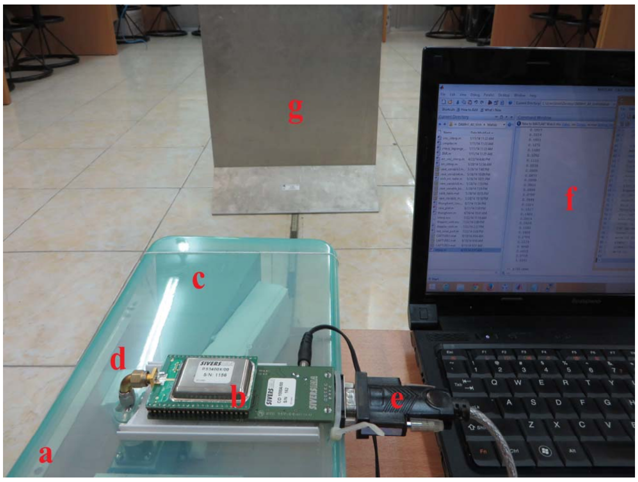


Fig. 4. Complete FMCW radar system.

Among simulated results of interpolation methods, the method using Gaussian interpolation and Gaussian window results in the minimum error ripple and minimum error distance. This method is chosen to implement on the real FMCW radar system in the next section.

IV. FMCW Radar System and Measurement Results

A. *FMCW Radar System*

Figure 4 shows the complete FMCW radar system and the set-up for measuring the location of targets. Transceiver RS3400X (Fig. 4(b)) is an X-band radar manufactured by SiversIMA [10]. It generates stepped frequencies from 9.25 GHz to 10.75 GHz with high stability. The maximum number of steps is 1500 and the minimum idle time for each step is 50us. Thus, one cycle of transceiver lasts 75ms, which helps the radar system respond quickly in real-time measurement. RS3400X comes along with a control board to manage the operation of transceiver. The ADC of control board has high resolution of 16-bit output per sample, which assures the high fidelity of digital signal before processing. Transceiver communicates with a computer (Fig. 4(f)) via Serial Port Interface (Fig. 4(e)). A program is built to control the transceiver, process the signal and display the ranging measurement results.

In order to build complete FMCW radar, RS3400X is connected with an X-band high-gain horn antenna (Fig. 4(c)) via a 90-degree male-to-female SMA connector (Fig. 4(d)). The connector must be of high quality with input/output matching to minimize reflected power of RF signal before it is radiated by antenna. The low insertion loss of connector is also necessary in order to expand the range of radar. Because the error distance of the proposed radar depends on Gaussian interpolation using amplitudes of two maximum adjacent spectrum peaks, the performance of radar in terms of distance depends on power of received signals. Thus, to achieve a radar system with high accuracy at long distance, not only is the algorithm optimized but also high transmitted power is needed.

The “hard” limit of FMCW radar resolution is $c/2BW$ which means if there are more than one target or the target is distributed in range of $\pm\ c/2BW$, the amplitude of received signal at the antenna equals to total reflected signal amplitudes of all targets in range of interest. In this case, no DSP algorithm can produce accurate result. Therefore, the measurement is conducted with assumption that there is only one target in range of interest.

Moreover, before measuring, the distance offset must be concerned and calibrated. The total time it takes for the signal to be transmitted from output of up-conversion mixer to target and to be reflected to the input of down-conversion mixer is twice as much as the time for signal propagating in the circuit and in free space. Thus, the result calculated after FFT must be subtracted by this distance offset, which corresponds to time for the signal to propagate in internal circuits. It is difficult to calculate this offset because of many factors such as: PCB layout of transceiver, characteristics of connector and antenna… In this work, the distance offset is measured by setting the target at the end of antenna (zero-distance reference point), then starting the radar to obtain the result. This offset remains unchanged in measurements and is subtracted to receive final result.

B. *Measurement Results*

The measurement is set up as in Figure 4: Transceiver module and horn antenna are connected together and packaged in a 25x20x10cm3 plastic box (Fig. 4(a)). Radar system is then connected and controlled by computer via Serial Port Interface. A program is built to control the radar and execute the algorithm for range resolution enhancement. Three consecutive measurement results are averaged to get the final. The system is put on a 30cm-thick surface, with the antenna to be pointed to the target. The target is a 50x50cm2 piece of flat aluminum (Fig. 4(g)) positioned in front of radar system.

Figure 5 shows the spectrum of IF signal when the target is placed 305.5cm away from radar before and after using enhancement method: the blue bars are discrete frequency spectrums without interpolation and the red line is the result after applying Gaussian interpolation. In this figure, the calculated location of target is 306.1cm which is greatly improved when compared with non-interpolated one (310cm).

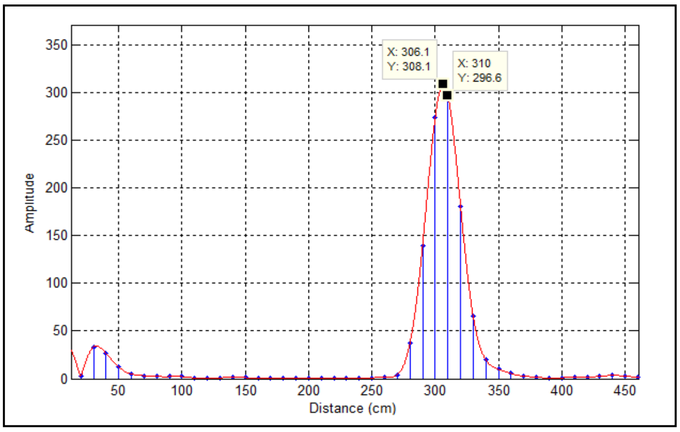


Fig. 5. Spectrum of IF signal.

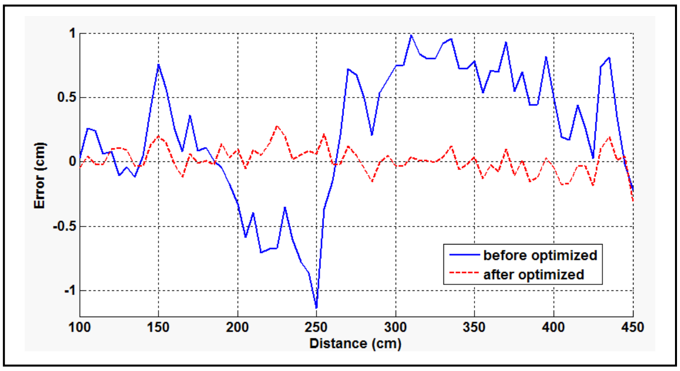


Fig. 6. Measurement error of FMCW radar before and after optimization.

Figure 6 demonstrates the radar's errors versus measurement distances. The solid line is the error without optimization and the dash line is that with optimization. From many practices without optimization, it is concluded that the results remain unchanged in range of measurement from 1 to 4.5m and the maximum error produced is about 10mm. The error is owing to various factors such as: characteristics of radar system (transceiver, horn antenna, connector…), environment, characteristics of target and random errors in measurements...

The solution to improve the measurement results is to measure the offset errors in the condition that characteristics of target and environment remain unchanged. The offset is determined by taking the average of many measurements in the same condition and then creating an error table for each range of distance. When measuring a target, the radar system searches corresponding error in the error table and subtract this value from interpolated result to obtain final result. The dash line in Figure 6 shows that in range of measurement from 1 to 4.5m, maximum error is only 3mm.

To improve the performance of radar system, offset errors must be determined precisely, hence the increase of system memory to store the error table. This trade-off can be solved by determining offset errors as a function of range and other variables. This task requires broad understanding of radar hardware and characteristics which will be investigated further.

V. Conclusion

The paper presented a complete short-range X-band FMCW radar system with high accuracy distance measurement capability using a proposed signal processing algorithm for range resolution enhancement. The proposed algorithm based on Gaussian interpolation and Gaussian window was simulated and implemented on a real radar system. The simulated results of the proposed algorithm show the range resolution improvement of over 500 times compared to the conventional method using FFT only. The designed FMCW radar system can measure targets in range of 1 to 4.5m with maximum errors of 3mm. A transmit/receive module is needed to increase transmitted power; hence the measurement range of the radar system. This radar system finds many high-accuracy non-contact ranging applications in VietNam.

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