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Analysis and Computer Simulation of a Continuous Wave Radar Detection System for Moving Targets

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Abstract
This paper presents the analysis and computer simulation of continuous wave radar detection system for moving targets. In the past, radio detection has been used as an integral part of complicated applications like reconnaissance mission, navigation, weather, air-traffic management, missile targeting and defense. Analysis of measuring systems for such applications needs the representation of radar operation and performance within the context of the system. The impact of measuring these systems needs to be evaluated and qualified. Signal Processing in radar systems was carried out using MATLAB with triangular Linear Frequency Modulated Continuous Waveform (LFMCW) to obtain the target distance and relative speed for moving targets. A model for the detection of continuous wave radar was developed to generate different frequencies as distance changes. The results obtained were able to detect normal frequencies whenever a change in radar distances occur within the moving targets' environment.

Keywords: *Radio detection, LFMCW, MATLAB, Signal processing*

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1. Introduction

Radio Detection and Ranging (RADAR) is a well-known active remote sensor application that is mostly used by researchers and engineers these days. Basically, radar technology transmits microwave signal into space until it hits a target and some portion of radiation return from a reflected target is collected by the receiver antenna. A signal processing technique is implemented to measure and analyze the collected raw data of the feedback signal to be able to earn information of the required object (Jing, 2010).

The radar system is generally operating at a microwave frequency range of 300MHz to 300GHz. Since it generates and emits a short wavelength of electromagnetic signals, its operation is unaffected by all types of weather and light conditions such as darkness, rain, snow, fog, smoke and dust during transmitting signal into space. In addition, radar is best used for long-range applications as the radiation travels with the speed of light in space and it is an efficient tool for scientific measurement (Akash and Anirudh, 2015).

Radar is an instrument that radiates electromagnetic waves in space, which detects and locates an object. Today, it is widely used for speed estimation, imaging, and many other functions. The principle of radar operates like the reflection of sound waves. If any sound wave is incident on an object (target), it will be reflected ahead and this sound wave reflection is called echo. The distance and direction of the objects can be estimated if the speed of sound is known (Mahmod and Samaa, 2013).

Radar systems are composed of a transmitter that radiates electromagnetic waves of a particular waveform and a receiver that detects the echo returned from the target. Only a small portion of the transmitted energy is re-radiated back to the radar. These echoes are processed by the radar receiver to extract target information such as (range, speed, direction and position). The range to the target is evaluated from the travelling time of the wave. The direction of the target is determined by the arrival angle of the echo wave. The relative velocity of the target is determined from the Doppler shift of the returned signal (Issakov, 2010). Radar system detection is the process in which the presence of the target is detected in form of competing signs arising from the background echoes, atmospheric noise, or noise generated in the radar receiver. Noise power present at the output of the radar receiver can be reduced by using filters and the frequency response function maximizes output peak signal-to-noise using a matched filter (Mihirkumar et al., 2018).

Continuous-wave radar is a type of radar system where known stable frequency continuous wave radio energy is transmitted and then received from any reflecting objects. Continuous-Wave radar uses Doppler, which renders the radar immune to interference from large stationary objects and slow-moving clutter. Continuous-wave and frequency modulated continuous wave radar have been used within the aeronautical industry and military for many years now. Due to its simplicity, low power, low-cost and range flexibility, this type of radar has been used for a wide range of applications. In recent times, frequency modulated continuous wave has made resurgence due to the improved processing power of computers (Wahju, 2013).

Frequency Modulated Continuous Wave (FMCW) radar provides range and range-rate information but it is not able to detect the velocity of beaming targets. Beaming is a term used to describe a target moving in a circular motion with respect to the radar location. In this case, the target has no relative velocity with respect to the radar position and therefore produces no Doppler shift within the received signal and this makes the target incorrectly defined by the radar as a stationary target. The ability of the frequency modulated continuous wave radar to provide range and range-rate for multiple targets is a nontrivial determination and this situation makes the radar prone to designate ghost targets (Guochao et al., 2014).

The military uses continuous-wave radar to guide Semi-Active Radar Homing (SARH) air-to-air missiles, and the Standard missile family. The launched aircraft illuminates the target with a continuous wave radar signal and the missile homes in on the reflected radio waves. Since the missile is moving at high velocities relative to the aircraft, there is a strong Doppler shift. Most modern air combat radars, even pulse-Doppler sets, have a continuous wave function for missile guidance purposes (Alexander et al., 2017).

This paper focuses on creating a MATLAB simulator to model the detection of continuous wave radar system in varying traffic densities and complexities. The simulation implements the algorithms and tests the effectiveness of the frequency modulated continuous wave radar system within the simulated environment.

2. Radar range equation

The distance of the target is determined by the traveling of electromagnetic waves at the speed of light ($C = 3 \text{ x } 10^8 m/\text{sec}$). The target's range (R) is computed by measuring the time delay Δt, it takes a pulse to travel two-way path between the radar and the target (Richards et al., 2010).

$$R = \frac{\Delta t.C}{2} \qquad (1)$$

In general, most functions of radar are time-dependent. The time synchronization between the transmitter and receiver of radar is required for range measurement. Radar radiates each pulse during transmit time (T) or pulse width τ, and wait for returning echoes during listening or rest time, and then radiate the next pulse, as shown in Fig. 1. The time between the beginning of one pulse and the start of the next pulse is called Pulse Repetition Time (PRT), and is equal to the inverse of pulse repetition frequency (PRF) as given in Equation (2).

$$PRF = \frac{1}{PRT} \qquad (2)$$

The radar transmitting duty cycle (dt) is defined as a ratio: $= \frac{\tau}{T}$. The radar average transmitted power is given in Equation (3).

$$P_{av} = Pt \ x \ dt \qquad (3)$$

where (Pt) indicate to the radar peak transmitted power. The pulse energy is given in Equation (4).

$$E_P = P_t \tau = P_{ave} T = \frac{P_{ave}}{f_r} \qquad (4)$$

2.1 Theoretical minimum detection range and maximum Signal-to-Noise Ratio (SNR) equation

The total peak power (watts) developed by the radar transmitter (P_t), is applied to the antenna system. Consider the antenna with an isotropic or omnidirectional radiation pattern. The power density (P_D) at a distance (R) from the radiating antenna would be the total power divided by the surface area of a sphere of radius (Mahafza, 2000).

$$P_D = \frac{\text{Peak transmitted Power (watt)}}{\text{Sphere area } (\mathrm{m}^2)} \qquad (5)$$

The power density at range (R) away from the radar is shown in Equation (6).

$$P_D = \frac{Pt}{4\pi R^2} \qquad (6)$$

where (P_t) = the peak transmitted power and $4\pi R^2$= the area of sphere of radius (R).

Radar systems use a directional antenna pattern in order to concentrate the power density in a certain direction, which is usually characterized by the gain (G) and the antenna effective aperture (A_e) is as shown in Equation (7).

$$A_e = \frac{G\lambda^2}{4\pi} \qquad (7)$$

The antenna gain (G) is directly proportional to aperture, and the dimensions of an antenna depend on the gain (G) and wavelength (λ) (Sulaiman et al., (2013).

When using a directive antenna of gain (G), then the power density is given in Equation (8)

$$P_D = \frac{PtG}{4\pi R^2} \quad (8)$$

The power reflected by the target toward the radar (P_r) defined as the product of the incident power density and the radar cross section, which is symbolized (σ) of the target as shown in Equation (9).

$$P_r = P_D \, x \, \sigma \quad (9)$$

By substituting Equation (8) into Equation (9) gives:

$$P_D = \frac{PtG\sigma}{4\pi R^2} \quad (10)$$

When the signal reflected from the target towards the radar system over a distance (R), the power density (P_{Dr}) return at the radar is given in Equation (11)

$$P_{Dr} = \frac{Pr}{4\pi R^2} \quad (11)$$

Substituting Equation (10) in Equation (11) gives Equation (12):

$$P_{Dr} = \frac{PtG\sigma}{(4\pi)^2 \times R^4} \quad (12)$$

The total power received (S) by antenna of effective area (A_e) from a target at range (R) is shown in Equation (13).

$$S = P_{Dr} \, x \, P_e \quad (13)$$

Evaluating Equations (7), (12) and (13) gives:

$$S = \frac{(P_t G^2 \lambda^2 \sigma)}{((4\pi)^3 x R^4)} \quad (14)$$

The received power (S) can be written in terms of signal-to-noise ratio (SNR), and thermal noise power (kT_0BF), where k is Boltzmann's constant and is equal to $1.38x\,10^{23}$, T_0 is the noise temperature of the radar, B is the noise bandwidth of the radar receiver and the noise figure is F. By substituting these terms into Equation (14) gives Equation (15).

$$S_{min} = kT_eBF(SNR)_{min} \quad (15)$$

By combining equations (14) and (15), the equation 16 becomes

$$R_{max} = \left[\frac{PtG^2 \times \lambda^2 \times \sigma}{(4\pi)\text{^}3 \times kTe \times BF \times (SNR)min}\right]^{\left(\frac{1}{4}\right)} \quad (16)$$

The minimum detectable Signal-to-Noise Ratio $(SNR)_{min}$is shown in Equation (17).

$$(SNR)_{min} = \frac{PtG^2 \times \lambda^2 \times \sigma}{(4\pi)^3 \times kTe \times BF \times R^4} \quad (17)$$

where $(SNR)_{min}$ is the minimum detectable SNR of the system. If a greater detection range is desired, then significant improvements to antenna gain or transmitted power must be realized, and the other parameters are often fixed.

The SNR is signal to noise ratio units in decibel (dB), when the units are transformed from system international units (SIU) to dB, the relationship is applied in Equation (18).

$$dB = 10log_{10}(SIU) \quad (18)$$

And inversion, when transformation from (dB) to (SIU) is made, then, Equation (19) is used.

$$SIU = 10^{\frac{dB}{10}} \quad (19)$$

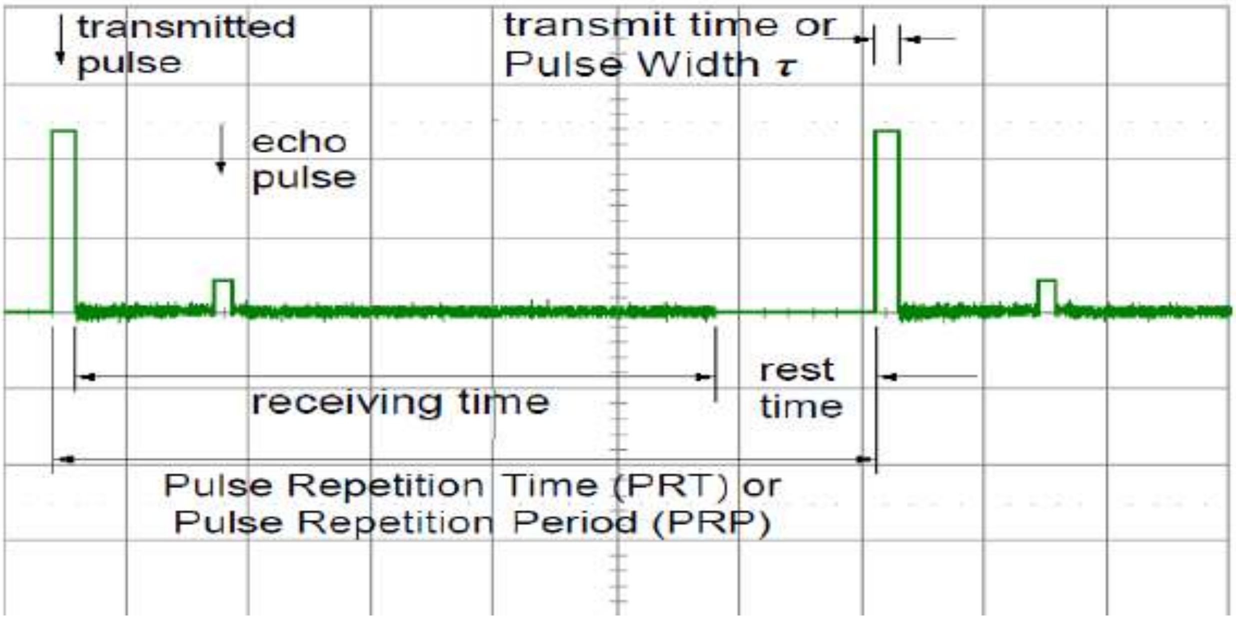

Fig. 1: Transmitted and received pulse

3. Materials and methods

3.1. Materials

The radar system consists of the following materials and parameters such as transmitter, receiver, power supply, synchronizer, antenna and display unit. The transmitter created the radio wave which was sent and modulated to form the pulse train. The transmitter amplified the signal to a high-power level to provide adequate range. The receiver was sensitive to the range of frequencies transmitted and provided amplification of the returned signal. The power supply provided the electrical power for all the components. The largest consumer of power was the transmitter which required several kilowatts of average power. The synchronizer coordinated the timing for range determination and regulated the rate at which pulses were sent and reset the timing clock for each pulse. The antenna took the radar pulse from the transmitter and sent it into the air. The antenna focused the energy into a well-defined beam which increased the power and permitted the determination of the direction of the target. The display unit took a variety of forms which presented the received information to the operator.

3.2 Method

Frequency Modulated Continuous Wave radars operate by sending out a continuous-wave signal while modulating the frequency. During operation, the emitted wave first strikes the target and then rebounds back to the radar where it was processed. These radars used two antennas, one to transmit the continuous wave and one that receives the echo return from the target. The radar began operating at a start frequency and ramps up to a specific stop frequency in a certain period of time. The echo received from a wave bouncing off a target is a time-delayed replica of the transmitted signal. After receiving the echo from the target, the radar will process it to acquire information about the target. The processing was done in two stages. In the first stage, the frequency will shift the signal to the baseband and identifies the difference in frequency between the original signal and the echo. In the second stage, the information from the first stage was used to calculate the range of the target. Frequency Modulated Continuous Wave radars mixed the incoming signal with the original signal to de-chirp it and then apply a Fourier transform to get the beat frequency. The range of the target was proportional to the beat frequency. The simulation was performed in MATLAB and the Frequency Modulated Continuous Wave signal was created, and the signal propagated through space strikes the target and reflected back. Then the target model was created that considered the radar cross section (RCS), distance, and velocity of the target used to compute the reflected signal.

3.3 Development of model for the detection of continuous wave radar system

Figure 2 illustrates the overall simulation model for the detection of a continuous wave radar system. The radar distance is dynamic and determines the actual frequency. The radar distance is connected to the transmitter which sends the signal in the form of a pulse. The type of pulses generated is time-based and the amplitude of the pulse is 1 and the period is 2 seconds. The pulse width period is 50% and there is no phase delay. A program was written and integrated into the transmitter as a pulse generator (Wang, 2016). The transmitter was then connected to Bandpass filter and Low pass filter, respectively. The filter structure is Direct-form Finite Impulse Response (FIR) filter (Yolanda et al., 2017). The bandpass filter was connected to the modulator which was responsible for converting the digital data into an intermediate frequency (IF) signal. The low pass filter was connected to the demodulator that converts the IF signals into digital format. The receiver receives the signals transmitted and provides amplification of the returned signal. The receiver was then connected to the error detector, actual frequency and error frequency subsystems. Each subsystem was connected to the scope which displays the values obtained from the changing radar distance.

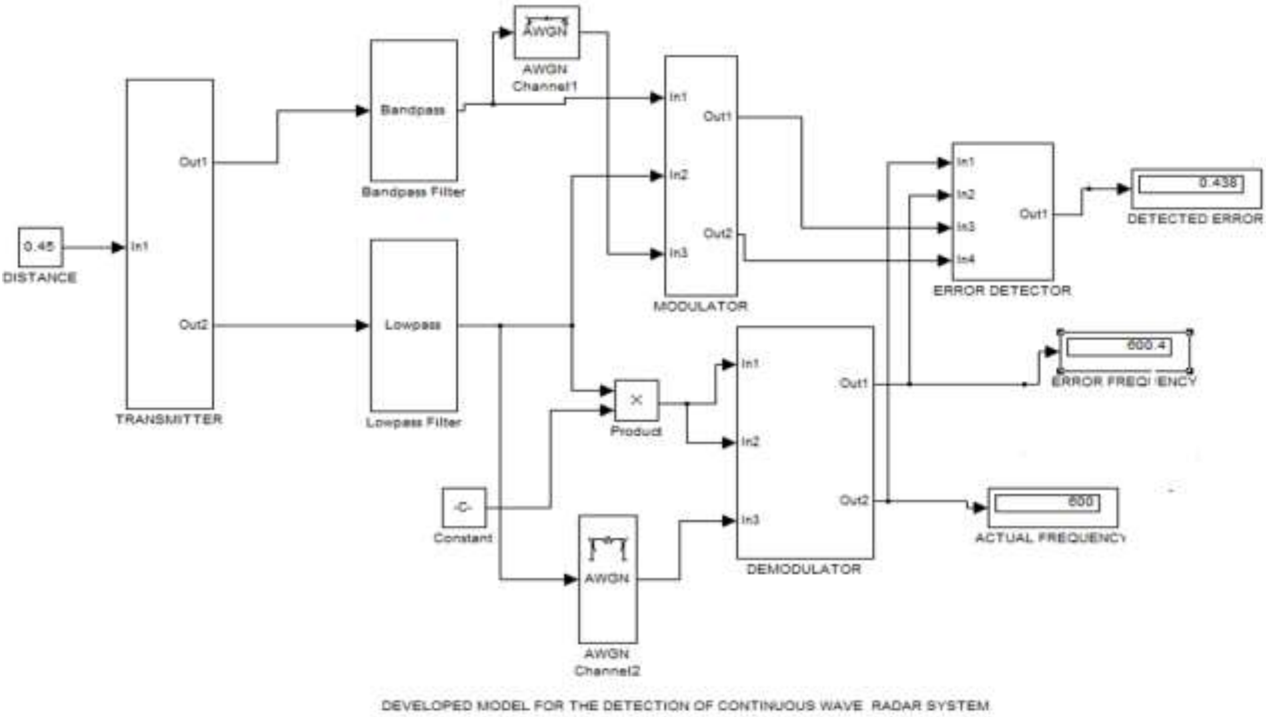

Fig. 2: Developed model for detection of Continuous Wave Radar System

4. Results and discussion

4.1 Result analysis

Five Key Performance Indicators (KPI) were used in the Analysis and Computer Simulation of a Continuous Wave Radar Detection System in MATLAB environment. The KPI are Delay time, beat frequency, maximum range, radar cross section and blind speed. In general, most function of radar system are time dependent and the time of synchronization between the transmitter and the receiver is required for range measurement. The beat frequency is the difference in frequency between the transmitted and received signals. The distance between the antenna and the reflecting objects is proportional to the beat frequency. The radar cross section measures the target ability to reflect radar signals impinged on it into the radar receiver. Blind speed refers to the relative velocity for which the frequency response of the single delay line canceller becomes zero.

Tables 1, 2, 3, 4, 5 and 6 show results obtained from the developed model. Table 1 shows the results of radar distance and normal frequency. When the radar distance range was between 0.45m and 5.4m, normal frequency range was between 600MHz and 7200MHz, respectively. It was observed that the difference between any two radar distances was 0.45m while the difference between any two normal frequencies was 600MHz. Again, the results of the radar distance and delay time is shown in Table 2. The radar distance was chosen between 0.45m and 5.4m while the delay time was chosen between 3ns and 36ns. It was found that the distance between any two radar distances was 0.45m and the difference between any two delay times was 3ns. Table 3 depicts the relationship between radar distance, normal frequency and beat frequency. When the radar distance was 0.45m, normal frequency was 600MHz and beat frequency was 0.072 KHz. Also, when the radar distance was 4.95m, normal frequency was 6600MHz and beat frequency was 87.120 KHz. The results of normal frequency and maximum range is shown in Table 4. When the normal frequency was 600MHz, the maximum range was 12.5mm. Again, when the normal frequency was 6600MHz, the maximum range was 1.14mm. Table 5 indicates the results of radar distance and radar cross section. For a distance of 0.45m, the radar cross section was $1.029\, x\, 10^{-6} m^2$. Also, when the radar distance was 4.05m, the radar cross section was $538.31\, x\, 10^{-3} m^2$. Again, when the radar distance was 5.4m, the radar cross section was $2.223 m^2$. However, the results of radar distance and radar blind speed is shown in Table 6. At the distance of 0.45m, 0.9m, 1.8, 2.25m, 3.6m and 4.5m, the blind speed gave a constant value of $125 m/s$. Also, at a distance of 2.7m and 3.15m, the blind speed gave almost the same value of $124.5 m/s$ and $124.25 m/s$ respectively. When these results/findings are compared with the previous studies (Akash and Anirudh, 2015), it was observed that the developed model gave a more significant results that are accurate, reliable and consistent than the previous studies.

Table 1: Radar distance and normal frequency

Distance (m)	Normal Frequency (MHz)
0.45	600
0.9	1200
1.35	1800
1.8	2400
2.25	3000
2.7	3600
3.15	4200
3.6	4800
4.05	5400
4.5	6000
4.95	6600
5.4	7200

Table 2: Radar distance and delay time

Distance (m)	Delay Time (nanosec)
0.45	3
0.9	6
1.35	9
1.8	12
2.25	15
2.7	18
3.15	21
3.6	24
4.05	27
4.5	30
4.95	33
5.4	36

Table 3: Radar distance, normal frequency and beat frequency

Distance (m)	Normal Frequency (MHz)	Beat Frequency (KHz)
0.45	600	0.072
0.9	1200	2.880
1.35	1800	6.480
1.8	2400	11.520
2.25	3000	18.000
2.7	3600	25.920
3.15	4200	35.280
3.6	4800	46.080
4.05	5400	58.320
4.5	6000	72.000
4.95	6600	87.120
5.4	7200	103.680

Table 4: Normal frequency and maximum range

Normal frequency (MHz)	Maximum Range (mm)
600	12.5
1200	6.25
1800	4.17
2400	3.125
3000	2.5
3600	2.08
4200	1.79
4800	1.5625
5400	1.39
6000	1.25
6600	1.14
7200	1.04

Table 5: Radar distance and radar cross section (RCS)

Distance (m)	RCS (m^2)
0.45	$1.029 x 10^{-6}$
0.9	$65.87 x 10^{-6}$
1.35	$721.15 x 10^{-6}$
1.8	$4.2156 x 10^{-3}$
2.25	$16.08 x 10^{-3}$
2.7	$48.40 x 10^{-3}$
3.15	$122.55 x 10^{-3}$
3.6	$269.80 x 10^{-3}$
4.05	$538.31 x 10^{-3}$
4.5	1.029
4.95	1.860
5.4	2.223

Table 6: Radar distance and radar blind speed

Distance (m)	Blind speed (m/s)
0.45	125
0.9	125
1.35	127.5
1.8	125
2.25	125
2.7	124.5
3.15	124.25
3.6	125
4.05	126
4.5	125
4.95	123.75
5.4	126

4.2 Analysis of radar distance and normal frequency

Figure 3 indicates the graph of normal frequency against distance. It is observed from the graph that when the frequency increases, the distance increases. Again, when the frequency decreases, the distance also decreases. The implication of this observation is that the modulation frequency needs to be increased for the detection of fast-moving objects and decreased for the detection of slow-moving objects. When this was compared with previous studies (Richards et al., 2010), it was discovered that the developed model gave an improved result in the modulation of frequency.

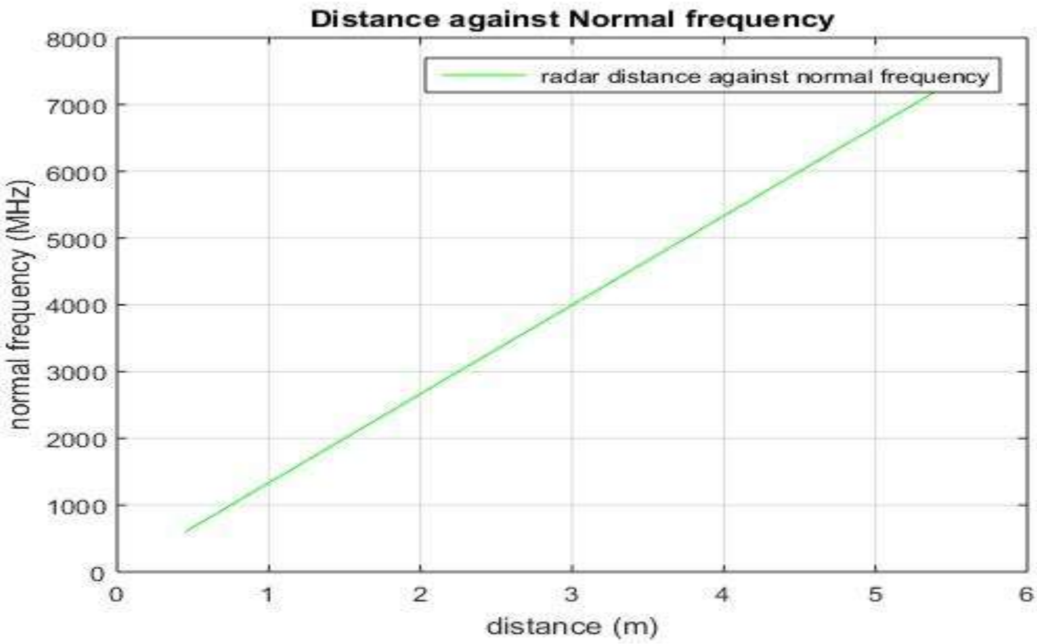

Fig. 3: Graph of normal frequency against distance

4.3 Analysis of radar distance and delay time

In Fig. 4, it is found from the graph that when the delay time increases, the distance increases. Also, when the delay time decreases, the distance also decreases This shows that the delay time contributes to the detection of targets. For the detection of fast-moving targets, higher delay time is required while for slow-moving targets, lower delay time is required. When compared with previous studies (Wahju, 2013), the developed model gave an improved result in the area of target detection as the sensitivity of the radar sensor was increased.

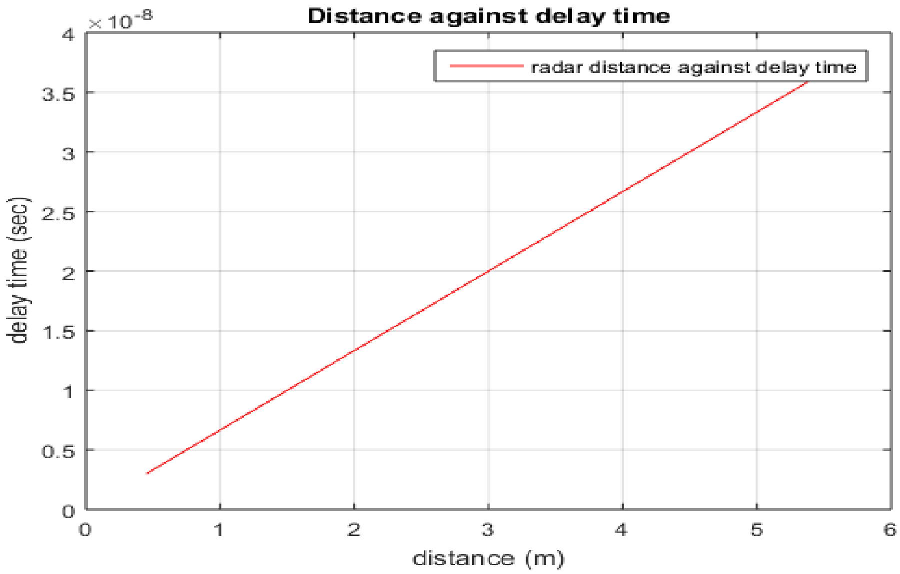

Fig. 4: Graph of delay time against distance

4.4 Analysis of radar distance, normal frequency and beat frequency

Figure 5 shows the graph of frequency against distance. It was observed from the graph that an increase in frequency brought about an increase in distance and a decrease in frequency brought about a decrease in distance. It is also observed that the plot of beat frequency against distance remains constant along with the distance range at a very low frequency. This shows a high degree of deviation of normal frequency from the beat frequency and also depicts the radar's high sensitivity to target detection. When this was compared with previous studies (Jing, 2010), there was a great difference in the beat frequency and normal frequency. Hence, the Doppler effect of the developed model was improved.

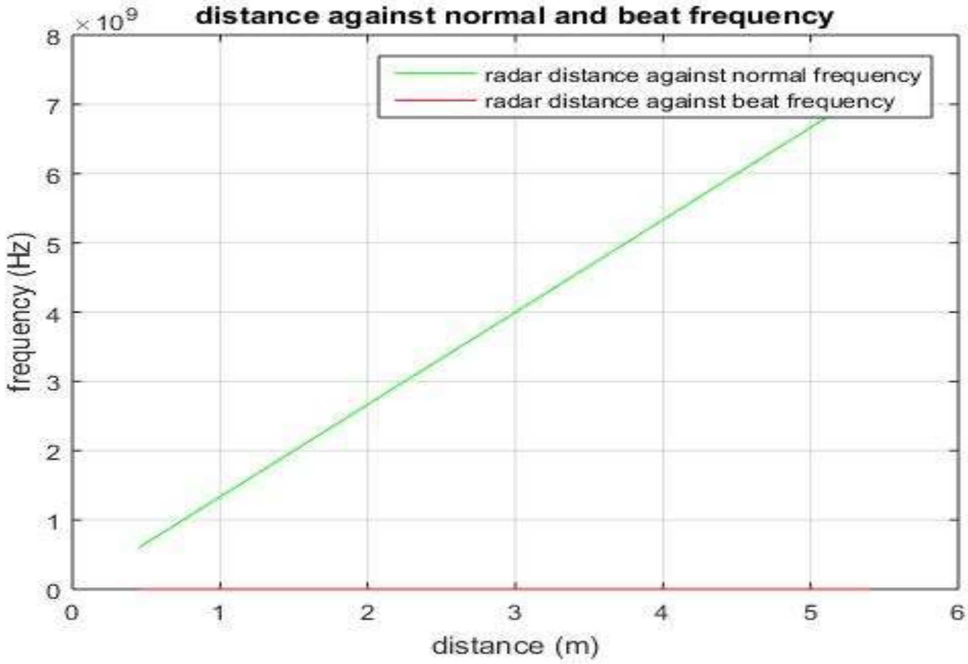

Fig. 5: Graph of frequency against distance

4.5 Analysis of normal frequency and maximum range

Figure 6 indicates the graph of maximum range against normal frequency. It was observed from the graph that the maximum range is decreasing exponentially with increasing normal frequency while normal frequency is decreasing linearly with increasing maximum range. This shows that target detection depends on the range of the target. Also, the more the maximum range, the higher the detection rate. When compared with previous studies (Mahmod and Samaa, 2013), the developed model gave an improved result as the radar sensitivity was increased in the model.

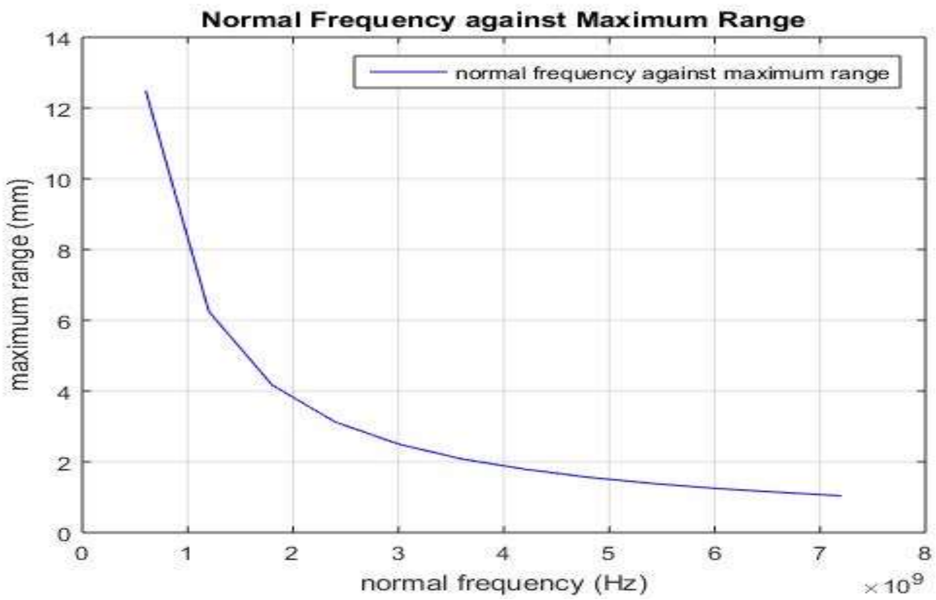

Fig.6: Graph of maximum range against normal frequency

4.6 Analysis of radar distance against radar cross section

Figure 7 shows the graph of radar cross section against distance. It was found from the graph that the radar cross section increases exponentially with an increase in radar distance and decreases linearly with a decrease in radar distance. This depicts that moving target is easily detected when the radar cross section is increased. When this was compared with previous studies (Sulaiman et al., 2013), the developed model gave an improved result as the sensitivity of the radar sensors was increased by the multiple filtration processes of the noise signal.

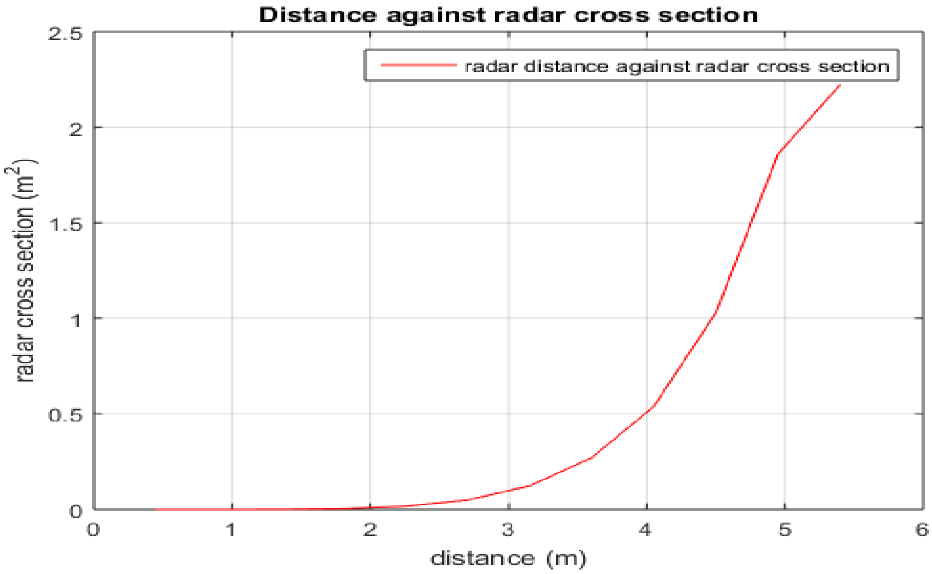

Fig. 7: Graph of radar cross section against distance

4.7 Analysis of radar distance and blind speed

Figure 8 indicates the graph of radar blind speed against distance. The graph shows a triangular wave of the modulation process and also indicates that moving targets in an irregular pattern can be detected by the designed model. However, the developed model is not limited to targets moving in a straight line but for targets moving in any direction. When compared with previous studies (Issakov, 2010), targets of irregular pattern in movement were identified as ghost targets but the developed model was able to observe the target's change in velocity even in an irregular direction.

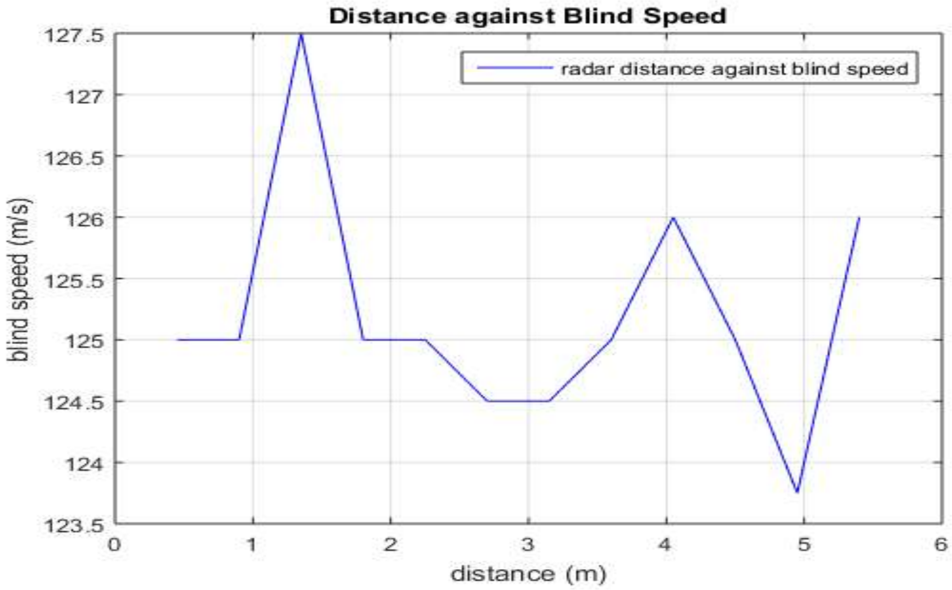

Fig. 8: Graph of radar blind speed against distance

5. Conclusions

MATLAB programs have been developed to determine the delay time, beat frequency, blind speed, normal frequency, radar cross section, and used to plot curves of these parameters against distances. The simulation of Frequency Modulated Continuous Wave radar used signals processing techniques in MATLAB to find the degree of deviation from the normal frequency to beat frequency of the radar. The performance of the FMCW radar system in a moving target environment was analyzed in accordance with the bandwidth of the modulating frequency, pulse repetition time, bandwidth of FIR filter and distances between targets. The results were able to effectively detect normal frequencies whenever there was a change in radar distance within the moving targets' environment.

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