S-band FMCW Radar for Target Tracking and Monitoring

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***Abstract*—A Frequency Modulated Continuous Wave (FMCW) Doppler radar was assembled to detect human as sample target. Its operating frequency is at 2.4GHz with transmitting power of 10.41 dBm. Range resolution of the radar is 2.8 meters at 53.2MHz signal bandwidth and chirp waveform of 40ms. The radar exploits Doppler principle to acquire the range and velocity information of targets whilst a Moving Target Indicator (MTI) pulse canceller is utilized to filter incoming noise signal. With the use of Chirp period-bandwidth product Frequency Modulated (FM) waveform and deramping process, the radars' Signal to Noise Ratio (SNR) was improved up to 42 dB. The attained maximum range is about 200 meters for a target with Radar Cross Section (RCS) of 1m^2. The constructed radar is capable to measure the speed of moving target at 0.645m/s and above with great accuracy. The radar can detect and determine the position of pedestrians with 0.18% percentage error.**

***Index Terms*—FMCW Radar; Doppler; Pulse-Canceller; Target Monitoring.**

I. INTRODUCTION

Safety of the community is of great concern in the present-day. Radar as a device to monitor the community i.e. in airport, shopping malls, neighborhood and road traffic has been employed since the 1950s. As an example of road traffic situation; more than 1500 pedestrians around the world are involved in road fatalities on a daily basis. It has also been noted that the number of cases is even higher in low-income countries as compared to the high-income countries [1-2]. Weak return echoes from a human being; in which sometimes failed to be detected by conventional sensors or radars is among the major factors why such the traffic accidents happened. Most installed sensors on vehicles are unable to detect the presence of the pedestrians due to very weak backscattering signals. Consequently, a detection and ranging system with greater sensitivity and ability to detect the weak signals have to be assembled. There are two main factors that influence the sensitivity of most radar systems namely the resolution and the sweep bandwidth [3]. Many research groups and designers from the industry are focusing on the best comprehensive approaches for decades in the pursuant of betterments in radar's sensitivity.

Multiple Input Multiple Output (MIMO) technique is among the latest technology approaches for an application that can improve pedestrian safety [4]. The assembly comprises of multiple transceiver antennas embedded on to the automotive remote sensor system. Such setup can produce equal resolution as of conventional phased array while at the same time have a reduced the number of array elements [5]. To date, it has been reported that a MIMO radar of 8 array elements can offer comparable resolutions as of a phased array radar with 16 array elements. In addition, higher sensitivity system can also be generated by using the MIMO technique. The drawback now is that the MIMO radar design can become super complex and much more complicated. It will become a requirement where an advanced Data Acquisition (DAQ) system is needed to support fast scanning of the radar system [6]. These are real challenges in the traditional and conventional ways of radar design where the result involves increases in cost in the per unit assembly. In retrospect, the radar would be too bulky to be applied as a mobile safety solution.

This paper aims to highlight the processes involved in the design of what can be considered as an inexpensive Single Input Single Output (SISO) FMCW radar system. The system is able to detect the target while maintaining the complexity of the radar circuitry and its size at a minimum. Prior to the inception of such system, numerous experiments had been previously conducted to investigate the feasibility of any radar for such purpose. In addition, linear-triangular of FM waveform and Doppler principle has been studied in order to apply the technology in coming up with a radar system that can accurately measure the range and velocity of every target.

II. RADAR DESIGN & BLOCK DIAGRAM

The block diagram of the FMCW Doppler radar design is displayed in Figure 1. It consists of two main sub-systems namely the transmitter and receiver systems. Each one of them was constructed by assembling numerous electronic components. Their specific aspects are outlined in the next sections. During the build-up of the radar design, every part was selected after considering their cost-effectiveness while maintaining the capability of detecting the weak signal of moving the target.

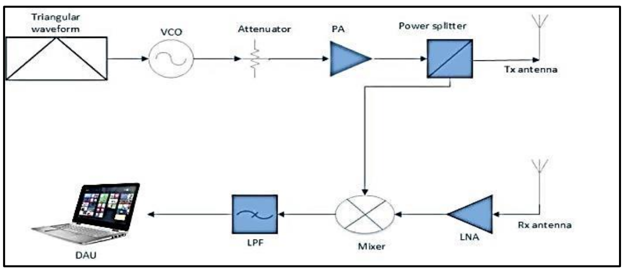

Figure 1: FMCW radar block diagram [7]

A. Selection of Operating Frequency

Operating frequency is one of the critical aspects that require close attention by radar designers. The FMCW Doppler radar system was set to operate at the S-band operating frequency of 2.4GHz. This can be considered the cheapest option since the frequency range transceiver is abundant and has been widely used in telecommunication as well as for industrial, scientific and medical applications. Initial consideration was also directed in the exploration of 5GHz as the operating frequency. However, the idea was called off after realizing that frequency higher than 3GHz can be severely subjected to atmospheric attenuation particularly in a tropical climate in which the signal energy decreases due to absorption [8] hence decreases the maximum detection of the target range. The radar sensor will require higher transmit power in order to achieve farther detection range just as outlined by the mathematical relationship in Equation (1).

$$R_{\max} = \sqrt[4]{\frac{P_t G^2 \lambda^2 \sigma}{4\pi^3 P_r}} \tag{1}$$

where *Pt* is the transmit power, *G2* presents for antenna gain, λ is the radar operating wavelength, δ is the radar cross section and *Pr* is the received power. From the mathematical analysis, it can be concluded that in order to achieve twice the normal target range would require factorized transmit power of 16.

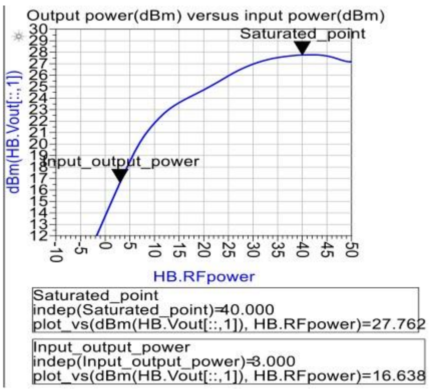

Figure 2: The measured output power of the amplifier for 2.4GHz operating frequency.

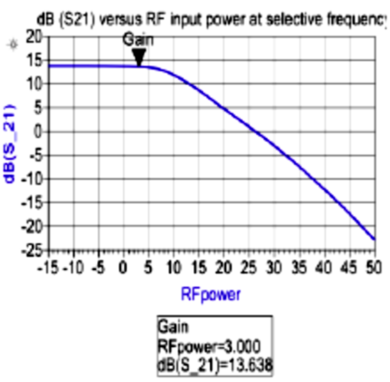

Figure 3: Gain power of the amplifier

B. Power Amplifier Modelling

The amount of energy signal emitted into space is very much depended on the output power produced by the power amplifier. RF waveform generator will not able to produce or manage high power transmission and for that reason, the power amplifier is deployed. As one of the components in the transmitter system, it amplifies the signal and ensures that the output power meets the radar requirement. Basically, by increasing the input power, such would increase the output power which is typically in parallel with its gain. Such principle is only valid prior the electronic component reaches its saturation point. During the assembly, in order to avoid excessive supply of input power as well as to determine the effective parameters for 2.4GHz operating frequency, all parameters were tested by using simulation platform the Agilent Advanced Design System (ADS) software.

Figure 2 demonstrates measured output power with the respective input power. As be seen in the shown figure, the output power increases gradually prior to point of 27.762 dBm. It then remains unchanged for a certain period and subsequently decreases. This suggests that input power lower than 40 dBm can be amplified effectively by using the amplifier component. Figure 3, on the other hand, shows power gain (dB unit) against input power. The figure illustrates that the gain starts to reduce at 5 dBm input power where the region is known as nonlinear operation. In a nutshell, 3 dBm input power with 13.638 dB gain power and 16.638 dBm output power can be recommended as the specification of the radar's power amplifier.

C. Radar Waveform

The linear triangular waveform in frequency modulation mode was adopted in the design in order to ensure that the radar system is capable of measuring range and velocity of the target. Figure 4 illustrates the modulation pattern of the waveform.

The respective linear up-chirp and down-chirp of the waveform managed to overcome the inaccuracy of range measurement. Linear frequency variation over time provides an equal and opposite effect on the Doppler frequency. The frequency of the beat signal oscillates around central beat frequency in which mimic the actual target range [7].

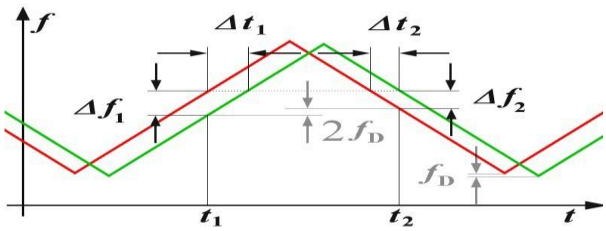

Figure 4: Linear triangular waveform [7]

The range and velocity of the moving target can be measured using the Doppler principle as shown in Equation (2) and Equation (3) respectively.

$$f_D = \left\| \frac{\Delta f_1 - \Delta f_2}{2} \right\| \tag{2}$$

$$R = \frac{c_0 * \Delta t}{2} = \frac{c_0 * f_D}{2 * \frac{B}{T}} \tag{3}$$

where f_D presents for Doppler frequency, C_0 is the speed velocity, B is the waveform bandwidth, T is the chirp period and Δt is the time difference.

D. Data Acquisition System (DAQ)

The computer-based system was used for the DAQ purposes. An i7 PC was used to collect, store, convert and process the raw data [7]. Since all the four applications were performed on one device, it optimizes the size and cost as well. Figure 5 summarizes the computer-based system configuration. The raw data was collected using an audio recorder with Waveform Audio (WAV) format, stored in computer hard disk and then processed by utilizing MATLAB computational software.

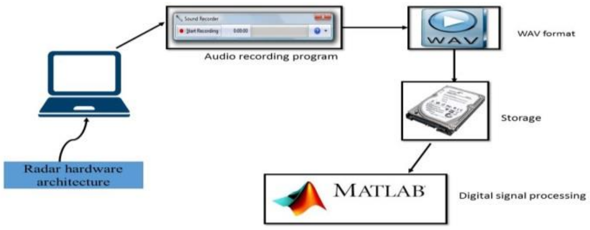

Figure 5: Computer-based DAQ system

III. RADAR HARDWARE ASSEMBLY

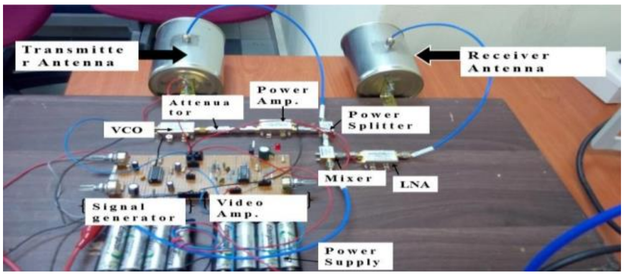

Figure 6: Assembled FMCW Radar [7], [9]

The proposed FMCW Doppler radar system can be observed in Figure 6. A linear triangular waveform with 3V maximum amplitude was applied to the Voltage Controlled Oscillator (VCO) in order to produce a linear frequency modulated waveform at the S-band range. A 3 dB attenuator was set up as prevention for any excessive input power before power amplifier of 13.638 dB gain was assigned. The transmit signal power was split into two ways; one to transmit antenna and another to mixer component. Two circular antennas with 8 dBi gain and 72.50 beam width were used as the transmitter and the receiver. Collected return signals by the receiver antenna were amplified by Low Noise Amplifier (LNA) with 14.1 dB gain and 0.74 dB Noise Figure. The deramping process i.e. a mixing process between return signals and a portion of transmitting signals was then executed. The beat signal which contains range and velocity information of the target can be produced using such process. All signals afterwards were henceforth compiled by the computer-based DAQ system readied for digital signal processing. The finalized radar parameters were measured and summarized as listed in Table 1.

IV. PRE-TRIAL MEASUREMENT & DISCUSSIONS

Several experiments were carried out in one of the laboratories at the department to validate the radar system's reliability when determining the range and velocity of targets. Figure 7 shows the measured velocity of a moving pedestrian which moved at the maximum speed of 13.735 meters. The Fast Fourier Transform (FFT) was used to extract the target

Table 1
Radar Parameter

No	Parameter	Value/ Selection	No	Parameter	Value/ Selection
1	System configuration	FMCW	7	Carrier frequency	2.4GHz
2	Waveform modulation pattern	Linear triangular modulation	8	RCS (Human body)	1m^2
3	Minimum detectable signal	-86.33dBm	9	SNR	42dB
4	Receiver gain	55.76dB	10	Range resolution	0.28meters
5	Transmit power	10.41dBm	11	Bandwidth	53.2MHz
6	Antenna gain	8dBi	12	Power supply	12V

frequency shift based on the Doppler principle. As be seen in the display, there are two types of energy distribution patterns exist. Hence, it can be assumed that the target moved at two different speeds at certain periods of time. The identification of the target movement is as follows.

1. Between 5s to 26s: walking away from the radar hardware with approximately 0.654 m/s speed
2. Between 26s to 27s: object halted for 1second
3. Between 27s to 24s: object ran towards the radar hardware with 1.962m/s average speed

From the result, it can be observed that the energy density was greater as when the target moved closer to the radar hardware and vice versa.

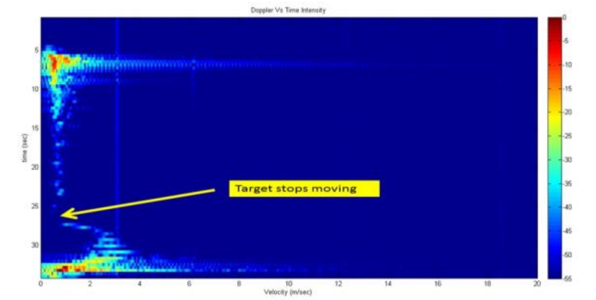

Figure 7: Measured velocity of the target movement

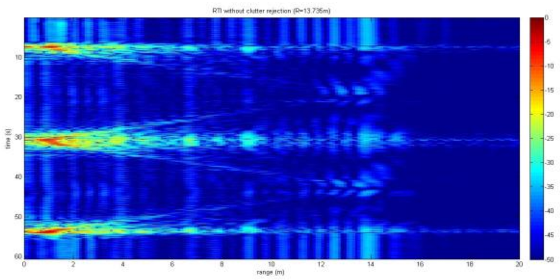

Figure 8: Range measurement without pulse canceller.

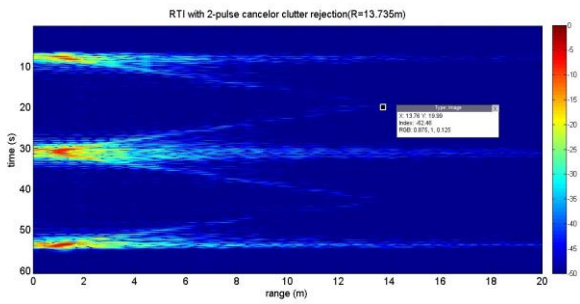

Figure 9: Range measurement with pulse canceller.

Figure 8 shows the measured range of the moving target. There were many clutters that originated from other objects which had higher reflectivity more than that of human body since the experiment was carried out in an indoor laboratory. For that reason, an MTI pulse chancellor technique was deployed to filter out the clutters. Two successive pulses were subtracted in order to identify the moving target signal.

Figure 9 shows a measured range of the target after the pulse chancellor technique implementation. It illustrates better view with the lesser noise signal. From the figure, the target movement can be classified clearly as follows.

1. Between 7.62s to 20s: target moves away
2. Between 20s to 30s: target moves forward
3. Between 30s to 42s: target moves away
4. Between 43s to 53s: target moves forward

The target moves at a maximum range of 13.6 meters while its real maximum range is at 13.735 meters. Hence, its percentage error is 0.18 %.

Another experiment conducted is in a lab where a target moves at a maximum range of 16 meters. Figure 10 depicted the targets' speed, energy distribution and direction of each scenario. In detail, the result characterizes the target movement scenarios as follows.

1. 6s until 18s: walk away from the radar hardware
2. 18s until 30s: walk towards from the radar hardware
3. 30s until 37s: run away from the radar hardware
4. 37s until 45s: run towards the radar hardware
5. 45s until 50s: sprint away from the radar hardware
6. 50s until 55s: sprint towards from the radar hardware.

Some of the findings are the average observed speed of the target during walking is 1.25m/s, running is 2.375m/s and sprint is 3.188m/s. It could also be concluded that the speed measurement at shorter target distance is more efficient and reliable as compared to the higher distance. One of the main factors is the amount of SNR is inversely proportional to the target range. It decreases when target range increases. This is because, transmit and the backscattered signals need to travel longer in space before they are collected by receiver antenna in which they suffer from severe losses along the travelling, for higher distance case. Hence, it decreases the target speed measurement reliability.

V. CONCLUSION

In conclusion, economical FMCW radar was constructed with the ability to detect weak signal from movements of the human target. From the preliminary result analysis, it can be concluded that the radar can measure target speed of higher than 0.654m/s as well as determining target range with 0.18% percentage error. With major improvements, it is expected that such proposed radar design has the potential to be incorporated into a system that can increase safety for the common public.

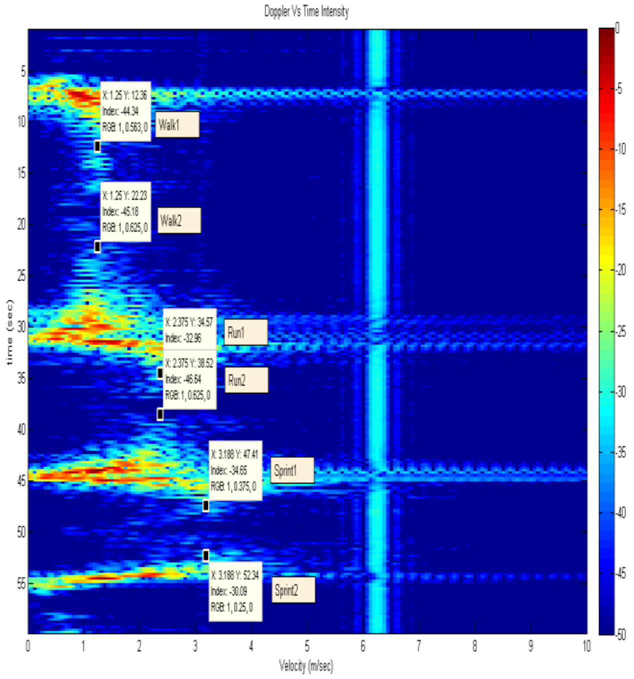

Figure 10: Human movements in three scenarios at 16m range.

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