Araid Journal of Science and Technology (AJST)
Higher Institute of Science and Technology-Al Shmokh

مجلة الرائد للعلوم والتقنية
المعهد العالي للعلوم والتقنية- الشموخ

Imaging and processing signals of a Moving Targets with FMCW Synthetic Aperture Radar for Different Velocities

Marai M. Abousetta and Salwa Mahmoud Ahmed Ibrahim
Department of Electrical and Computer Engineering Libyan Academy, Tripoli, Libya

m.abousetta@ academy.edu.ly   220100114@ academy.edu.ly

ABSTRACT

This paper simulates the operation of Frequency Modulated Continuous Wave Synthetic Aperture Radar (FMCW-SAR) with nonlinearity compensation to assess its impact on contrast and range resolution. The simulation generates an FMCW signal and models target movement at various velocities, illustrating how speed variations affect received signals and range profiles. Nonlinearity compensation mitigates distortions that could hinder target detection accuracy.

The analysis underscores the importance of signal processing in radar performance, with visualizations revealing insights into the relationship between target velocities and sensor energy. Additionally, the study explores object detection and tracking techniques to identify and follow moving humans in real-time video streams, particularly in border control scenarios. By utilizing a cascade classifier for face detection and hue channel tracking, the system effectively monitors individuals, enhancing safety and operational effectiveness in dynamic environments. Overall, this simulation provides valuable insights into FMCW-SAR performance and its applications in surveillance and target monitoring.

KEYWORDS: Frequency Modulated Continuous Wave FMCW Radar , Synthetic Aperture Radar SAR , HSV Hue saturation value

.

الملخص

تحاكي هذه الورقة تشغيل رادار الموجة المستمرة ذات الفتحة الاصطناعية المعدل التردد (FMCW-SAR) مع تعويض اللاخطية لتقييم تأثيره على التباين ودقة المدى. كما تولد المحاكاة إشارة FMCW ونماذج الحركة المستهدفة بسرعات مختلفة، مما يوضح كيفية تأثير تغيرات السرعة على الإشارات المستقبلة وملفات تعريف النطاق. يعمل التعويض اللاخطي على تخفيف التشوهات التي قد تعيق دقة اكتشاف الهدف.

ويؤكد التحليل على أهمية معالجة الإشارات في أداء الرادار، حيث تكشف التصورات عن رؤى حول العلاقة بين السرعات المستهدفة وطاقة المستشعر. بالإضافة إلى ذلك، تستكشف الدراسة تقنيات الكشف عن الأشياء وتتبعها لتحديد ومتابعة البشر المتحركين في تدفقات الفيديو في الوقت الفعلي، خاصة في سيناريوهات مراقبة الحدود. ومن خلال استخدام المصنف المتتالي لاكتشاف الوجه وتتبع قنوات الألوان، يقوم النظام بمراقبة الأفراد بشكل فعال، مما يعزز السلامة والفعالية التشغيلية في البيئات الديناميكية. بشكل عام، توفر هذه المحاكاة رؤى قيمة حول أداء FMCW-SAR وتطبيقاته في المراقبة ومراقبة الأهداف.

1. INTRODUCTION

Frequency Modulated Continuous Wave (FM-CW) radar altimeters are widely used in aircraft to accurately measure altitude above ground level. These altimeters transmit a frequency-modulated continuous wave signal and mix it with the reflected signal to produce a beat frequency proportional to the target range.

FM-CW altimeters offer several advantages over pulsed radar altimeters, including lower transmitter power, higher resolution, and the ability to track multiple targets simultaneously.

A comprehensive reviews of FMCW SAR technology reveals several developments. The novel combination of FMCW technology and SAR techniques leads to lightweight, cost-effective high-resolution imaging sensors[1]. Signal Processing Techniques with Relative Speed-Based Refocusing, A single-channel FMCW-GBSAR moving target refocusing method based on relative speed has been proposed by researchers like Wan, J., Zhou, Y., and Zhang, L.[3]. The researchers Xin Qin, Jiang Zhihong, Cheng Pu, and He Mi introduced Digital Beamforming (DBF) technology to improve FMCW SAR system performance. This approach combines multiple receive apertures to obtain high resolution at low pulse repetition frequency in Digital Beamforming Approach [2]. Also Meta, Adriano, Peter Hoogeboom, and Leo P. Ligthart had been studied A Moving target indication enhancement in FMCW SAR using deramped randomized stepped-frequency signals [4] , while Casalini, E., Frioud, M., and Small, D. have worked on refocusing FMCW SAR moving target data in the wavenumber domain for Advanced Imaging Techniques [3]. However Park, Junhyeong and colleagues proposed a novel method for SAR image extraction using an automobile SAR (AutoSAR) system, demonstrating improved image quality in Emerging Research [6]. Authors, He, Jing, et al. evaluated High resolution moving targets imaging algorithm of FMCW SAR. [7], Also For Comprehensive System Design, Ting, Jui-wen explored FMCW-SAR system design for near-distance imaging, addressing critical challenges like phase noise and signal nonlinearity [8].

2. RADAR OPERATION

Basically, radar consists of an antenna, a duplexer, a transmitter, and a receiver (Figure-1). Since the same antenna is used for both transmitted and reflected waves, this system is known as monostatic radar [9]. The duplexer is used to send power to antenna that emits periodic pulses of electromagnetic waves. [10]

When there is an item present, the incident waves are absorbed by it as they move through open space. After then, the item reradiates the surrounding waves. A portion of this reradiated wave makes a reflected wave back to the antenna. The duplexer directs the wave that is reflected at the antenna toward the receiver. [11]

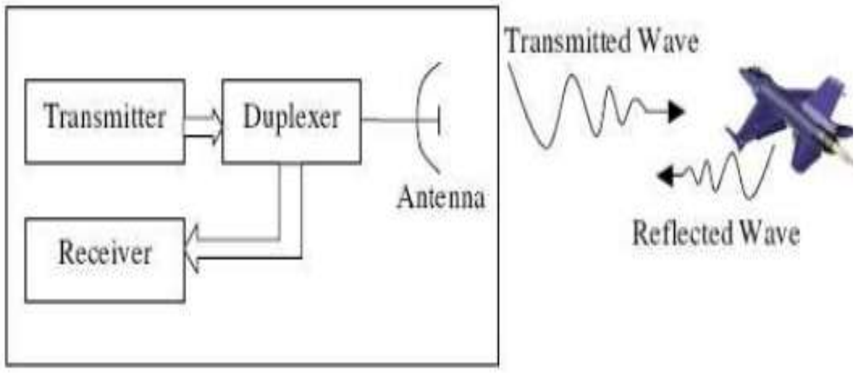


Figure 1 :Simple monostatic radar configuration

- As a result, an object's presence at the receiver detects a signal after the pulse is transmitted (Figure-2).The range of radio waves, which are a type of light, and their speed are related to the delay π. The speed of light, represented by c, is 3x108 m/s in free space.

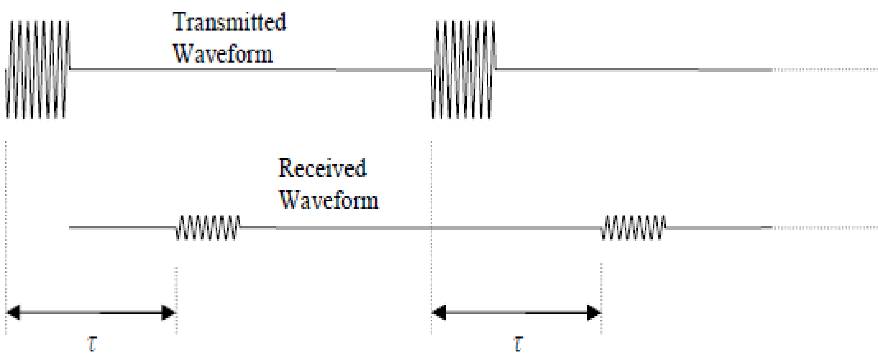


Figure 2: Signal waveforms in pulse modulated radar. The delay τ and received power are related to range of object.

2.1 FM-CW Radar

FMCW radars assess velocity and range using frequency modulation techniques. A signal containing these data will be produced as a function of the signals that are transmitted and received. Chirping is the term for a frequency modulated signal whose frequency varies with time. A fundamental schematic of an FMCW radar sensor

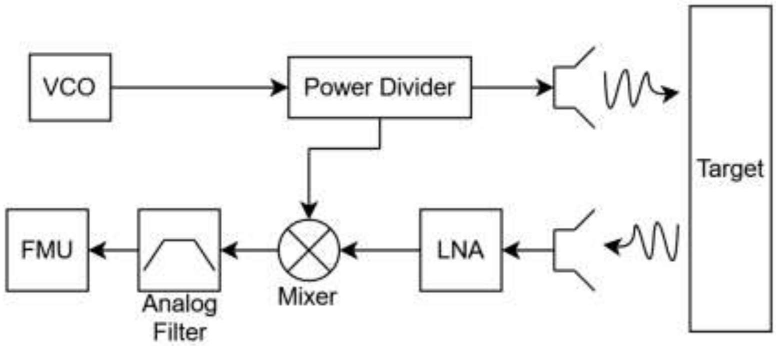


Figure 3: FMCW radar schematic

Operation of FM-CW Radar Continuous wave (CW) modulation is used by FM-CW radars in place of pulse modulation. A subclass of CW radars is called FM-CW. However, in addition to CW, which only has speed detection), it is capable of range detection. It is a well-known fact of the Doppler effect that a shift in frequency happens if the oscillation source and observer are moving relative to one another. Given a transmitted wavelength of λ and an object's range of R, the total phase difference φ between the transmitted and received waves may be calculated using 4πR / λ. R and φ vary over time in the case of relative motion. The angular frequency expression for this change is as follows:

$$w_d = \frac{d\phi}{dt} = \frac{4\pi}{\lambda}\frac{dR}{dt} = \frac{4\pi V_r}{\lambda} \qquad (1)$$

Vr is the radial velocity of object with respect to radar. If f_o is the frequency of oscillation of radar , Doppler frequency is:

$$f_d = \frac{2V_r f_o}{c} \qquad (2)$$

When relative motion occurs, CW radars pick up a signal that has a frequency shift of f_d. However, using this information to calculate the range of a received signal is not appropriate.

The transmitted signal in FM-CW radars is frequency modulated. Hence, even when the target is stationary, the delayed signal is received at a different frequency. The radar creates a mixed signal that contains information about the target's speed and range by combining transmitted and received waves. A basic FM-CW radar's block diagram is shown in Figure

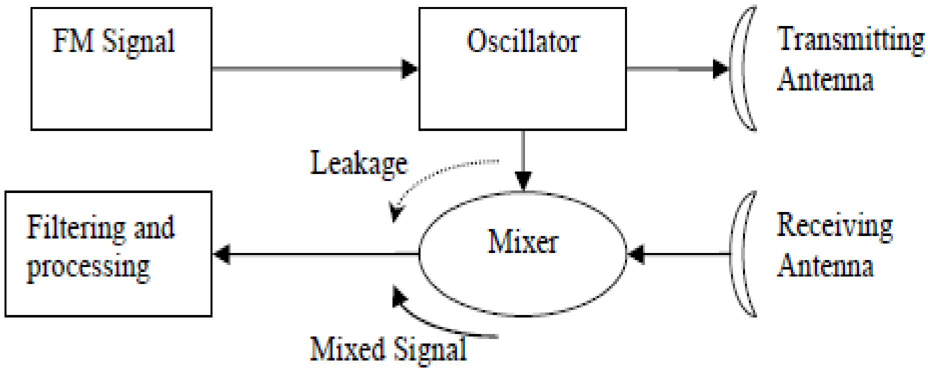


Figure 4 : Block diagram of a simple FM-CW radar.

FM modulated signal s_t (t) is transmitted where θ_t (t) is phase and A is the amplitude of the transmitted wave. Because of the reflection mechanism of electromagnetic waves and reflections from different ranges s (t) r is received.

$$s_r(t) = A_r(t-\tau)\cos(\theta_t(t-\tau)+\phi_0) \quad (3)$$

The performance of the Continuous Wave (CW) radar on detecting the target depends upon demanded value of Signal to Noise Ratio (SNR) and resolution range [16] by the radar system. Therefore, some considerations have been taken close

2.2 Direction of Arrival Estimation in FMCW Radar System:

The angle from which a signal, such as a wave or radio frequency, arrives at a particular location is known as the Direction of Arrival (DOA). When it comes to wireless communications and radar systems,

DOA estimation is essential for figuring out where a signal originates from or where an object is in relation to a receiving antenna or sensor array.

2.3 Calculating the Direction of Arrival Estimation in FMCW Radar System

The use of frequency modulated continuous wave (FMCW) technology for radar processing. The most popular method for accurately detecting targets with radar is this one.

Determine the difference in time between the radar signal's emission and receipt to determine a target's range using a radar signal. The range value (R) can be determined using the following equation if the difference in time (Δt) is known.

$$R = c \times \frac{\Delta t}{2} \quad (4)$$

Equation 4: Determining the target's range based on the interval between emission and receipt Emitting frequency-modulated sinusoids, also referred to as ramps or chirps, and comparing the emission with the received signal is the basic idea. This comparison, which is the mixture of the transmitted and received signals, is known as intermediate frequency (IF).

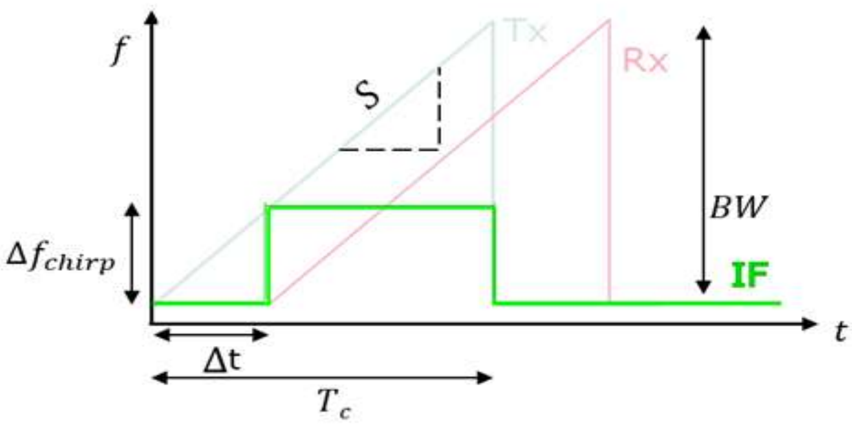


Figure 5 Representation of a ramp frequency value in relation to time (Rx and Tx). In yellow, IF

The below equation (5) is used to calculate the time difference (Δt), that show relationship between the time difference and the frequency difference

$$\frac{\Delta t}{T_c} = \frac{\Delta f_{chirp}}{BW} \quad (5)$$

- Δf_{chirp} = Frequency difference
- BW = Band width
- T_c = signal duration

Use the following equation (6) to calculate the range (R) , Calculation of the range depending on the frequency value of IF

$$R = c \times \frac{\Delta f_{chirp} \times T_c}{2 \times BW} \quad (6)$$

The value of range is solely dependent on Δf chirp. As a result, do an FFT on every ramp to identify the peak that corresponds to the range value. [13] .This FFT further gives a phase value for every ramp. [12].The phase value of an FFT with a moving target will differ significantly, but the range peak will only slightly differ on each FFT. Owing to the variations in values for every peak, it is possible to execute an additional FFT, yielding a second peak that aligns with the target's velocity. Utilize the subsequent formula to determine the velocity (v). the equation 7 for Calculation of the velocity depending on the difference in phase between each ramp

$$v = \frac{\lambda \times \Delta\omega}{4\pi \times T_c} \quad (7)$$

After completing these two FFTs, the result is a peak map with the range value and the velocity value—also referred to as the Doppler—as its two dimensions. This map, sometimes referred to as the Range-Doppler map, is a crucial outcome for determining the Direction of Arrival (DoA). The angle of the target with respect to the radar position can be found by computing the Angle of Arrival (AoA), which will yield the DoA of a target identified by a radar. A radar requires at least two antenna receivers in order to compare the receipt of the same signal across each antenna in order to determine this value.[14]

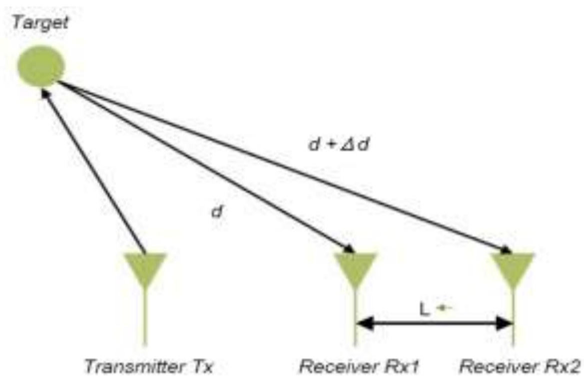


Figure 6 Representation of the difference of phase between two receivers

The phase difference between each antenna in Figure 2 is a value that may be compared. A determination of this phase value is possible at each target peak on the Range-Doppler map. Furthermore, an FFT can be performed across the antennas to generate a peak that represents the phase difference (Δω), as each antenna has a single Range-Doppler map. Let be the distance between two antennas and λ be the IF's wavelength. Utilize the subsequent formula to determine the target's angle (θ). Equation 8 is calculate of the angle depending on the difference of phase between antennae

$$\theta = \sin^{-1}\left(\frac{\lambda \times \Delta\omega}{2\pi \times L}\right) \quad (8)$$

Because $\sin^{-1}$ is a non-linear function, numbers around "0" will yield a more precise resolution of "θ" than values around "-1" and "1." Although two antennas are given as examples in this article, more antennas on the radar will yield more precise results because the FFT will have more points. The following three values are found for each target after completing these three FFTs, and they produce the DoA Range is the target's separation from the radar. The target's movement in relation to the radar antenna is measured by its velocity. The target travels away from the radar if the speed value is negative. The object moves in the radar's direction if the speed value is positive. Angle: The target's angle in relation to the radar antenna

III. MODELING AND SIMULATIONS

1. **RADAR DESIGN SYSTEM AND PARAMETERS**As illustrated in Fig. 7, a Radar system is composed of five components: transmitter, receiver, antenna, data collector, and signal processing. First, off-the-shelf electronic components are assembled to create the FMCW Radar Doppler. To assess the effectiveness of the suggested radar design, a number of experiments have been conducted. [15]

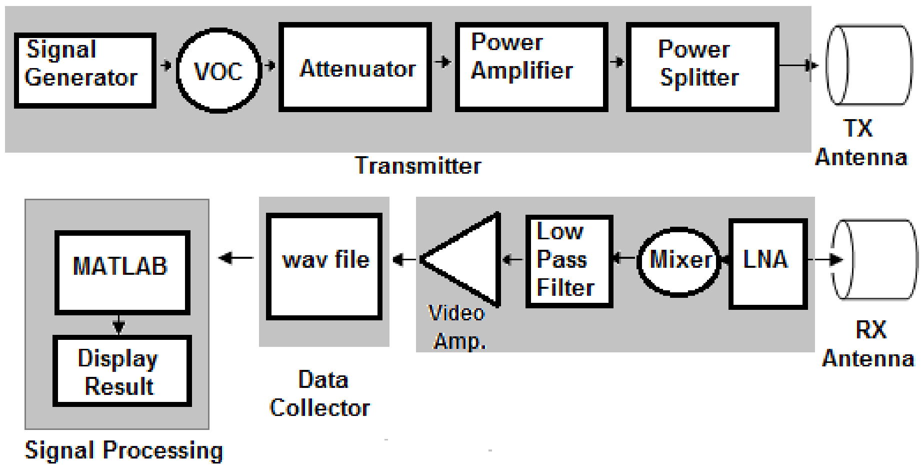


Figure 7 Proposed radar design system block diagram

2. SYNTHETIC APERTURE RADAR SAR

SAR uses a single-moving sensor to simulate a long antenna array, allowing for a finer resolution in the cross-range direction [16] .

Typically, the antenna is installed on a satellite or plane, which gives the moving platform. Motion that occurs between consecutive broadcast pulses, between a pulse's transmission and reception, and during transmission and reception are the three types of motion that can be identified during the gathering of SAR data [17].

The first type of motion is used by traditional monostatic SAR methods. Bistatic effects arise in the second type, although mobility during pulse transmission and reception is typically disregarded. But when the pulse duration lengthens, its effects become significant [18].

When employing FMCW radar sensors, this is true. One antenna is used to send and receive continuous waves in frequency modulation continuous wave (FMCW) synthetic aperture radar (SAR), a unique technology for observing the properties of ground objects.[18]

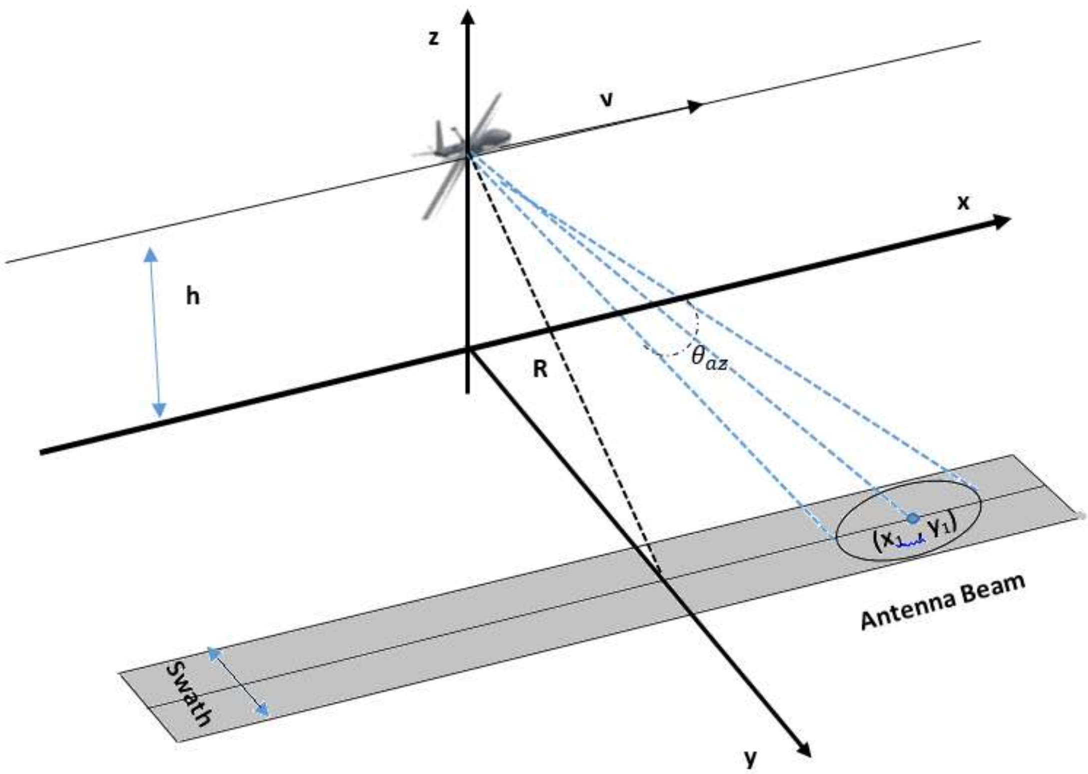


Figure 8 SAR system Geometry

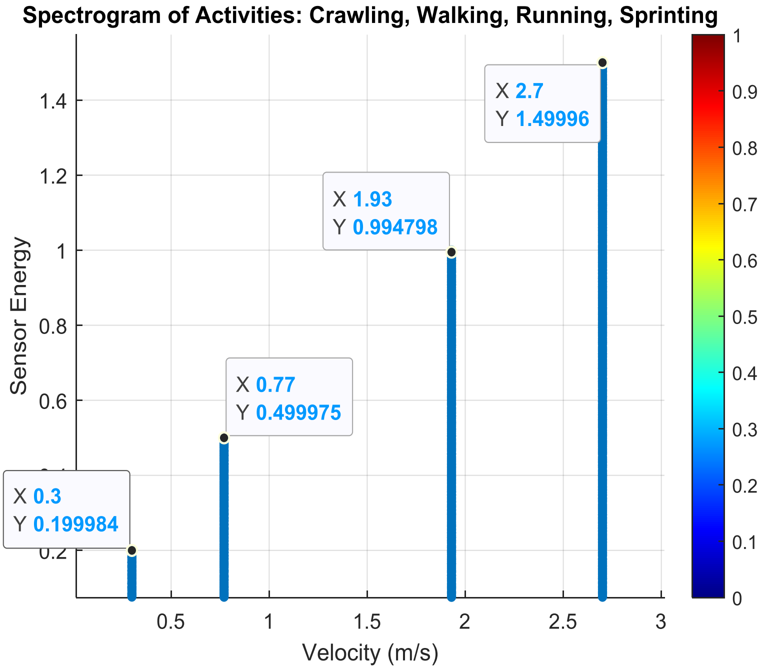


Figure 9 spectrogram of Activities: Crawling, Walking, Running and sprinting for Sensing energy of movement

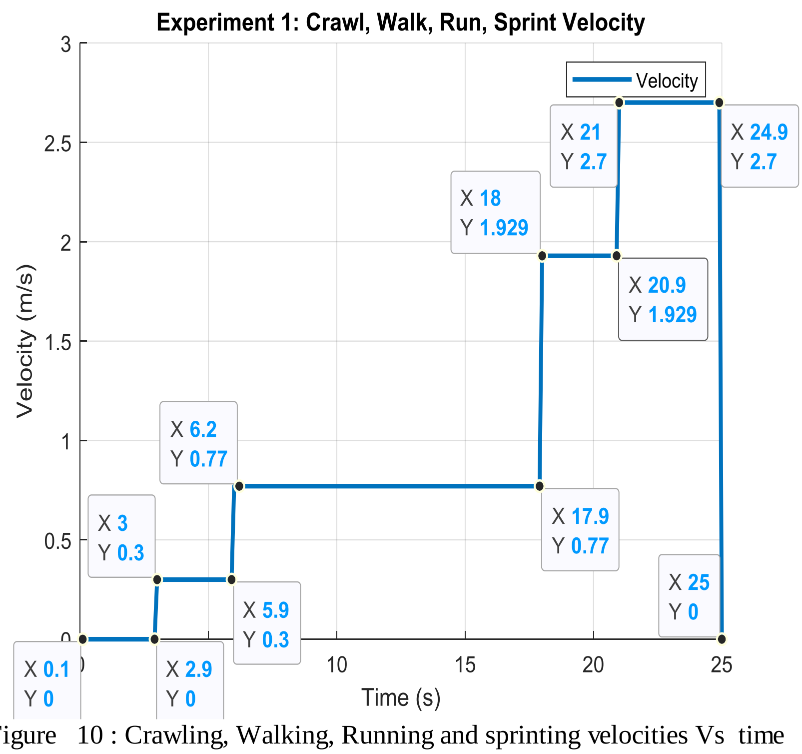


Figure 10 : Crawling, Walking, Running and sprinting velocities Vs time

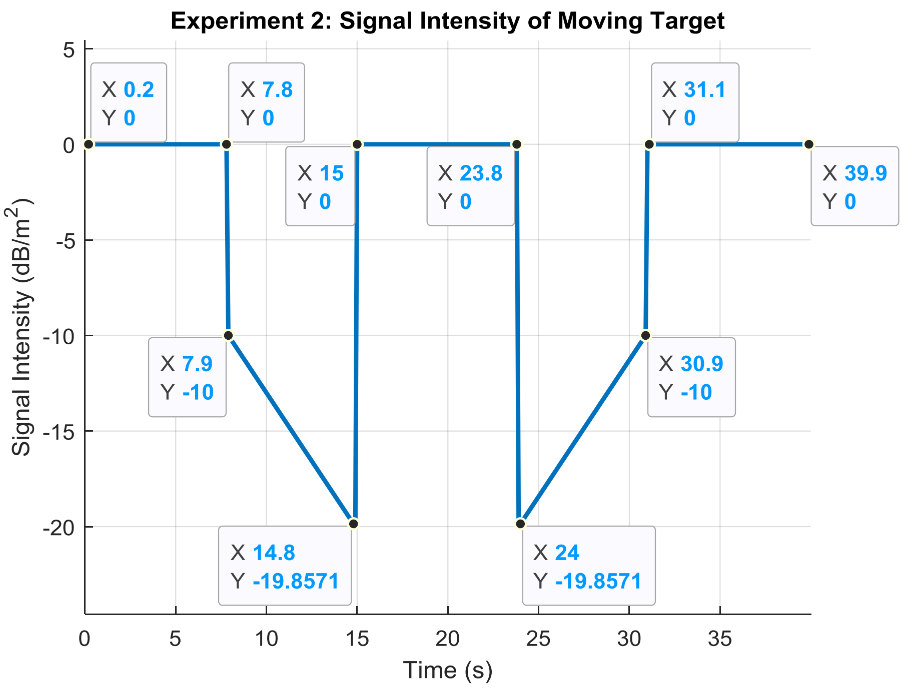


Figure 11 Signals intensities of moving Targets with different velocities Vs Time

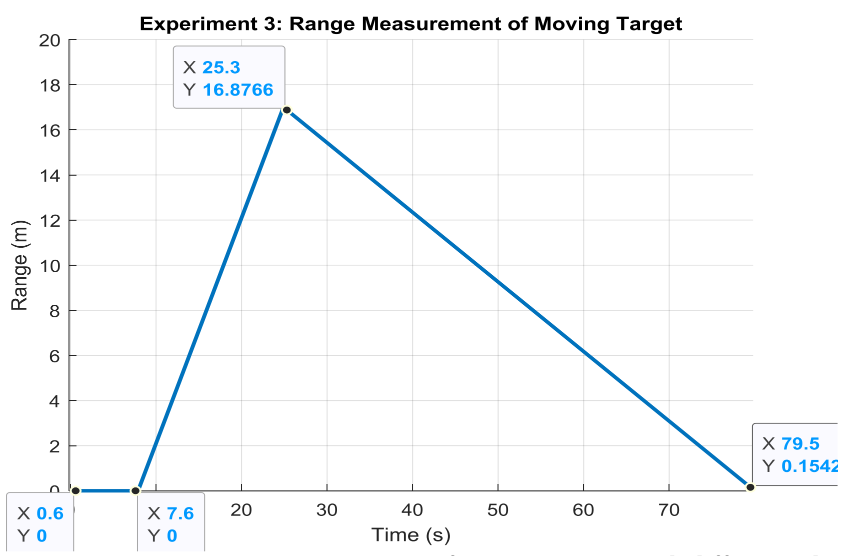


Figure 12 Range measurement of moving Targets with different velocities

Table 1 of Contrast and Range Resolution Degradation Analysis for Different Targets velocities

Target velocities m/s	Contrast 1.0e+06 *	Range Resolution Degradation:
0.3	1.9685	3.1196
0.77	2.0304	3.1459
1.929	2.2861	2.9212
2.7	1.7758	3.1481

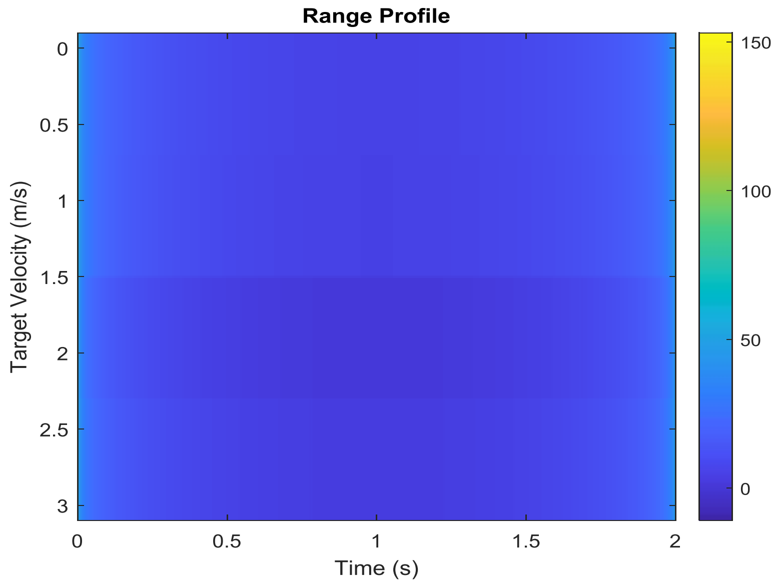


Figure 13 Range profile for Different Targets velocities

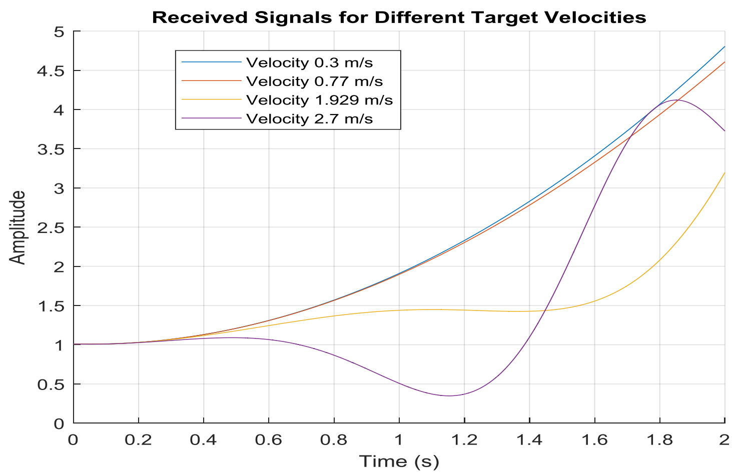
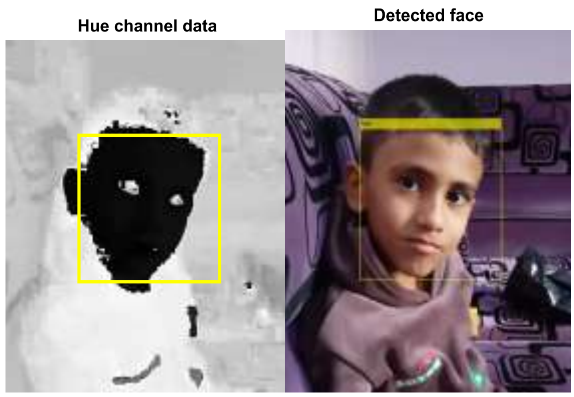


Figure 14 Received Signals for Different Target Velocities

3. FACIAL RECOGNITION:

Facial detection and tracking begins by creating a cascade classifier for detecting faces, allowing it to identify facial regions in each video frame efficiently. Once a face is detected, the code annotates the frame with a bounding box, visually indicating the detected face. Subsequently, the system processes the video frames by converting them to the HSV color space, which enhances tracking accuracy by focusing on distinctive features, such as the nose. A histogram-based tracker is employed to continuously track the face across multiple frames, adapting to changes in position and lighting conditions. This approach is particularly useful for applications in surveillance, security, and human-computer interaction, where continuous monitoring of individuals is essential.

The code demonstrates a robust method for detecting and tracking faces in dynamic environments, contributing to enhanced safety and operational effectiveness in various real-world scenarios.



(a) (b)

Figure 15: (a) face is detected, with annotates the frame with a bounding box
(b) HSV colour space focusing on distinctive features(nose).

Figure 16: Identify several moving facial regions in each video frame efficiently

CONCLUSION

The purpose of using the object detection and tracking technique is to effectively identify and follow moving objects, such as humans with different targets velocities in real-time video streams, particularly in border control scenarios where individuals may be moving at different speeds and altitudes. By employing a cascade classifier for initial face detection, the system can quickly locate facial regions within video frames, enabling rapid identification of individuals regardless of their movement dynamics.

The subsequent use of hue channel tracking, focusing on distinctive features like the nose, enhances tracking accuracy and reliability, even as subjects vary in their speed and position.

This dual approach allows for robust tracking of individuals as they navigate through the environment, making it particularly suitable for applications in border control, surveillance, and security monitoring.

It facilitates efficient monitoring of human presence and behaviour, ensuring that potential threats or irregularities can be detected and addressed promptly, regardless of how fast or at what altitude individuals are moving.

So, this method combines detection and tracking to provide a comprehensive solution for recognizing and following individuals in dynamic environments, significantly improving safety and operational effectiveness in border control.

List of Symbols and Abbreviations

FMCW: Frequency modulation continues wave
SAR Synthetic Aperture Radar
IF: intermediate frequency
FFT: Fast Fourier Transform
HSV: Hue saturation value
$\Delta\omega$: Phase Difference
T_c : Ramp Duration
λ : Wavelength

REFERENCES

[1] Meta A." Signal processing of FMCW synthetic aperture radar data." Delft: IRCTR/ Meta, A, 2006. 123 p.

[2] Xin, Qin, et al. "Signal processing for digital beamforming FMCW SAR." Mathematical Problems in Engineering 2014.1 (2014): 859890

[3] Shen W, Wang S, Lin Y, Li Y, Ding F, Wang Y. Ground-Based SAR Moving Target Refocusing Based on Relative Speed for Monitoring Mine Slopes. Remote Sensing. 2022; 14(17):4243. https://doi.org/10.3390/rs1417424

[4] Meta, Adriano, Peter Hoogeboom, and Leo P. Ligthart. "Moving target indication enhancement in FMCW SAR using deramped randomized stepped-frequency signals." 2006 International Waveform Diversity & Design Conference. IEEE, 2006.

[5] Cheng, Pu, et al. "Efficient detection of ground moving targets in FMCW SAR by focusing." 2015 IEEE International Geoscience and Remote Sensing Symposium (IGARSS). IEEE, 2015.

[6] Park, Junhyeong, Dae-Hwan Jung, and Seong-Ook Park. "FMCW SAR with New Synthesis Method Based on A-SPC Technique." arXiv preprint arXiv:2009.14415 (2020).

[7] He, Jing, et al. "High resolution moving targets imaging algorithm of FMCW SAR." Fourth International Conference on Sensors and Information Technology (ICSI 2024). Vol. 13107. SPIE, 2024.

[8] Ting, Jui-Wen, Daniel Oloumi, and Karumudi Rambabu. "FMCW SAR system for near-distance imaging applications—Practical considerations and calibrations." IEEE Transactions on Microwave Theory and Techniques 66.1 (2017): 450-461.

[9] Bi, Hui, et al. "FMCW SAR sparse imaging based on approximated observation: An overview on current technologies." IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 13 (2020): 4825-4835.

[10] Maisto, Maria Antonia, Rocco Pierri, and Raffaele Solimene. "Sensor arrangement in monostatic subsurface radar imaging." IEEE Open Journal of Antennas and Propagation 2 (2020): 3-13.

[11] Baker, Chris. "Multistatic radar processing and systems." NATO SET-136 Lecture Series" Multistatic Surveillance and Reconnaissance: Sensor, Signals and Data Fusion (2009).

[12] Selvaganesh, M., and H. Mangalam. "Computation of range velocity and direction of arrival in FMCW radar." Materials Today: Proceedings 62 (2022): 4946-4952.

[13] Huang, Yanchuan, et al. "FMCW based MIMO imaging radar for maritime navigation." Progress In Electromagnetics Research 115 (2011): 327-342.

[14] Suleymanov, Suleyman. Design and implementation of an FMCW radar signal processing module for automotive applications. MS thesis. University of Twente, 2016.

[15] Lin, Jau-Jr, et al. "Design of an FMCW radar baseband signal processing system for automotive application." SpringerPlus 5 (2016): 1-16.

[16] Nor Fatin Muhd, Farah Nadia Mohd Isa, and Ahmad Fadzil Ismail. "FMCW radar for slow moving target detection: Design and performance analysis." 2016 International Conference on Computer and Communication Engineering (ICCCE). IEEE, 2016.

[17]Meta, Adriano, Peter Hoogeboom, and Leo P. Ligthart. "Signal processing for FMCW SAR." IEEE Transactions on geoscience and remote sensing 45.11 (2007): 3519-3532.

[18] Kumar, Satyam, and AA Bazil Raj. "Design of X-band FMCW radar using digital Doppler processor." 2021 International Conference on System, Computation, Automation and Networking (ICSCAN). IEEE, 2021.