Advancements in Signal Processing Algorithms for Moving Target Indication: A Comprehensive Review

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***Abstract*—Radar technology has undergone remarkable advancements in recent years, propelled by ongoing innovation in signal processing algorithms. This comprehensive review explores the evolution of radar systems for moving target indication (MTI), with a focus on the latest developments in signal processing techniques. Beginning with the refinement of Linear Frequency Modulated Continuous Wave (LFMCW) radar systems and extending to novel approaches for interference mitigation in automotive radar, this review showcases the diverse array of innovations contributing to improved radar performance and reliability. Notably, the integration of adaptive array processing algorithms and innovative radar configurations in automotive radar systems demonstrates significant progress in target detection and tracking capabilities. Moreover, the utilization of advanced signal processing techniques, including Fast Fourier Transform (FFT) analysis and Moving Target Indication (MTI) filtering, highlights the interdisciplinary nature of radar technology. Whether it's detecting slow-moving targets or monitoring vital signs non-invasively, radar systems are increasingly versatile in their applications. As radar technology continues to evolve, driven by innovative research and development efforts, its impact across various domains — from healthcare to homeland security — promises to be profound and far-reaching. This review offers a compelling narrative of ongoing innovation and advancement in radar signal processing, heralding a new era of accuracy, efficiency, and adaptability in radar technology.**

***Index Terms*—Signal Processing, Radar Systems, FFT , FMCW**

I. Introduction

The quest for high-resolution imaging in radar systems continues to be a mainstay in the field of remote sensing, providing priceless information for a range of applications, from defence surveillance to environmental monitoring. Doppler beam sharpening (DBS) is one of several methods used to improve radar imaging capabilities [1]. It is unique in that it may use the Doppler effect caused by moving objects to obtain better resolution. Nevertheless, traditional DBS techniques frequently struggle to strike a balance between sidelobe suppression and resolution improvement, which limits their ability to retrieve accurate scene information. In response, the research presents a revolutionary combined super-resolution technique together with aperture extrapolation, so introducing a groundbreaking method for DBS imaging. This novel approach seeks to resolve the inherent trade-offs between sidelobe reduction and resolution augmentation, providing a viable path to more precise and sharper radar imaging [2]. By means of an extensive investigation of spectrum estimating methods and the incorporation of sophisticated signal processing approaches, the suggested methodology aims to transform DBS imaging and pave the way for novel applications involving high-resolution radar technology.

Radar, short for Radio Detection and Ranging, operates by emitting pulses of electromagnetic radiation to detect and recognize objects nearby [4]. It functions similarly to how sound waves bounce off surfaces and return as echoes, except radar employs electromagnetic waves instead. Here's a breakdown of radar's functioning:

Emitting Electromagnetic Waves: The radar system sends out electromagnetic waves in different directions through its antenna.

Interacting with Objects: When these waves encounter objects like aircraft, ships, or terrain, some energy is absorbed, and the rest is reflected back in various directions.

Receiving Reflected Signals: The radar system's receiver captures a portion of these reflected signals.

Detection and Analysis: By analyzing the received signals, the radar determines if there are reflected signals from objects within its range. If detected, the radar calculates the object's distance, direction, and speed, providing crucial information about its whereabouts and movement.

Overall, radar systems are pivotal in various fields, including military surveillance, weather forecasting, and air traffic control, utilizing electromagnetic wave propagation and reflection principles to gather vital environmental data.

The Doppler Effect, also known as Doppler shift, occurs when there's relative motion between a wave source and an observer, resulting in a change in the wave's frequency [5]. This phenomenon can be explained as follows:When the source moves towards the observer, consecutive waves are emitted from positions closer to the observer, causing the waves to appear grouped together. Consequently, the time between successive wave crests reaching the observer decreases, resulting in a shorter wavelength and an increased frequency.Conversely, when the source moves away from the observer, each wave is emitted from positions farther away, leading to more spread-out waves, longer wavelengths, and reduced frequencies.The Doppler Effect finds application in certain radar systems for measuring the speed of moving objects [6]. For instance, police radar uses this principle to detect speeding vehicles as they approach or move away from the radar source. By analyzing the changes in wavelength as radar waves bounce off the moving object, the speed of the object can be accurately determined.

This paper embarks on a comprehensive exploration of signal processing algorithms for moving target indication in radar systems. By delving into various radar classifications and signal processing techniques, we aim to provide a thorough understanding of radar technology and its applications. The subsequent sections of this paper will delve deeper into radar classifications (Section II) , signal processing algorithms(Section III), providing valuable insights into the advancements driving the field of radar technology forward (Section IV) at the last the and finally, the last section concludes the study.

II. Classification of radars

In the field of radar technology, the categorization of radars provides an essential structure for comprehending their many uses and functional features. This study examines the many characteristics and standards that are used to distinguish between different kinds of radars, delving into the complex classification of radar systems. With a focus on functionality, frequency, platform, and application, this research attempts to give a thorough introduction to radar technology, clarifying its complex nature and emphasising its crucial role in contemporary society.

A. *FMCW and LFMCW*

Frequency Modulated Continuous Wave (FMCW) and Linear Frequency Modulated Continuous Wave (LFMCW) radar are variants of continuous wave radar systems that utilize frequency modulation for range measurement, target detection, and velocity estimation. In FMCW radar, the transmitted signal consists of a continuous wave that is linearly modulated in frequency over time.The radar transmits a continuous wave signal with a frequency that increases or decreases linearly over time. The signal is then reflected off targets, and the echo is received. By measuring the frequency difference (beat frequency) between the transmitted and received signals, FMCW radar determines the range to targets using the frequency modulation characteristics. FMCW radar is commonly used in automotive radar systems, distance measurement applications, altimeters, and industrial sensing applications due to its high accuracy, range resolution, and immunity to interference.

LFMCW radar is a variant of FMCW radar where the frequency modulation is linear.· The transmitted signal in LFMCW radar undergoes a linear frequency sweep, where the frequency increases or decreases linearly over time. Similar to FMCW radar, LFMCW radar measures range by analyzing the beat frequency between the transmitted and received signals. LFMCW radar is particularly suited for applications requiring high range resolution, such as ground-penetrating radar (GPR), environmental sensing, and precision measurement applications.

B. *Pulse and ultra-Wide-band Pulse Radar*

Pulse radar is a type of radar system used for detecting and locating objects by transmitting short pulses of radio frequency (RF) electromagnetic waves and then analyzing the echoes reflected back from objects in the radar's field of view. Here's how it works: The radar system starts by generating short pulses of RF energy. These pulses are typically generated by a high-power transmitter.The radar system then directs these pulses outward into the surrounding space using an antenna. The antenna serves to focus the transmitted energy into a narrow beam, which helps in accurately determining the direction of detected objects.The transmitted pulses travel through the air at the speed of light until they encounter an object in their path. When the pulses encounter an object, such as an aircraft, ship, or terrain feature, a portion of the energy is reflected back towards the radar system. The amount of energy reflected depends on various factors, including the size, shape, and material composition of the object. The radar system's receiver detects the echoes of the transmitted pulses that are reflected back from objects. The receiver amplifies and processes these echoes, extracting information such as the distance, direction, and relative speed of the detected objects. The radar system's signal processing algorithms analyze the received echoes to extract useful information about the detected objects. This information may include their range (distance from the radar), bearing (direction relative to the radar), and radial velocity (speed towards or away from the radar). Finally, the processed radar data is typically displayed on a screen for interpretation by operators. This display may show the positions of detected objects overlaid on a map or other reference imagery.

Pulse radar systems are commonly used in applications such as air traffic control, weather monitoring, maritime navigation, military surveillance, and automotive collision avoidance systems. They are valued for their ability to accurately detect objects at long ranges and in various environmental conditions.

C. *Synthetic Aperture Radar (SAR)*

Synthetic Aperture Radar (SAR) utilizes radar technology to generate high-resolution images of the Earth's surface, independent of daylight or weather conditions. By emitting microwave pulses from an antenna and measuring their return times, SAR collects data along its path, forming a synthetic aperture that enhances image resolution. Complex algorithms process this data, depicting the radar signal's intensity from various objects on the Earth's surface. SAR finds extensive use in remote sensing for land use monitoring, environmental assessment including ice cover and forest density analysis, disaster management for damage assessment post-natural disasters, military surveillance, and cartography, offering invaluable insights across multiple domains.

D. Passive Radar

Passive radar, sometimes referred to as passive coherent location (PCL) or passive covert radar, is a type of radar system that does not send its own signals; instead, it depends on receiving transmissions from other emitters, such as cell towers, commercial radio and television stations, or other radar systems.

It operates by identifying and interpreting the signals that naturally bounce off of surrounding objects, such cars and aeroplanes. Passive radar systems identify the existence, position, and motion of objects within their coverage area by comparing the signals as received after reflection with the initial broadcast signal.

Since passive radar doesn't produce its own radar signals, it has a number of benefits over conventional active radar systems, including fewer costs, lower emissions, and maybe higher stealth. However, because advanced signal processing methods are required to glean meaningful information from the received signals, its implementation may be more difficult. Applications for passive radar technology include border security, air traffic control, military surveillance, and environmental monitoring.

E. Coherent Radar

Coherent radar, often referred to as coherent pulse radar, is a kind of radar system that enhances performance by applying coherent processing methods. Target properties like range, velocity, and angle may be measured with greater accuracy in coherent radar systems because the sent and received signals have a consistent phase relationship.

The word "coherent" describes the radar system's capacity to keep the emitted and received signals in phase with one another. Many sophisticated signal processing methods, including as coherent integration, coherent Doppler processing, and pulse compression, are made possible by this coherence.

Compared to non-coherent radar systems, coherent radar systems provide a number of benefits, such as increased sensitivity, enhanced target discrimination, and enhanced performance in crowded areas. These systems are widely utilised in both civilian and military contexts. In the former, they are employed for weather monitoring, air traffic control, and marine navigation; in the latter, for missile guidance, target tracking, and surveillance.

F. Bistatic Radar

Unlike standard monostatic radar, which has the transmitter and receiver co-located, bistatic radar has the transmitter and receiver physically separated. A second receiver receives the signal that the transmitter in a bistatic radar system puts out after it has been reflected off the target.

III. Signal Processing Algorithms Studied

The following section delves into an array of signal processing algorithms meticulously studied for their efficacy in radar systems, ranging from continuous wave to pulse wave radar technologies. Each algorithm is scrutinized for its capacity to enhance target detection, mitigate interference, and optimize radar performance across diverse operational scenarios.

A. Signal Processing Techniques for Continuous Wave Radar

This section elucidates various methodologies crucial for extracting meaningful information from continuous wave radar signals.

1) 2D MUSIC Algorithm (2D DFT Assistance, Multilevel Resolution Searching): The 2D Multiple Signal Classification (MUSIC) algorithm estimates the directions of multiple signals in radar and sonar. It involves data collection, preprocessing, 2D DFT, covariance matrix calculation, eigenvalue decomposition, spatial spectrum estimation, peak detection, multilevel resolution searching, and Direction of Arrival (DOA) estimation. It's crucial for accurate signal arrival direction estimation in various applications.The 2D MUSIC algorithm with 2D DFT assistance and multilevel resolution searching is widely used in radar, sonar, wireless communications, and array processing applications.It's applied for tasks such as target tracking, beamforming, source localization, and interference suppression.

2) Moving Target Tracking Algorithm (Gradient Descent Method): The Moving Target Tracking algorithm with Gradient Descent estimates the trajectory of moving objects. It starts with an initial guess, predicts the target's next state, updates based on sensor measurements, and iteratively adjusts the estimate using gradient descent to minimize error. This process continues until convergence, resulting in an accurate trajectory estimation. Moving target tracking algorithm based on the gradient descent method finds applications in surveillance, autonomous vehicles, aerospace, robotics, and medical imaging, offering real-time tracking with high accuracy and adaptability. The general equation for a gradient descent algorithm can be represented as:

$$\theta_{j+1} = \theta_j - \alpha \cdot \nabla J(\theta_j) \tag{1}$$

Where:

- θ_j represents the parameter vector at iteration j.
- α denotes the learning rate, which determines the step size for each iteration.
- $\nabla J(\theta_j)$ is the gradient of the cost function J with respect to the parameters θ evaluated at θ_j.
- θ_{j+1} is the updated parameter vector for the next iteration.

3) Low Pass Filter / Band Pass Filter: Low-pass filters allow low-frequency signals to pass while attenuating high frequencies, useful for noise removal and signal smoothing. Band-pass filters pass signals within a specific frequency range while attenuating others, commonly used in communications and signal isolation. In radar systems, both low-pass and band-pass filters play crucial roles in enhancing target detection, clutter suppression, and signal processing to improve overall radar performance and capability.

4) Interference Mitigation Using Adaptive Noise Canceller (ANC): Interference Mitigation with Adaptive Noise Canceller (ANC) uses an adaptive filter to estimate and subtract unwanted interference from a received signal. This process improves signal quality by removing noise, enhancing performance. In radar systems, ANC helps mitigate interference caused by clutter, atmospheric conditions, or electromagnetic interference, enabling better detection and tracking of targets. It's particularly useful in surveillance and weather radar systems where accurate target detection is critical. The general equation for an Adaptive Noise Canceller (ANC) can be represented as:

$$y[n] = x[n] - \hat{d}[n] \tag{2}$$

where,

- $y[n]$ is the output signal after noise cancellation.
- $x[n]$ is the input signal contaminated with noise.
- $\hat{d}[n]$ is the estimated noise component that is adaptively cancelled from the input signal.

5) FFT & DopplerFFT: FFT (Fast Fourier Transform) is a widely-used algorithm for converting time-domain signals into frequency-domain representations, essential for various applications including radar. DopplerFFT, a specialized form of FFT, is specifically designed for analyzing Doppler-shifted signals in radar systems to extract velocity information from moving targets. FT and DopplerFFT are essential tools in radar signal processing, enabling the analysis of Doppler-shifted signals from moving targets and facilitating various applications in air traffic control, weather monitoring, automotive safety, and defense surveillance. In discrete-time signal processing, the FFT algorithm computes the Discrete Fourier Transform (DFT) of a sequence of N complex numbers $x[n]$ defined as:

$$X[k] = \sum_{n=0}^{N-1} x[n] \cdot e^{-i2\pi \frac{kn}{N}} \tag{3}$$

The equation involves applying FFT to a series of radar returns collected over time, where:

- $X[k]$ represents the DFT of the sequence.
- $x[n]$ is the input sequence.
- N is the number of samples in the sequence.
- $e^{-i2\pi \frac{kn}{N}}$ is the complex exponential term.

Additionally, in the context of radar processing:

$$f_D = cv \cdot f_c \tag{4}$$

Where:

- f_D is the Doppler frequency shift.
- c is the speed of light.
- v is the velocity of the target relative to the radar.
- f_c is the carrier frequency of the radar signal.

6) Space-Time Adaptive Processing (STAP): Space-Time Adaptive Processing (STAP) is a radar signal processing technique that combines spatial and temporal information to enhance target detection in cluttered environments. By leveraging the diversity provided by antenna arrays and processing multiple radar pulses, STAP adaptively suppresses clutter and interference, improving radar performance in complex scenarios. STAP has broad applications across radar systems used in various domains including airborne, ground-based, maritime surveillance, aerospace, defense, weather monitoring, and satellite radar. It enhances radar performance by adaptively processing received signals in both space and time domains to mitigate clutter, interference, and improve target detection and tracking capabilities.

7) 2D FFT: 2D FFT (Two-Dimensional Fast Fourier Transform) is an algorithm used to analyze the frequency components of two-dimensional signals or images. It efficiently converts spatial coordinates to frequency coordinates, making it valuable in image processing tasks like filtering, compression, and feature extraction, as well as in radar signal analysis. 2D FFT plays a vital role in radar signal processing by enabling range-Doppler processing, spectral analysis, clutter mitigation, Doppler processing, and adaptive beamforming. It enhances radar performance by providing valuable insights into target characteristics, velocity estimation, and clutter rejection, essential for various radar applications in defense, aerospace, weather monitoring, and surveillance.

8) SDLI/SDLC Structure: SDLI (Single Delay Line Integrator) and SDLC (Single Delay Line Canceller) are crucial signal processing components in radar and communication systems. SDLI integrates signals over a delay line, enhancing detection sensitivity, while SDLC cancels unwanted interference, ensuring signal clarity and reliability. SDLI and SDLC find applications in radar systems for clutter suppression, interference mitigation, and adaptive signal processing. They play critical roles in improving radar performance by isolating desired target signals from clutter and interference, thereby enhancing detection and tracking capabilities in challenging radar environments.

9) Inverse Fast Fourier Transform (IFFT): The Inverse Fast Fourier Transform (IFFT) is the reverse of the Fast Fourier Transform (FFT), converting frequency-domain signals back to the time domain. It's essential for tasks like signal synthesis and modulation in digital signal processing applications. In radar systems, IFFT is utilized for pulse compression, where frequency-modulated radar pulses are compressed in the time domain to improve range resolution. It enables the reconstruction of high-resolution radar echoes from frequency-domain representations, enhancing target detection and tracking capabilities.

10) Doppler Frequency Shift: Doppler frequency shift in digital signal processing (DSP) involves analyzing frequency changes caused by relative motion between a signal source and observer. Using techniques like Fast Fourier Transform (FFT), the shift is determined digitally, enabling applications in radar, sonar, and medical imaging for velocity measurement and motion analysis. Doppler frequency shift is a fundamental aspect of radar signal processing in DSP applications. It is utilized for target velocity estimation, moving target indication, clutter suppression, Doppler filtering, Pulse-Doppler radar operation, and Range-Doppler mapping, enabling radar systems to detect and track moving targets with accuracy and reliability in various environments.

11) Range Time Indicator (RTI): Range-Time Indicator (RTI) in DSP processes radar signals to display detected targets' range and time information. It's a vital tool for real-time monitoring and analysis in radar systems. The Range-Time Indicator (RTI) finds applications across various domains, including target detection, clutter mitigation, weather monitoring, air traffic control, and military surveillance. It serves as a valuable tool for radar operators and meteorologists to visualize radar echoes and track the movement of targets and weather phenomena over time and distance.

12) Background Subtraction: Background subtraction in DSP extracts foreground objects from images or videos by removing the background. It's vital for tasks like object tracking and motion detection in computer vision applications. Background subtraction is a versatile DSP method used in various applications such as surveillance, traffic monitoring, gesture recognition, augmented reality, and medical imaging, enabling the detection and segmentation of foreground objects from a static or dynamic background in images and videos.

13) Finite Impulse Response (FIR) Filtering: Finite Impulse Response (FIR) filtering is a digital signal processing method used to filter and modify signals. FIR filters have a finite-duration response to input signals, determined by a set of coefficients. They are designed to achieve specific frequency response characteristics. FIR filtering plays a crucial role in radar signal processing for tasks such as pulse compression, clutter rejection, Doppler filtering, range-Doppler processing, and adaptive beamforming. These applications contribute to enhancing radar performance, improving target detection capabilities, and providing valuable situational awareness in various radar systems.

14) Infinite Impulse Response (IIR) Filtering: Infinite Impulse Response (IIR) filtering is a digital signal processing technique used to filter and modify signals. Unlike Finite Impulse Response (FIR) filters, IIR filters have a response to an input signal that can extend infinitely into the past. IIR filtering in radar systems is applied for clutter suppression, Doppler filtering, pulse compression, adaptive beamforming, and range-Doppler processing. These applications contribute to enhancing radar performance, improving target detection capabilities, and providing valuable situational awareness in various radar systems.

15) 3 Tap MTI Filter (32 Bit) (MAC & MAD Operation): A 3-tap MTI filter with 32-bit precision typically involves Multiply-Accumulate (MAC) operations for filtering and Mean Absolute Difference (MAD) operations for error estimation or adaptive filtering. It's commonly used in radar and sonar systems for clutter suppression and moving target detection. the 3-tap MTI filter with 32-bit precision, incorporating Multiply-Accumulate (MAC) and Multiply-Add (MAD) operations, finds widespread use in radar applications for clutter rejection, moving target detection, and enhancing radar performance in various environments, including airborne, maritime, weather, and ground surveillance.The equation for a 3-tap Moving Target Indicator (MTI) filter can be expressed as follows:

$$y[n] = x[n] - 2 \cdot x[n-1] + x[n-2] \tag{5}$$

This equation corresponds to the current sample and the two previous samples in the time domain, where:

- $y[n]$ represents the output of the MTI filter at time index n.
- $x[n]$ is the input signal at time index n.
- $x[n-1]$ and $x[n-2]$ are the input signal values at the two previous time indices.

16) Pipelined FIR Filtration: Pipelined FIR filtration enhances throughput and efficiency by concurrently processing multiple segments of the input signal. This parallel processing approach reduces latency and improves performance in real-time signal processing applications like digital communications and audio processing. Pipelined FIR filtering in radar systems enhances clutter rejection, improves moving target detection, enables pulse compression, facilitates range-Doppler processing, supports adaptive beamforming, and enhances digital beamforming capabilities, contributing to enhanced radar performance and target detection capabilities. The equation describes how each output sample y_n is computed by summing the products of the input samples x_{n-i} and their corresponding filter coefficients b_i:

$$y_n = \sum_{i=0}^{N-1} b_i \cdot x_{n-i} \tag{6}$$

Here:

- y_n represents the output sample at time index n.
- x_{n-i} denotes the input sample at time index $n-i$.
- b_i are the filter coefficients.
- N is the number of taps or coefficients in the filter.

The filter coefficients determine the filter's frequency response and characteristics, such as its passband and stopband behavior.

17) 3DFFT: 3D FFT (Three-Dimensional Fast Fourier Transform) analyzes the frequency components of three-dimensional data sets, converting spatial coordinates into frequency coordinates. It's used for tasks such as image reconstruction and turbulence analysis. Efficient algorithms ensure high performance due to the large data volumes involved. 3D FFT in radar applications enables comprehensive analysis of radar echoes in three-dimensional space, supporting target detection and tracking, airborne surveillance, ground moving target indication, terrain mapping, weather radar, and phased array radar systems. It plays a crucial role in enhancing radar performance and situational awareness in various military, civilian, and meteorological applications. The 3D Fast Fourier Transform (FFT) is an extension of the traditional FFT to process three-dimensional data. The equation for the 3D FFT operation can be represented as follows:

$$Y(u, v, w) = \text{FFT3D}(X(x, y, z)) \tag{7}$$

Here:

- $Y(u, v, w)$ represents the 3D Fourier transform of the input volume $X(x, y, z)$.
- FFT3D denotes the operation that computes the 3D Fast Fourier Transform.
- (u, v, w) are the frequency coordinates in the Fourier domain.
- (x, y, z) are the spatial coordinates in the input volume.

18) LCMVADBF: LCMVADBF (Linearly Constrained Minimum Variance Adaptive Direct Beamforming) is a DSP technique used for array processing and beamforming. It optimizes array weights to enhance desired signals while suppressing interference and noise. LCMVADBF plays a crucial role in radar applications by improving clutter rejection, interference mitigation, directional sensitivity, moving target detection, electronic warfare capabilities, and the performance of phased array radar systems. It enables radars to operate effectively in diverse environments and fulfill various mission requirements, ranging from surveillance and reconnaissance to air defense and electronic warfare. In matrix notation, the equation can be represented as follows:

$$\mathbf{w} = \arg\min_{\mathbf{w}} \left(\mathbf{w}^H \mathbf{R}^{-1} \mathbf{w}\right) \tag{8}$$

Where:

- $\mathbf{w}$ is a vector representing the weights.
- $\mathbf{R}$ is a matrix representing the covariance matrix.
- $\arg\min_{\mathbf{w}}$ denotes the argument that minimizes the expression.

19) CSOMP: CSOMP (Compressive Sensing Orthogonal Matching Pursuit) is a DSP technique used for signal recovery in compressive sensing applications. It enhances the OMP algorithm by incorporating thresholding for improved signal reconstruction from underdetermined measurements. CSOMP offers a powerful framework for sparse signal recovery and radar imaging, enabling radar systems to efficiently detect, localize, and classify targets in complex and cluttered environments. Its applications span various radar domains, including surveillance, reconnaissance, security, and defense. This equation represents the update step where the estimate of the sparse signal, $\hat{x}^{(k+1)}$, at iteration $k+1$ is obtained by minimizing the squared Euclidean distance between the measured signal y and the measurement matrix Φ multiplied by the signal x:

$$\hat{x}^{(k+1)} = \arg\min_{\hat{x}} \|y - \Phi\hat{x}\|_2^2 \tag{9}$$

Similarly, another representation is given for the update step where the estimate of the signal $x^{(k+1)}$ is obtained:

$$x^{(k+1)} = \arg\min_{x} \|y - \Phi x\|_2^2 \tag{10}$$

Where:

- $\hat{x}^{(k+1)}$ and $x^{(k+1)}$ represent the estimates of the sparse signal at iteration $k+1$.
- y is the measured signal.
- Φ is the measurement matrix.
- $\|\cdot\|_2^2$ denotes the squared Euclidean norm.

20) RADWT: RADWT (Radar Wavelet Transform) is a DSP technique used in radar systems for signal analysis. It employs wavelet transform principles to extract valuable information from radar echoes, enabling multiscale analysis for target detection and tracking. RADWT offers versatile capabilities for radar signal processing, including target detection and classification, signal denoising, pulse compression, terrain and target imaging, radar data fusion, and analysis of non-stationary signals. Its applications span various radar domains, including surveillance, reconnaissance, weather monitoring, and remote sensing. The wavelet coefficient at scale a and translation b, denoted by $W(a,b)$, is computed as follows:

$$W(a,b) = \int_{-\infty}^{\infty} s(t) \cdot \psi_{a,b}^*(t)\, dt \tag{11}$$

Where:

- $W(a,b)$ represents the wavelet coefficient at scale a and translation b.
- $s(t)$ is the radar signal in the time domain.
- $\psi_{a,b}(t)$ is the wavelet function or mother wavelet, which is dilated by a and translated by b.
- $\psi_{a,b}^*(t)$ denotes the complex conjugate of the wavelet function.
- The integral is taken over the entire time domain.

21) Low-Complexity FMCW Radar Algorithm Using 2 Beats Signal (1D FFT, 2D FFT): The Low-Complexity FMCW Radar Algorithm with 2-beat signals uses 1D FFT and 2D FFT processing for efficient target detection and clutter rejection in radar systems. It's ideal for real-time applications with limited computational resources

22) FMCW Synthetic Aperture Radar (SAR) Algorithm: The FMCW Synthetic Aperture Radar (SAR) algorithm generates high-resolution radar images by processing data collected from FMCW radar systems. It compensates for motion-induced phase errors and performs range and azimuth processing to create focused SAR images. The transmitted frequency $f(t)$ as a function of time t is described by:

$$f(t) = f_c + K(t - t_0) \tag{12}$$

Where:

- $f(t)$ is the transmitted frequency as a function of time t.
- f_c is the carrier frequency.
- K is the chirp rate.
- t_0 is the start time of the chirp.

This equation describes how the transmitted frequency varies linearly with time during the transmission of the radar signal, resulting in a linear frequency modulation known as a chirp.

23) Long Integration Time MTI Technique: The Long Integration Time Moving Target Indication (MTI) technique is a method used in radar signal processing to enhance the detection of moving targets against clutter or background noise. It involves integrating radar returns over a longer period of time compared to traditional MTI methods. This extended integration time helps to improve the signal-to-noise ratio and enhances the ability to detect and track moving targets, especially in environments with high clutter or noise levels. Radar signal processing frequently uses the Long Integration Time (LIT) Moving Target Indication (MTI) approach to identify and track moving objects in congested situations. Applications like aerial or ground-based radar systems, where targets must be identified in the midst of intense background clutter, benefit greatly from it.The integrated signal over time T, denoted by $X(T)$, is defined as:

$$X(T) = \int_{t_0}^{t_0+T} x(t)\, dt \tag{13}$$

Where:

- $X(T)$ represents the integrated signal over time T.
- $x(t)$ is the received radar signal at time t.
- t_0 is the start time of integration.

24) Matched Filtering: It entails comparing the received signal to a template waveform, also called the "matched filter," which is essentially the predicted signal conjugated and time-reversed. By maximising the signal-to-noise ratio, this procedure improves the ability to detect the intended signal even in the midst of interference and noise. Matched filtering is widely used for target identification, communication signal recovery, and pattern recognition in a variety of applications, including radar, communications, sonar, and biomedical signal processing. The frequency-domain representation of the signal, denoted by $X(k)$, is computed as:

$$X(k) = \sum_{n=0}^{N-1} x(n) \cdot e^{-j\frac{2\pi}{N}kn} \tag{14}$$

Where:

- $X(k)$ is the frequency-domain representation of the signal.
- $x(n)$ is the time-domain signal.
- N is the number of samples in the signal.
- k is the index of the frequency bin.
- j is the imaginary unit.

B. Signal Processing Techniques for Pulse Wave Radar

This section explores a myriad of signal processing algorithms tailored specifically for pulse wave radar applications offering insights into their functionalities and applications.

1) FFT Processing by FPGA Device: FPGAs are highly configurable to specific FFT algorithms and signal processing requirements because they are reconfigurable hardware platforms that allow the implementation of custom logic circuits. By taking advantage of FPGAs' built-in parallel processing capabilities, FFT calculations can be completed quickly and effectively, enabling real-time signal analysis for things like audio, video, radar, and telecom data.

FFT processing by FPGA devices is employed across diverse fields including wireless communications, radar and sonar systems, medical imaging, audio and video processing, and scientific computing, enabling high-speed signal processing and real-time data analysis.

2) FFT on Consecutive Pulses: Applying the Fast Fourier Transform (FFT) method to a sequence of successive time-domain signals or pulses allows for the efficient conversion of those signals into their frequency-domain representations, allowing for the quick analysis and extraction of frequency components from each pulse.

Matched filtering is widely used for target identification, communication signal recovery, and pattern recognition in a variety of applications, including radar, communications, sonar, and biomedical signal processing.

3) Doppler Count for Phase Measurement: The phrase "Doppler count" refers to a phase measuring method in which the Doppler frequency shift resulting from the relative velocity between the transmitter and receiver is ascertained by analysing the phase shift between sent and received signals. This technique is frequently applied in radar systems to determine a target's or object's velocity based on the phase shift of the received signal.

The Doppler count for phase measurement is used in applications such as radar systems for velocity estimation of moving objects or targets.

4) Pulse Pair Processing: In radar signal analysis, pulse pair processing is a method that helps detect weak objects better when there is noise present. In order to maximise the signal-to-noise ratio and increase detection sensitivity, it entails comparing successive radar pulses and taking use of the correlation between them. By successfully separating genuine target echoes from random noise, this technique helps radar systems detect and track targets more precisely.

Pulse pair processing is utilized in radar systems for target detection and tracking in environments with high levels of noise and clutter.

5) Frequency Measurement Error: The difference between a signal's true frequency and its measured frequency is known as frequency measurement error. It can be brought about by errors in the measurement process, equipment malfunctions, or environmental conditions. As a result, frequency measurement error can affect the accuracy and dependability of applications involving frequencies.

Frequency measurement error affects various applications such as telecommunications, power system monitoring, and scientific research, where accurate frequency determination is crucial for system stability and performance assessment.

6) Clutter Rejection Filter: In radar and sonar systems, a signal processing method called a clutter rejection filter is employed to reduce clutter, or undesired signals or interference. It improves the precision and dependability of target recognition and tracking by suppressing signals that do not correspond to the predicted features of the target signal.

Clutter rejection filters are used in radar systems to remove unwanted echoes from stationary objects, such as buildings or terrain, and enhance detection of moving targets like aircraft or ships.

7) CFAR(Constant False Alarm Rate) Thresholding: Signal processing techniques like CFAR (Constant False Alarm Rate) thresholding are used to find targets in noisy settings like sonar or radar systems. CFAR maintains a consistent likelihood of false alarm in spite of environmental changes by dynamically adjusting the target detection threshold depending on the local noise level. Adaptive thresholding makes it possible to reliably recognise targets in a range of noise environments.

CFAR thresholding is commonly used in radar systems for target detection amidst varying levels of noise.

8) Fast Iterative Multipleburst ML Estimation: A computer technique for estimating parameters in signal processing and communication systems is called Fast Iterative Multipleburst ML Estimation. It uses several data bursts to iteratively update parameter estimations with the goal of increasing convergence speed and accuracy. This strategy works especially well in situations when noise or incomplete data might make previous methods ineffective.

Fast Iterative Multipleburst ML Estimation finds applications in wireless communication systems for accurate parameter estimation in noisy environments.

9) Normalized Matched Filter (ANMF): In signal processing and pattern recognition, the Normalised Matched Filter (ANMF) is a method used to find a known signal in a noisy environment. In order to minimise the impact of noise, it correlates the received signal with a template of the predicted signal, highlighting the similarities between the two.

The normalisation procedure makes the output independent of the noise level and signal strength, which makes it a reliable technique for signal identification in a variety of applications, including image processing, communications, and radar.

10) Discrete Fourier Transform (DFT): A mathematical method for examining the frequency content of discrete signals, such those represented by digital data, is the Discrete Fourier Transform (DFT). It converts a series of complex numbers that indicate the amplitudes of the signal's various frequency components into a separate series of complex numbers that indicate the same information in the frequency domain. Said another way, it dissects a signal into its individual frequencies and shows the relative amounts of each frequency in the original signal.

For tasks like filtering, compression, and signal and image analysis, this is widely used in signal processing, communications, image processing, and many other domains.

11) RSP Techniques: Within the field of signal processing, random signal processing addresses signals that exhibit random variations in terms of time, space, or other parameters. Statistical measurements or probability distributions are frequently used to characterise these signals. Despite these signals' unexpected character, the aim of random signal processing is to examine, modify, and extract valuable information from them.

Applications for this discipline may be found in many different areas, including image processing, radar, sonar, control systems, and communication systems. Statistical analysis, stochastic modelling, and techniques like spectrum analysis and estimation theory are frequently employed in random signal processing.

12) Combined Superresolution Algorithm: Typically, combined superresolution algorithms combine many methods to improve an image's resolution beyond what it may have been before. These strategies frequently combine machine learning techniques with conventional signal processing methods. Combining several techniques, combined superresolution algorithms seek to generate detailed, high-quality pictures with a higher resolution than the initial low-resolution input.

Combined superresolution algorithms are used in various fields such as medical imaging, satellite imaging, surveillance, and digital photography to enhance image quality and extract more detailed information from low-resolution images.

13) The Correlation Processing Technique for Pulse Compression in Radar Pulse Detection: The correlation processing technique in radar pulse compression involves transmitting long coded pulses, then correlating them with a matched filter at the receiver, enhancing weak signal detection and improving range resolution for target identification, particularly useful in cluttered or noisy environments. The correlation processing technique for pulse compression in radar pulse detection enhances target detection, weather radar accuracy, air traffic control precision, remote sensing resolution, biomedical imaging clarity, space exploration imaging detail, and non-destructive testing sensitivity. The correlation processing technique for pulse compression in radar pulse detection can be represented by the following equation:

$$y(t) = \int_{-\infty}^{\infty} r(\tau)h(t-\tau)\,d\tau \tag{15}$$

Where:

- $y(t)$ is the output signal.
- $r(\tau)$ is the autocorrelation function.
- $h(t-\tau)$ is the transmitted pulse waveform.
- τ is the delay or lag.

14) Pulse Doppler Processing: Pulse Doppler processing is a radar technique that combines pulse radar with Doppler radar to detect moving targets while filtering out stationary clutter. It measures the Doppler shift in returned radar signals to determine the velocity of detected objects, enhancing the radar's ability to track fast-moving targets such as aircraft, vehicles, and weather systems. Pulse Doppler processing integrates pulse and Doppler radar principles, enabling applications such as weather monitoring, air traffic control, military surveillance, ground moving target indication, maritime surveillance, remote sensing, and aerospace/defense systems for target detection, tracking, and discrimination amidst clutter and varying environmental conditions. The received radar signal, modulated by both range and Doppler effects, is processed to extract information about the target's range and velocity using the following equation:

$$P_d(fd) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} s(t)\cdot e^{-j2\pi f dt}\cdot e^{-j2\pi f r\tau}\,dt\,d\tau \tag{16}$$

Where:

- $P_d(fd)$ represents the processed radar signal.
- $s(t)$ is the received radar signal.
- f_d is the Doppler frequency.
- f_r is the carrier frequency.
- τ represents the time delay.
- t represents time instances.

This equation describes how the received radar signal, modulated by both range and Doppler effects, is processed to extract information about the target's range and velocity. It involves integrating over time delays (τ) and time instances (t), covering the entire duration of the received signal, and includes terms representing Doppler frequency (f_d) and carrier frequency (f_r).

15) Logarithmic Amplifier for Detection of Received Signals: Logarithmic amplifiers in Pulse Doppler radar systems convert received signals into a logarithmic scale, enabling detection of weak signals from distant targets while preventing saturation from strong signals, crucial for accurate target tracking. Logarithmic amplifiers are crucial for accurately measuring signal strength and enabling automatic gain control in various systems like radar, wireless communication, and sensors. They enhance detection capabilities amidst interference, optimize reception, and facilitate intuitive signal representation in spectrum analyzers

16) Algorithms Involved in Bandpass Filtering, Spectrogram Computation, and Adaptive Adjustment of Filter Cutoff Frequencies: These algorithms are utilized for signal processing tasks such as extracting relevant frequency components through bandpass filtering, analyzing signal frequency content over time with spectrogram computation, and dynamically adjusting filter parameters for optimal signal extraction, benefiting applications ranging from radar systems to biomedical signal analysis.These algorithms, crucial in diverse domains, encompass speech and audio processing for tasks like speech recognition, biomedical signal processing for EEG and EMG analysis, radar and sonar signal processing for target detection, and structural health monitoring for vibration analysis of infrastructure.

17) Open Multi Processing (OpenMP) Was Evaluated as a Digital Signal Processing Technique: Open Multi Processing (OpenMP) was assessed as a digital signal processing technique, leveraging parallel computing to enhance the efficiency and performance of signal processing tasks across various domains. OpenMP accelerates high-performance computing tasks like scientific simulations and computational fluid dynamics, while also optimizing image and video processing for smoother multimedia applications. Moreover, it streamlines computational finance for tasks such as option pricing and risk management and expedites bioinformatics processes like genome sequencing and protein structure prediction for drug discovery. OpenMP accelerates high-performance computing tasks like scientific simulations and computational fluid dynamics, while also optimizing image and video processing for smoother multimedia applications. Moreover, it streamlines computational finance for tasks such as option pricing and risk management and expedites bioinformatics processes like genome sequencing and protein structure prediction for drug discovery.

18) Direct Positioning Determination (DPD) is the Coherent Accumulation Maximum Likelihood Direct Position Determination (CA-ML-DPD) Algorithm: The Coherent Accumulation Maximum Likelihood Direct Position Determination (CA-ML-DPD) algorithm directly computes precise positions by accumulating coherent measurements and applying maximum likelihood estimation, finding applications in navigation, radar, communication, sonar, and astronomy for high-accuracy positioning. The CA-ML-DPD algorithm is essential for precise positioning in satellite navigation, aerospace, aviation, maritime navigation, and geodetic surveying applications. It enables accurate determination of receiver positions, navigation during flight operations, maritime vessel positioning, and Earth surface coordinates for mapping and construction.

19) Radial Basis Function Network (RBFN): A Radial Basis Function Network (RBFN) is a type of artificial neural network (ANN) that uses radial basis functions as activation functions. Unlike traditional feedforward neural networks, where neurons typically use sigmoid or ReLU activation functions, RBFNs employ radial basis functions, which are centered at specific points in the input space.Radial Basis Function Networks (RBFNs) are versatile tools with applications spanning finance, engineering, pattern recognition, and anomaly detection. In finance, they excel in modeling stock prices and forecasting financial trends, while in engineering, they aid in system identification and control. Additionally, RBFNs are pivotal in pattern recognition tasks such as character and speech recognition, as well as in detecting anomalies like fraudulent transactions and industrial faults.

$$y(x) = \sum_{i=1}^{M} w_i \phi_i(d_i) + b$$

Where:

- $y(x)$ represents the output function.
- M is the number of terms in the summation.
- w_i are the weights associated with each term.
- $\phi_i(d_i)$ are basis functions with associated parameters d_i.
- b is the bias term.

20) Prony's Method for Resonance Extraction, Difference Equation-Based Pole Suppression, Correction for Distortion, and Backward Prediction for Waveform Reconstruction: Prony's method is a mathematical technique used to extract information about resonant frequencies and damping factors from signals. It decomposes a signal into a sum of exponentially damped sinusoids, allowing the identification of the frequencies and decay rates of underlying resonances. Prony's method, developed by Gaspard de Prony, has applications across diverse fields. It aids in resonance analysis in electrical, mechanical, telecommunications, medical imaging, seismology, geophysics, and chemical engineering.

$$x[n] = \sum_{k=1}^{M} A_k e^{j(\omega_k n + \phi_k)} + v[n]$$

Where:

- $x[n]$ represents the signal at time index n.
- M is the number of components in the signal.
- A_k are the amplitudes of the components.
- ω_k are the angular frequencies of the components.
- ϕ_k are the phases of the components.
- $v[n]$ represents any noise or interference.

IV. Signal Processing Algorithms for Radar Signals

A. Review of Signal Processing Techniques for Continuous Wave Radar

The section on "Review of Signal Processing Techniques for Continuous Wave Radar" begins with a focus on advancements in FMCW radar systems.

In [7], the authors present a novel approach utilizing an LFMCW Radar system. The paper introduces a 2D MUSIC algorithm enhanced by 2D DFT assistance and multilevel resolution searching, tailored for moving target tracking. The proposed methodology employs a gradient descent method for the precise localization of moving targets in two dimensions, achieving superresolution capabilities. This advancement facilitates the effective 2D localization of multiple moving targets, particularly in small-range settings, demonstrating promising potential for real-world applications. The research contributes significantly to the field of radar signal processing, offering a refined approach to moving target indication with enhanced accuracy and efficiency.

Another work [8] focuses on combating interference in automotive radar systems. Employing both Chirp sequence FMCW and Triangular FMCW radar configurations, the study introduces a novel approach utilizing low-pass and band-pass filters alongside an adaptive noise canceller (ANC). The methodology incorporates FFT and DopplerFFT techniques to analyze and mitigate interference effectively. Through simulations and experimental validations, the proposed method demonstrates substantial improvements in interference mitigation performance. This research holds significance for the automotive radar industry, offering a robust solution to enhance radar system reliability and accuracy in real-world environments.

In [9], the authors introduce an innovative FMCW radar system tailored for vehicular target detection. Leveraging adaptive array processing algorithms, particularly Space Time Adaptive Processing (STAP), the study enhances radar performance for automotive applications. By incorporating an array antenna equipped with STAP, the proposed radar system effectively addresses challenges related to simultaneous communication and radar sensing. Notably, the intelligent radar system achieves accurate detection of vehicular targets, capable of discerning relative speeds up to 8.4 m/s. This research marks a significant advancement in automotive radar technology, offering a sophisticated solution to improve target detection and tracking capabilities in vehicular environments.

The paper [10], addresses the challenge of detecting targets with small apparent Doppler frequencies in LFMCW radar systems. Through the utilization of 2D FFT and the SDLI/SDLC structure, the study aims to enhance detection capabilities, particularly in automotive and military applications such as border and building protection. The proposed SDLCSDLI structure significantly improves detection for targets with both small and high Doppler frequencies. Notably, the detection capability is enhanced by 80 at an SNR of 0 dB. By integrating this combined structure, the radar system effectively overcomes detection degradation issues associated with middle Doppler targets. This research presents a notable contribution to the field of radar signal processing, offering a refined approach to enhance target detection performance in LFMCW radar systems for critical applications.

Another work [11] focuses on slow-moving target detection using FMCW radar systems. Employing techniques such as the Inverse Fast Fourier Transform (IFFT), Doppler frequency shift analysis, and Range Time Indicator (RTI), the radar system is tailored for various applications including snow avalanche monitoring, homeland security, wireless channel sound analysis, and airport security checkpoint operations. The research highlights the radar's capability to accurately detect and measure the velocity and range of targets. Notably, the system achieves a minimum velocity measurement of 0.77 m/s for short-range moving targets. Experimental results demonstrate the radar's efficacy in precisely determining the position of moving individuals, with observed static velocities of approximately 1 m/s. This paper contributes significantly to advancing radar technology for the detection and monitoring of slow-moving targets in diverse operational scenarios, showcasing its potential for critical applications in security and safety.

In [12] the authors explore the utilization of digital moving target indication techniques in short-range FMCW radar systems. The study focuses on background subtraction, Finite Impulse Response (FIR) Filtering, and Infinite Impulse Response (IIR) Filtering methods, assessing their applicability in various scenarios including airborne surveillance radar, through-the-wall radar, and indoor tracking applications. The research identifies background subtraction as particularly effective for detecting slow-moving targets. Moreover, for cases requiring moving target segmentation, FIR and IIR filtering techniques are recommended due to their simplicity and effectiveness as one-step processes. This paper provides valuable insights into optimizing digital signal processing techniques for short-range FMCW radar systems, enhancing their performance in diverse operational environments for target detection and tracking applications.

The paper [13], focuses on the FPGA implementation of a moving target indicator (MTI) filter for FMCW radar data processing. The study introduces a 3-tap MTI filter utilizing MAC (Multiply-Accumulate) and MAD (Multiply-Accumulate-and-Divide) operations, alongside pipelined FIR filtration techniques. Targeting both long-range radar (LRR) and short-range radar (SRR) applications, the research spans diverse domains including environmental perception, nano and micro object detection, tracking, classification, and in-cabin health monitoring systems. Simulation results evaluate the performance of 2-tap and 3-tap FIR filters, showcasing the efficacy of carefully designed and implemented filters in enhancing radar measurement accuracy and reliability. The study highlights the advantages of pipelined filters in terms of performance and scalability, albeit with potential resource requirements. This research contributes to advancing radar signal processing methodologies, particularly in FPGA-based implementations, for improved detection and tracking capabilities across various operational scenarios.

In [14] the author introduces a novel approach for vital signs detection utilizing FMCW radar technology. Employing advanced signal processing techniques such as 3DFFT, LCMVADBF, CSOMP, and RADWT, the study focuses on detecting vital signs including heart rate, pulse rate, and respiration. The proposed method demonstrates radar-based detection of respiratory and heartbeat signals, achieving substantial agreement rates of 89% for respiratory and 87% for heartbeat signals. Moreover, the level of agreement for three human targets reaches 87% for respiratory signals. These results underscore the effectiveness of the proposed method in accurately detecting vital signs using FMCW radar technology. This research represents a significant advancement in non-contact vital signs monitoring, offering promising applications in healthcare, surveillance, and safety systems.

Another work presents an innovative approach to FMCW radar signal processing tailored for surveillance applications [15]. The proposed algorithm utilizes two random beat signals and employs 1D FFT and 2D FFT techniques to achieve low complexity yet effective target detection. Notably, the algorithm effectively addresses the blind-speed problem associated with surveillance radar systems. Simulation and experimental results demonstrate the superior performance of the proposed algorithm compared to previous methods. This research represents a significant advancement in FMCW radar signal processing for surveillance applications, offering improved target detection capabilities with reduced computational complexity.

Another paper focuses on signal processing algorithms tailored for FMCW Synthetic Aperture Radar (SAR) systems [16]. The study specifically addresses the effects of moving targets as they manifest in FMCW SAR images and their relevance to Moving Target Indicator (MTI) capabilities. By highlighting the radial velocity effect, the research elucidates how moving targets impact FMCW SAR imagery, providing valuable insights to enhance MTI approaches. This study underscores the significance of understanding target motion dynamics in SAR imaging scenarios, offering implications for improving target detection and tracking capabilities in radar systems.

In [17], the authors explore the effectiveness of utilizing Global Navigation Satellite Systems (GNSS) for maritime target detection, particularly small targets at sea. It introduces the Long Integration Time MTI technique, enhancing target detection by processing signals over extended periods, typically around one minute. By analyzing range and Doppler characteristics, the radar system effectively distinguishes target reflections from background noise. The study validates the technique's efficacy through experimental data from maritime campaigns, highlighting its practical utility in enhancing maritime surveillance capabilities. Additionally, it discusses future research directions, including leveraging multiple GNSS transmitters and focusing on multistatic acquisition to further improve system performance and scalability.

The paper [18]focuses on enhancing maritime target detection through passive GNSS-based bistatic radar systems. It explores the utilization of FPGA technology for coherent signal processing, enabling tasks such as filtering, IQ splitting, and Doppler processing to compute target velocities efficiently. The study employs matched filtering and moving target indication (MTI) algorithms to detect targets with varying Radar Cross Section (RCS) values, presenting results demonstrating the feasibility of long-time integration MTI processing for improved target detection. Future work includes power budget evaluation, algorithm upgrades for MTI schemes, multistatic operation exploration, and further development of synchronization and signal processing algorithms to optimize system performance.

The paper [19] introduces a novel structure for Linear Frequency Modulated Continuous Wave (LFMCW) radar systems, specifically addressing the challenge of detecting tangential targets. LFMCW radars employ continuous transmission with linearly varying frequency to measure target distances precisely. Tangential targets, moving perpendicular to the radar beam, typically produce zero Doppler shift, rendering them indistinguishable and usually removed by Moving Target Indication (MTI). The proposed structure enhances LFMCW radar performance through a combination of Fast Fourier Transforms (FFTs), Single Delay Canceller (SDC) MTI, and Constant False Alarm Rate (CFAR) processing. By incorporating clutter map processing inspired by pulsed radar systems, the proposed radar system achieves significant improvements in detecting slowly moving and tangential targets, outperforming traditional methods in simulated severe conditions. Notably, it achieves a 100% detection probability for tangential targets under specific CNR and SCNR conditions.

Another paper [20] introduces a method to modify the frequency response of Moving Target Indication (MTI) in LFMCW radar systems. By incorporating a Single Delay Line Integrator (SDLI) after the MTI, the structure enhances gain for small Doppler frequencies while sacrificing some detection capability for middle Doppler targets. This modification is crucial for LFMCW radars, which excel in measuring small ranges and velocities accurately. The proposed method improves frequency response for small Doppler frequencies, demonstrated through analysis of FFT outputs and Receiver Operating Characteristic (ROC) curves. While detection performance for slowly and very speedy moving targets is significantly enhanced, a combined structure is proposed to address degradation in middle Doppler target detection. Overall, the research underscores the effectiveness of the proposed SDLC/SDLI structure in enhancing LFMCW radar's capability to detect targets with small and very high apparent Doppler frequencies.

B. Review of Signal Processing Techniques for Pulse Wave Radar

Transitioning to the section on "Review of Signal Processing Techniques for Pulse Wave Radar," the first paper explores an innovative approach to radar signal processing for marine applications, leveraging FPGA technology [21]. The authors present an innovative approach to radar signal processing, aiming to make coherent radar systems more accessible for marine applications by leveraging FPGA technology. Through hardware modifications and FPGA implementation, the study focuses on enhancing signal processing efficiency, particularly in Doppler processing for target velocity estimation. The main contribution lies in the development of a coherent Doppler processor tailored for marine radar, facilitating advanced signal processing techniques for improved target detection and tracking, particularly in moving target indication scenarios. Future research directions include optimizing FPGA algorithms, integrating advanced techniques like adaptive beamforming, exploring real-time processing capabilities, enhancing target tracking algorithms, conducting comprehensive system integration and testing, designing cost-effective radar systems, and investigating multi-radar configurations for enhanced surveillance capabilities.

TABLE I: Summary

Ref.	Radar classification	DSP Algorithms	Usage/Application	Results
7	LFMCW	2D MUSIC algorithm , Moving target tracking algorithm	2D localization of multiple moving targets.	The approach enables effective super-resolution 2-D localization of multiple moving targets, facilitating 2-D MUSIC in realistic small-range scenarios.
8	Chirp sequence FMCW, Triangular FMCW	Low Pass Band Pass filter, Adaptive Noise Canceller (ANC), FFT & Doppler FFT	Automotive	enhancement in interference mitigation performance, validated through simulation and experimental results.
9	FMCW	Adaptive array processing algorithms, Space Time Adaptive Processing	Automotive	Addressed simultaneous communication and radar sensing challenges with intelligent radar.
10	LFMCW	2D FFT, SDLI/SDLC	Automotive, Military Application	Combined structure overcomes detection degradation for middle Doppler targets.
11	FMCW	Inverse Fast Fourier Transform, Doppler frequency shift, Range Time Indicator	Moving target detection and measurement, homeland security and airport security	Minimum velocity measured for short-range moving target is 0.77 m/s. Velocity of moving person remains static at approximately 1 ms.
12	FMCW	Background subtraction, Finite Impulse Response Filtering	Airborne surveillance radar, Through the wall and indoor tracking	The FIR and IIR filtering techniques are the simplest, one-step processes
13	FMCW	3 tap MTI filter , Pipelined FIR filtration	Long-range radar and Short-range radar , Environmental perception, Nano object detection, Health monitoring system	Carefully designed and implemented filters can significantly enhance radar measurement accuracy and reliability.
14	FMCW	3D FFT, LCMVADBF, CSOMP, RADWT	Radar-based detection of respiratory and heartbeat signals for vital signs.	Proposed method shows 89% agreement for respiratory and 87% for heartbeat.
15	FMCW	2-beat signal (1D FFT, 2D FFT)	Vital Signs detection (heart rate, pulse rate, respiration etc)	Simulation and experiment show better performance compared to previous algorithm.
16	FMCW	Synthetic Aperture Radar algorithm	Surveillance	This study highlights the radial velocity effect in describing the effects of a moving target as they appear in an FMCW SAR image.
17	Passive and Continuous Radar	Long Integration Time MTI Technique	Maritime Surveillance	GNSS-based passive radar, validated through maritime campaigns, enhancing detection of low observable maritime targets.
18	Coherent Radar, Pulse Radar	FFT processing by FPGA device	Affordable computation of target velocities	modifying marine radar for coherent signal capture, and enabling efficient Doppler analysis for improved moving target detection.
19	Passive , Bistatic and Continuous Radar	FFT, Long Integration Time, Matched Filtering	Maritime Surveillance	Everaging GNSS signals for passive radar, deploying signal processing techniques like matched filtering and MTI.
20	Pulse	FFT on consecutive pulses, Doppler count, Pulse Pair processing	Evaluation of the performance of Doppler frequency measurement techniques	Ambiguity function shows SNR-independent errors until critical threshold. Doppler count emphasizes phase for accurate measurements. SNR inversely related to error standard deviation.

21	LFMCW	FFT	Tangential targets detection having 0 Hz doppler frequency	achieving superior detection of slowly moving and tangential targets, including 100% detection probability for the latter under specified conditions.
22	LFMCW	2D FFT	For small and very high Doppler frequencies	Proposed a combined structure to address degradation in middle Doppler targets.
23	Pulse	FFT, clutter rejection filter, CFAR thresholding	Work in environments with random noise	The study highlights the impact of adaptive CFAR thresholding on FFT-based signal processing, significantly reducing error at low SNRs compared to simple methods.
24	Pulse	Fast iterative multipleburst, Normalized Matched Filter, Discrete Fourier Transform	Detect small and slowly moving targets	Show significant gain with a multiple-burst approach for covariance matrix estimation, enhancing detection of small and slow-moving targets.
25	Pulse	RSP techniques, matched filter , CFAR	Analyse five targets with different ranges, velocities, and RCS	The paper analyzes radar system behavior in detecting targets with varied ranges, emphasizing radar signal processing for accurate target extraction
26	Pulse	Combined superresolution algorithm	Amplitude and phase estimation of a sinusoid, ground surveillance	The proposed algorithm significantly boosts sharpening ratio and enhances scene quality in Doppler beam
27	Pulse	Correlation processing technique	Usage for target detection in pulse radar systems	The results demonstrate that using polyphase P4 code in pulse radar improves range resolution
28	Pulse	Pulse Doppler Processing	Velocity estimation, Doppler-based target detection	Proposed digital technique for Doppler frequency estimation in pulse-Doppler radar systems
29	215 GHz pulsed radar	Peak detection for signal detection	Bckscatter measurements from terrain targets at several km	The radar system demonstrates accurate scattering measurements of various terrestrial targets with instrument stability of 1.0 dB
30	Pulse	bandpass filtering, spectrogram computation, adjust cutoff frequencies	Estimate fall risk and enable interventions for the elderly	It effectively distinguishes targets from clutter, ensuring robust performance in challenging environments
31	Pulse	Open Multi Processing (OpenMP)	Applied in radar applications that require high computing power	The overall parallel efficiency achieved was 95%, surpassing state-of-the-art implementations
32	Ultra-Wideband pulse radar	PulseDoppler Processing	Personalized healthcare, and detection of sleep in drivers	Experimental tests demonstrate the radar sensor's capability to detect small variations in target positions
33	Synthetic Aperture Radar	PulseDoppler Processing	Targets buried in soil, mine detection, target imaging	Demonstrated the challenges and potential of radar-based detection and identification
34	Coherent short-pulse radar	Coherent Accumulation Maximum Likelihood Direct Position Determination (CAMLDPD) algorithm	Underwater acoustics for passive localization	The proposed method substantially enhances locating accuracy compared to existing methods
35	Pulse	Radial Basis Function Network (RBFN)	Improvements signal to sidelobe ratios, noise rejection	RBFN demonstrated improved noise rejection performance and range resolution ability for pulse radar tracking
36	Pulse	Prony's method, backward prediction for waveform reconstruction	For collecting data on underground targets	Crafted a pole suppression process and a backward prediction method, employing a difference equation approach

In another paper [22], "Radar Doppler Frequency Measurements—Accuracy Versus SNR in Practical Processors" explores the accuracy of Doppler frequency measurements in radar systems and its correlation with the Signal-to-Noise Ratio (SNR) through various methodologies. It discusses the Pulse-Doppler processor, phase measurement approaches, and pulse compression techniques used for Doppler processing. The study highlights the importance of SNR in measurement accuracy, showcasing SNR-dependent errors and emphasizing the significance of signal phase for precise measurements. Additionally, Monte Carlo simulations are employed to evaluate measurement error under different SNR conditions, with future work focusing on assessing radar system parameters' impact and field trials for validation.

In [23], the author compares single and double delay line cancelers for Moving Target Indication (MTI) processing and evaluates the impact of Adaptive Constant False Alarm Rate (CFAR) thresholding on FFT-based signal processing in noisy environments. The study discusses the utilization of Doppler shift to differentiate moving from stationary targets and the implementation of MTI processing through Delay Line Cancelers to filter out stationary clutter. It introduces Adaptive CFAR thresholding to enhance FFT-based signal processor performance in environments with random noise, highlighting its effectiveness in reducing errors and improving detection accuracy, particularly at low Signal-to-Noise Ratios (SNRs). Results demonstrate substantial improvements in detection results and a significant reduction in error percentage across various SNR levels with the implementation of adaptive CFAR thresholding.

Authors in [24], addresses the limitation of classical Doppler processing in suppressing small and slowly-moving targets while rejecting ground clutter returns. To overcome this, a two-step Doppler method is proposed. The first step employs a new iterative algorithm to resolve ambiguities and detect fast targets, while the second step utilizes an adaptive detection scheme with a new covariance matrix estimation technique to detect slowly-moving targets. The research evaluates the performance of an adaptive nonparametric matched filter (ANMF) on simulated and real data obtained from a ground-based pulse Doppler radar. The radar operates under challenging conditions, illuminating heavy sea clutter. Results demonstrate the effectiveness of the ANMF technique in detecting small and slow-moving targets, especially when employing a composite filter processor for covariance matrix estimation, thus showing promise for radar surveillance applications.

In [25], the authors present a comprehensive simulation-based tutorial on radar signal processing (RSP) techniques. It outlines an end-to-end modular framework for radar signal processing, covering matched filtering at the receiver front-end, followed by Moving Target Indication (MTI) filtering, Doppler processing for velocity detection, and Constant False Alarm Rate (CFAR) detection. The tutorial includes comparisons of different signal processing techniques, discussing the effects of varying parameters such as pulse type, number of FFT points for Doppler shift computation, windows, MTI filtering, and CFAR algorithms on output signals. Simulation results focus on detecting five targets with different ranges, velocities, and Radar Cross Sections (RCS), highlighting the influence of these factors on signal strength and the role of signal processing techniques in accurately characterizing detected targets. Additionally, the paper addresses design issues faced by radar system designers and outlines a modular framework for radar signal processing, providing insights into radar system development and optimization.

In [26],the authors present a novel combined super-resolution algorithm with aperture extrapolation designed for Doppler beam sharpening (DBS) imaging. Unlike traditional methods utilizing Fast Fourier Transform (FFT) for Doppler analysis, this algorithm employs spectral estimation techniques, enhancing the sharpening ratio significantly. By incorporating amplitude and phase estimation of sinusoids and utilizing aperture extrapolation to increase data length in the azimuth direction, the algorithm achieves clearer and sharper scene information with reduced side lobes and narrower peaks. Experimental validation on simulated and real data confirms the effectiveness of the proposed approach in improving DBS imaging quality. Additionally, the paper suggests future research directions, focusing on Ground Moving Target Indication (GMTI) and target relocation techniques on high-resolution DBS maps for improved accuracy.

Th paper [27], focuses on utilizing polyphase P4 code for target detection in pulse radar systems, employing correlation processing techniques for pulse compression. Through the integration of Matlab and GNU Radio, the study investigates the application of polyphase P4 code in pulse radar and demonstrates its effectiveness in improving range resolution. The results underscore the significance of employing polyphase P4 code, indicating enhancements in target detection capabilities within pulse radar systems.

Authors in [28] explore a proposed digital technique for Doppler frequency estimation in pulse-Doppler radar systems. Focused on velocity estimation and Doppler-based target detection and tracking, the study delves into novel methods for enhancing signal processing capabilities within pulsed radar systems. By introducing this digital technique, the research aims to advance Doppler frequency estimation, thus improving the efficacy of pulse-Doppler radar systems in target detection and tracking applications.

In [29], the authors present a radar system operating at 215 GHz, featuring a logarithmic amplifier for signal detection. This system showcases the capability to perform backscatter measurements from terrain targets at ranges of several kilometers under typical atmospheric conditions. Notably, the radar system achieves accurate scattering measurements of diverse terrestrial targets, exhibiting instrument stability of 1.0 dB.

In [30], the authors introduce algorithms for pulse-Doppler radar systems, involving bandpass filtering, spectrogram computation, and adaptive adjustment of filter cut-off frequencies. These techniques are applied in everyday environments to estimate fall risk and enable interventions for the elderly. Notably, the radar system effectively distinguishes targets from clutter, ensuring robust performance even in challenging environments.

The authors [31], explores the evaluation of Open Multi Processing (OpenMP) as a digital signal processing technique for pulse-Doppler radar systems. These methods demonstrate applicability in radar applications demanding high computing power. Notably, the study achieves an overall parallel efficiency of 95%, surpassing state-of-the-art implementations.

In an other paper [32], focuses on integrating planar differential antennas with Ultra-Wideband (UWB) pulse radar technology. Employing Pulse-Doppler Processing, the radar system aims at applications such as monitoring respiratory rates in adults and infants, enabling personalized healthcare, and detecting sudden sleep in drivers early. Experimental tests showcase the radar sensor's effectiveness in detecting small variations in target positions, highlighting its potential for precise and reliable applications in various domains.

The study explores Ultra-Wideband, Short Pulse Synthetic Aperture Radar (SAR) technology, employing Pulse-Doppler Processing [33] . The radar system is designed for detecting and identifying targets buried in soil, with diverse applications in mine detection, target imaging, and resonance-based identification. Through simulation and measurement, the study demonstrates both the challenges and potential of radar-based detection and identification, offering insights into the capabilities of this technology for various real-world applications.

In [34], the authors introduce the Coherent Accumulation Maximum Likelihood Direct Position Determination (CAMLDPD) algorithm for coherent short pulse radar systems. This method finds applications in signal processing, communications, and underwater acoustics for passive localization. Notably, the proposed method significantly enhances locating accuracy compared to existing methods, representing a substantial advancement in radar signal processing techniques.

Another paper explores the application of Radial Basis Function Network (RBFN) in pulse radar systems [35]. The study indicates significant improvements in error convergence speed, signal-to-sidelobe ratios, noise rejection, and range resolution ability. Particularly, RBFN demonstrates enhanced noise rejection performance and range resolution ability for pulse radar tracking, marking a notable advancement in radar signal processing techniques.

At the end the paper [36] focuses on enhancing identification accuracy of underground targets with pulse radar systems. It employs Prony's method for resonance extraction, difference equation-based pole suppression, distortion correction, and backward prediction for waveform reconstruction. Specifically designed for video pulse radar systems aimed at gathering data on underground targets such as tunnels, the study introduces a pole suppression process and a backward prediction method utilizing a difference equation approach. These methods contribute to improved target identification by mitigating undesired natural resonances and enhancing radar signal processing capabilities for underground target detection.

V. Conclusion

In conclusion, the review of signal processing algorithms for radar signals offers a compelling narrative of ongoing innovation and advancement in the field. From the refinement of LFMCW radar systems to the development of novel approaches for interference mitigation in automotive radar, each study contributes significantly to enhancing radar performance and reliability. Particularly noteworthy is the focus on automotive radar systems, where the integration of adaptive array processing algorithms and innovative radar configurations demonstrates substantial progress in target detection and tracking capabilities. Furthermore, the utilization of advanced signal processing techniques, such as FFT analysis and MTI filtering, underscores the interdisciplinary nature of radar technology. Whether it's detecting slow-moving targets or monitoring vital signs non-invasively, radar systems are proving increasingly versatile in their applications. As radar technology continues to evolve, driven by innovative research and development, its impact across various domains, from healthcare to homeland security, promises to be profound and far-reaching, heralding a new era of accuracy, efficiency, and adaptability in radar signal processing.

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