High Resolution 2D Time Frequency Representation of Radar micro-Doppler Pedestrian Signal

Sidrah Liaqat[1], Mojeeb bin Ihsan, S. Zeeshan Asghar, Aqib Ejaz, Aamir Javed

College of Electrical and Mechanical Engineering
National University of Sciences and Technology
Islamabad, Pakistan
[1]`sidrah@ee.ceme.edu.pk`
[1]`sidrah@ieee.org`

***Abstract*— In this paper, a modified 2D time-frequency minimum variance spectral estimation method has been applied to non-stationary micro-Doppler signal of radar targets. Pulse Doppler radar has been employed to capture returns from targets possessing vibrating sub-parts which cause micro-Doppler phenomenon. The aim is to obtain a high resolution time-frequency representation of the acquired micro-Doppler radar signal for use in feature extraction for the purpose of automatic radar target recognition.**

***Keywords*— micro-Doppler, joint time-frequency, 2D Capon spectral estimator, ATR**

I. INTRODUCTION

In the field of automatic target recognition (ATR) of radar targets, there are variations in the radars being used in terms of operating frequency and waveform, resulting in a number of different observable phenomena exhibited by targets such as 1-dimensional (1D) range profile using stepped-frequency radar or 2-dimensional (2D) images of targets using SAR or ISAR technique. One such phenomenon which is being employed in ATR research is the micro-Doppler phenomenon which comes into play when radar targets having sub-parts with additional vibratory or oscillatory motion interact with the radar signal. Some common radar targets which exhibit this phenomenon are humans, quadrupedal animals, helicopters, jet engine aircraft, missiles etc. Micro-Doppler phenomenon causes a characteristic time-varying frequency modulation on the return radar signal making it non-stationary and is a good candidate for feature extraction for ATR.

V. C. Chen et al. have given a detailed mathematical formulation of the micro-Doppler effect in radar [1]. They have also proposed mathematical formulae for describing micro-Doppler phenomenon caused by the basic motions of vibration, rotation, tumbling and coning. This mathematical formulation shows that the micro-Doppler signal is a non-stationary signal. In the literature, for analysis and processing of signals with time-varying frequency content, joint time-frequency transforms or distributions have been employed most frequently [2] which show how the energy of the signal is distributed over the two-dimensional time-frequency space. Processing of the signal may then exploit the features produced by concentration of signal energy in two dimensions (i.e time and frequency) instead of only one (time or frequency). Because of the non-stationary nature of the micro-Doppler phenomenon, joint time-frequency domain is most suitable for the analysis of micro-Doppler signals because it has the capability of showing variations in signal spectrum over time.

NR-V2 is a pulse doppler ground surveillance radar which detects moving ground targets such as vehicles, humans and quadrupedal animals. Work is ongoing to incorporate ATR capability in NR-V2 radar during which it was observed that the spectrogram of vehicles and pedestrians is very different and can become a basis for classification between them [3]. However, the spectrogram of micro-Doppler signature obtained using short-time Fourier transform method does not possess adequate resolution for extracting features for classification. In this paper, a high-resolution 2-D time-frequency representation of pedestrian micro-Doppler signature has been computed.

II. MICRO-DOPPLER PHENOMENON

Fig. 1 shows the spectrogram of pedestrian targets observed through GSR NR-V2 in a single range bin. The horizontal axis corresponds to increasing time and the vertical axis corresponds to target speed (which is inferred from target Doppler by scaling) with centre indicating zero speed. For this radar, pedestrian targets typically remain visible in a range bin for a duration of 7 seconds. The main body Doppler return is at a frequency which corresponds to pedestrian speed of 4.94 km/hour. The time-frequency signature of this target has a wide spread along speed axis ranging from approximately 10 km/hr to 0 km/hr because of vibrating sub-parts (target limbs). This spread is not persistent over all time. Instead there is a periodic alternately increasing and decreasing trend in target Doppler which is similar to the Doppler spectrum obtained by simulation results of scatterers with vibrating sub parts as reported by [1]. This evidence of the presence of micro Doppler signature in pedestrian audio data served as the motivation for this work. However, there are some difficulties in obtaining a time-frequency representation of pedestrian micro-Doppler signature which will be discussed next.

For a radar system with carrier wavelength λ_c which is observing a target having vibrating sub-parts moving with radial velocity v_r towards the radar, the Doppler frequency shift induced by the target exhibits a time varying sinusoidal

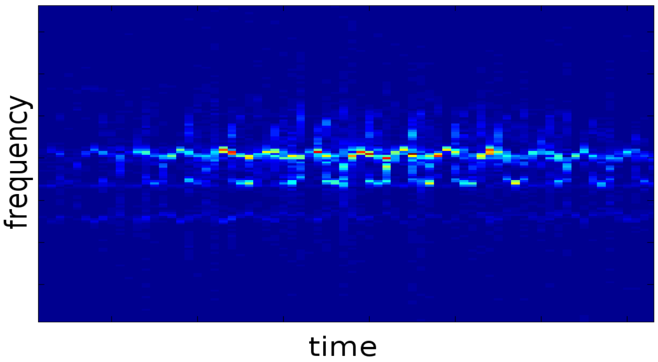

Fig. 1: STFT of pedestrian micro-Doppler signature captured by NR-V2 ground surveillance radar

frequency modulation $f_d(t)$ on the main body Doppler [4] given by (1):

$$f_d(t) = \frac{2v_r + 2D\omega cos(\xi) cos(\omega t + \psi)}{\lambda_c} \quad (1)$$

where $2D\omega \cos(\xi)$ gives the amplitude of vibration of sub-parts having a vibration rate ω and maximum displacement D from their centre position at an angle ξ with the radar LOS. The Doppler signal returned from such a target with vibrating sub-parts is composed of returns from the main body and vibrating limbs.

From (1) it can be seen that higher the vibration rate and the maximum displacement of the vibrating sub-part, higher will be the resultant Doppler shift thus giving a higher Doppler resolution for the same system. So at a particular carrier wavelength, it is easier to capture and analyse the micro-Doppler signature of a helicopter than that of a pedestrian because helicopters blades have higher maximum displacement D as well as higher vibration rate ω as compared to pedestrians. For instance, in [5], the maximum micro-Doppler shift recorded by an X-band radar induced by helicopter blades is reported to be 16 kHz. In comparison, for an X-band radar operating at a wavelength λ_c of 3 cm, observing a pedestrian with maximum arm displacement D of 1 m and vibration rate omega of 1.2 Hz, the maximum induced micro-Doppler shift is approximately 80 Hz. Larger maximum micro-Doppler shift can be achieved by increasing λ_c or by improving Doppler resolution, since, for typical pedestrians, D and ω can't be increased significantly. Higher frequency systems are more suitable for capturing micro-Doppler signature. For NR-V2 operating at Ku band, the maximum micro-Doppler shift ranges from approximately 96 Hz to 144 Hz which makes capturing micro-Doppler signature of pedestrian targets with good Doppler resolution difficult.

III. EXTRACTING TIME-FREQUENCY SIGNATURE FROM NON-STATIONARY SIGNALS

Time-frequency transforms include linear transforms, such as short-time Fourier transform (STFT) and bilinear transforms, such as the Wigner-Ville distribution (WVD). STFT is the classical technique for obtaining time-frequency representations of non-stationary signals [6]. The frequency resolution of STFT is determined by the window duration and has a minimum time-bandwidth product equal to one, thus limiting the resolving detail of this transform. Wigner distribution and other bilinear transforms exhibit time-bandwidth product greater than one as they do not suffer from time localization vs frequency resolution trade-off problem of linear time-frequency representations [7]. However, bilinear transforms have the problem of cross-terms introduced in the resulting distribution for multi-component signals.

Marple has suggested a linear time-frequency representation called 2D TFMV (time-frequency minimum variance) [5] having the resolution of a quadratic time-freq representation but without the disadvantage of cross-terms. In [8], Marple has applied this technique to radar Doppler audio signal of a two-engine Eurocopter Deutschland BO-105 helicopter which exhibits micro-Doppler phenomenon.

In this paper, the same technique has been applied to radar Doppler audio signal of pedestrians captured by NR-V2 for obtaining a high resolution time-frequency representation of the pedestrian micro-Doppler signature.

IV. 2D TIME FREQUENCY MINIMUM VARIANCE TECHNIQUE

We begin with a finite 1D time series of length N, which in our case is target audio signal taken from a single range bin containing micro-Doppler signal. The 1D data record is converted to a 2D data matrix $x_{WDF}(t,\tau)$ (named Windowed Data Function WDF by Marple [8]) by moving a sliding window of M samples over 1D data one step at a time. Each time step gives a short-time windowed signal $x_h(t,\tau) = x(\tau)\, h^*(\tau - t)$.

At each time step, the resulting windowed data vector is placed in the 2D matrix row-wise, using the analysis window center time t as the row index. The row index t ranges from $-\frac{M+1}{2}$ to $\frac{M+1}{2}$ which requires zero filling at the beginning and end of the original 1D time series. The data samples in each row are indexed by τ (termed as 'lag') where τ ranges from 1 to M. These are all linear operations. The resultant WDF is given by:

$$x_{WDF}(t,\tau) = \begin{bmatrix} 0 & \cdots & \cdots & 0 & x[1] \\ 0 & \cdots & 0 & x[1] & x[2] \\ \vdots & & & & \vdots \\ x[1] & \cdots & \cdots & x[M-1] & x[M] \\ x[2] & \cdots & \cdots & x[M] & x[M+1] \\ \vdots & & & & \vdots \\ x[N-1] & x[N] & 0 & \cdots & 0 \\ x[N] & 0 & \cdots & \cdots & 0 \end{bmatrix}$$

This method of arranging 1D data into a 2D matrix with zero padding at the beginning and end of the 1D data record is called autocorrelation method by Haykin [8]. This method yields a toeplitz correlation matrix for the input data.

This WDF corresponds to the IAF (Instantaneous Autocorrelation Function) in the WVD framework [9]. Taking 1D Fourier transform of WDF along τ (or lag) will give the STFT. Marple, however, suggested in [8] that by taking 1D Fourier transform of WDF along time axis instead of lag axis, we get a 2D matrix called CWT (complex WDF transform) indexed by v,τ. In [9], Marple has suggested two such techniques namely the 2D autoregressive and 2D minimum variance technique.

A. 2D Capon spectral estimator - basis of 2D TFMV method

For this work, 2D TFMV method was selected for finding high resolution 2D time-frequency representation from CWT. TFMV method has been derived from minimum variance spectrum estimator which is a nonparametric adaptive spectrum estimation technique also called Capon spectral estimator. S. Kay has referred to the Capon spectrum estimator as the MVSE (minimum variance spectrum estimator) [10]. However, this estimator does not possess the statistical property of minimum variance. It is a high resolution spectrum estimation technique adapted from Maximum Likelihood Method. In literature Capon spectral estimator has also been referred to as Maximum Likelihood estimator, but it does not possess any properties of the maximum likelihood estimator. In [11], Hayes has also referred to the Capon spectrum estimator as MVSE. In S. Haykin's book [13], Capon's method appears as MVDR spectrum estimate. An introduction to capon spectral estimator using both weighted least squares and matched-filterbank interpretations can be seen in [12].

2D Capon spectral estimator problem formulation has been given in [14]. The 2D data is evaluated for the presence of sinusoids of frequency ω, ω'. The objective is to find power of spectral content for the resultant time-frequency matrix at all the frequencies of interest in the range $\omega = [-\pi, \pi]$ and $\omega' = [-\pi, \pi]$. Capon spectral estimator given by Equation (11) in [14] is based on the constraint that the energy of filter output should be minimized such that the filter output at the centre frequency ω, ω' remains undistorted. Here R is the covariance matrix of the input data having Toeplitz-Block-Toeplitz structure with dimensions $M1 \times M2$. $a(\omega, \omega')$ is the 2D Fourier vector of length T, F thus deciding the size of the output 2D matrix. $a\left(\omega, \omega'\right) \triangleq a\left(\omega\right) \otimes a\left(\omega'\right)$ is the Kronecker product of $a(\omega) = a(\omega') = [\begin{matrix} 1 & e^{-\omega} & e^{-2\omega} & \cdots & e^{-M\omega} \end{matrix}]$.

B. Modification in 2D Capon spectral estimator

In the formulation of the 2D Capon spectral estimator mentioned above, the 2D Fourier vector is meant to find the 2D spectrum of a matrix having time on both axis. In this case, the input CWT is a time-frequency matrix. Therefore, a modification in the 2D Fourier matrix has to be made that $a(\omega)$ is changed to $[\begin{matrix} 1 & e^{\omega} & e^{2\omega} & \cdots & e^{M\omega} \end{matrix}]$. Resultantly, Fourier transform is taken along t dimension and inverse Fourier transform is taken along v dimension on the CWT. This modified form of 2D capon spectral estimator forms 2D TFMV method to obtain a time-freq representation of the 1D non-stationary signal.

V. APPLICATION OF SPECTRAL ESTIMATION METHOD TO RADAR DATA

We have collected radar audio data in the form of a finite 1D complex time series of length M_{sw}, with a sample rate of 625 Hz. This 1D data is converted to 2D matrix by moving a window of length M over it. Decision of window length depends on temporal correlation of the non-stationary signal.

The resultant time-time WDF matrix is indexed by t along columns where $t = 1 : M$. Here t keeps track of time index of each data vector picked up from the window function. The rows are indexed by τ where $\tau = -\frac{M+1}{2}$ to $N + \frac{M+1}{2}$ resulting in $N + M - 1$ rows. Here τ keeps an index of the columns of WDF.

The 2D TFMV spectral estimator is applied to this CWT resulting in a high resolution time-frequency representation indexed by t along columns and f along rows. Here t keeps track of the time of occurrence of the micro-Doppler signal and f, ranging from approximately $-10.5 Km/hr$ to $10.5 Km/hr$, represents the spectral components in the micro-Doppler signal at any time instant t.

In the application of the 2D Capon spectral estimator, the size of the covariance matrix R is dictated by the parameter $order$. This parameter directly affects the resolution of the resultant time-frequency representation. The size of the resultant time-frequency representation is determined by the parameters T and F. Table 1 lists four sets of parameters which were used for generating time-frequency grams from radar audio data using modified 2D TFMV technique.

TABLE I

PARAMTERS FOR GENERATING HIGH RESOLUTION REPRESENTATION OF BO – 105 HELICOPTER DATA AND PEDESTRIAN DATA CAPTURED BY NR-V2 RADAR USING 2D TFMV METHOD

Parameters	**Description**	**Set 1**	**Set 2**	**Set 3**	**Set 4**
M_{sw}	Length of 1D input data	1024	256	1024	512
M	Length of window	512	128	128	128
T	Time resolution	16	16	64	64
F	Frequency resolution	128	128	512	512
Order	Size of R	12	16	16	16

VI. RESULTS

A. Time-Frequency gram of BO-105 Helicopter micro-Doppler signal for different parameter settings

In order to verify the approach, the modified 2D TFMV gram was applied to Doppler radar signal of a two-engine Eurocopter Deutschland BO-105 helicopter illuminated by an X-band CW radar [15]. The resulting time-frequency grams generated by using parameter set 1 and set 2 from Table 1 are respectively given in Fig. 2 and Fig. 3.

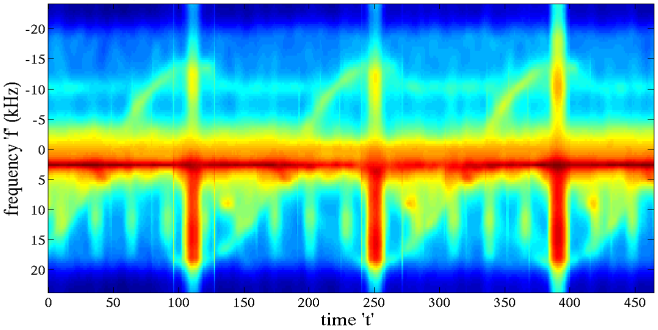

Fig. 2 Time–frequency representation of BO-105 Helicopter signature using 2D modified TFMV technique with parameter set 1 from Table 1

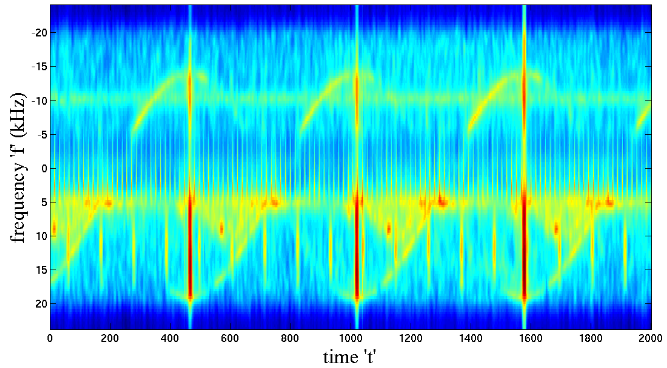

Fig. 3 Time-frequency representation of BO-105 Helicopter signature using 2D modified TFMV technique with parameter set 2 from Table 1

B. Time-Frequency gram of pedestrian micro-Doppler signal captured through NR-V2 ground surveillance radar

The 2D TFMV spectral estimator was applied to micro-Doppler return signal from pedestrian target collected by NR-V2 radar. The resulting high resolution time-frequency representation of pedestrian micro-Doppler signal is shown in Fig. 4 and Fig. 5 using parameter set 3 and 4 respectively given in Table 1. This comparison highlights that in order to obtain a good joint time-frequency representation of a non-stationary signal, the signal should be windowed carefully and according to its time correlation properties. This high resolution time-frequency representation shows a considerable improvement in resolution as compared to short-time Fourier transform spectrogram of pedestrian target given in Fig. 1.

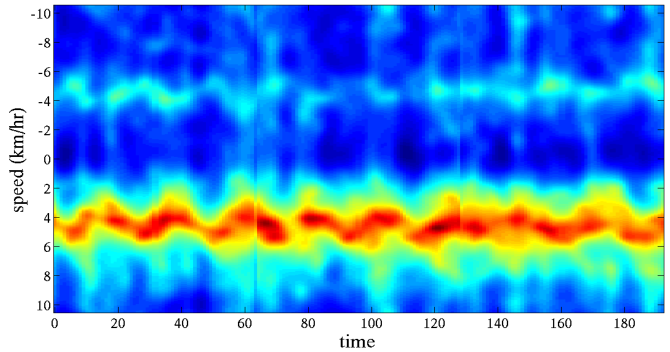

Fig. 4 Time–frequency representation of pedestrian signature using 2D modified TFMV technique with parameter set 3 from Table I.

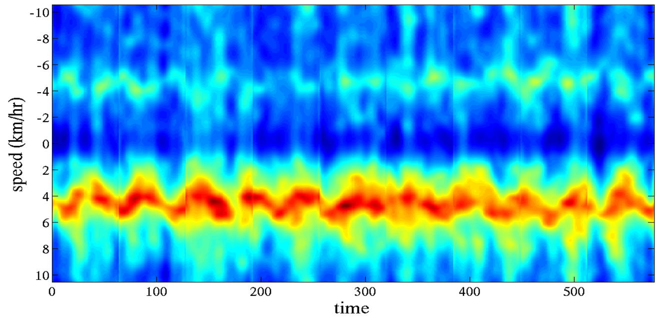

Fig. 5 Time-frequency representation of pedestrian signature using 2D modified TFMV technique with parameter set 4 from Table I.

VII. CONCLUSION

This papers reports the result of applying a high resolution 2-D time-frequency spectrum estimation technique to Doppler audio data of pedestrian target acquired through NR-V2 radar which is a pulse doppler ground surveillance radar. The resulting high resolution time-frequency gram has been reported which shows considerable improvement in time-frequency resolution over STFT of pedestrian signature.

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