Micro-Doppler signature based helicopter identification and classification through Machine learning

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Abstract—This paper focuses on identification of helicopter by exploiting the concept of micro-Doppler effect which is prominent in targets containing rotating, oscillating or vibrating parts in it. Radar received signal is analyzed by Short Time Fourier Transform (STFT) to extract the micro Doppler (mD) signature. From the mD signature, the helicopter parameters are estimated. In a multiple helicopters scenario, estimated parameters will be a mixture, pertaining to the multiple helicopters. These parameters are classified further using a machine learning algorithm, namely k-means clustering to classify the helicopters. Simulated results for the synthesized received signal shows the better estimates of the helicopter parameter through mD signature. Dataset containing basic parameters like number of blades, blade length and rotational rates of the UN-1N helicopter (rotor with 2 blades), the SH-3H helicopter (rotor with 5 blades) and the CH-54B helicopter (rotor with 6 blades) are considered for the classification. Results show a good classification. When analysed with different SNR level in dataset, at lower SNR, observed some overlapping in the classification.

Keywords—k-means clustering, Micro-Doppler effect, Micro-Doppler signature, Short Time Fourier Transform.

I. INTRODUCTION

The micro-Doppler signatures extracted from the target’s backscattered signal contain a lot of information about the target which can be extensively used in target detection and identification. Target detection and tracking dates way back in time. It’s just the methodologies that keep advancing day by day. Initially detection of a target was based on its Radar Cross Section (RCS). This indicates how much a target is detectable by a radar based on the property of the object’s reflectivity. This RCS is dependent on so many features of the target such as the material of the target, shape of the target, the angle at which the transmitted signal hits the target (i.e., incident angle), the angle at which the received signal is reflected from the target (i.e., reflected angle), etc. When the target has a high RCS then it is considered to be easily detectable. RCS is the earlier method used for aircraft detection over various ranges. But in recent times the concept of micro-Doppler (mD) effect is used to identify the target.

Micro-Doppler effect is caused due to the micro-motions in the target, when there are rotating, oscillating or vibrating parts in it. The extraction of these micro-Doppler signatures from the received signal of the target contains phase modulations. These phase modulations are extracted using time-frequency analysis techniques. There exist wide varieties of time-frequency analysing techniques such as Short Time Fourier Transform (STFT), Wigner Ville distribution (WVD), wavelet transform and so on. The pioneer of Micro Doppler effect in Radar is Victor C Chen. His book [1] contains research in extraction of micro-Doppler signatures from helicopters, human body, pendulum, bird, etc.

The micro-Doppler (mD) features in the time-frequency domain has also been studied in [2]. Further the received signal from the targets with micro-motions are analysed in both rigid and non-rigid bodies. These signals contain modulations that provide the information about the target. When special sensors are used to detect the living things at many instances wrong detections are made such as identifying other mammals as human beings. In [3] the author has overcome these confusions by introducing micro Doppler signatures for detection. Due to this the false alarm rate is reduced significantly. The blade length as well as rotation rate of the blades in a drone is calculated by extracting its micro-Doppler signatures using W-Band Micro-Doppler Radar [4, 5]. Identification for 1, 2 and 4 rotors are verified through simulation. In [6], Using mD, ballistic targets are classified based on the precession, nutation and wobble which are further used for categorizing them into warheads and decoy. They have achieved this by considering the occlusion effect as well as the point scatter model in the micro Doppler. Multi-static passave radars are used in [7] to extract the mD signature of the helicopter. Here the target appears to be at different angles for each receiver, giving rise to different micro-Doppler signatures, used as an additional information about the target to be identified. The concept of wavelet transform [8] and Inverse Radom transform (IRT) [9] along with the time frequency analysis is also used for feature extraction of helicopters and human models. The results of the main and the tail rotor blades appears as flashes. Other information like speed of the rotor and the number of blades in each rotor are used for the target categorizing [10]. Wavelet coefficients are
The translational motion of the target may result in a frequency shift in the backscattered or received signal. Sometime the target may consist of certain motions apart from translation which include rotations, vibrations or oscillations. These come under the category of “micro motions”. Not all the parts of the target which might be in motion cause frequency shifts in the received signal. Instead, they produce the phase shift and get modulated with the received signal. The phase modulations found in the backscattered signal are due to the presence of micro motions in the target and this is known as the micro-Doppler effect.

B. Radar signal model for micro Doppler shift

Consider a RADAR with space fixed coordinates as (X, Y, Z). The target of interest is available at a range, R from the RADAR with the body fixed coordinates (x, y, z). Here it is assumed that the target is a helicopter and the position of its rotor blade is assumed to be at (x, y, z) where the values of x, y and z are 0.

Consider that the target’s reference frame coordinates are (X’, Y’, Z’). This reference frame is located at the same origin as the body fixed coordinates and it is the translated version of the space fixed coordinates. These coordinates are clearly depicted in Fig.1. The blades in the rotor rotate along the z-axis with a certain angular rotation rate, Ω, which is measured in rev/s. These are the initial set of parameters to be taken into consideration.

Let the radar transmitted signal \( T(t) \) be assumed as

\[
T(t) = \exp(j2\pi ft) \quad \text{.....(1)}
\]

In case of a non-stationary target, the received signal consists of a time delay (\( \tau \)), and a modulated Doppler frequency (\( f_D \)). Then the received signal, \( S(t) \) is as follows:

\[
S(t) = \exp[-j(2\pi ft + \tau)] \quad \text{.....(2)}
\]

where \( \tau = \frac{4\pi}{\lambda} R(t) \) \quad \text{.....(3)}

In the helicopter, there are rotatory motions of blades, which further cause phase modulations in the received signal. This is due to the micro-Doppler effect. In case of the micro Doppler this \( \tau \) may be represented by

\[
\phi(t) = \frac{4\pi}{\lambda} R(t) \quad \text{.....(4)}
\]

### II. METHODOLOGY

A. Micro-Doppler Effect

Mechanical rotations or vibrations of an object or any part of the target may cause additional frequency modulations on the radar backscattered signal. This leads to the generation of sidebands about the target’s Doppler frequency. This phenomenon is called the micro-Doppler effect. The extraction of micro-Doppler signatures from the received signal provides additional information of the target which in turn helps in its identification.
Here $\Phi(t)$ is the phase function of the point of scattering and $R(t)$ is the varying distance between the scattering point on the rotating blade and the radar, with $f$ as the transmitting frequency and $\lambda$ as the wavelength of the radar as shown in Fig.2.

When the rotor height is $Z_0$, with a blade length of $L$, then the phase function in equation (3) for the scattered point is modified as [1]:

$$\phi(t) = \frac{4\pi}{\lambda} \left[ R_0 + \cos \beta (L \cos \phi_0 \cos \Omega t + L \sin \phi_0 \sin \Omega t) + z_0 \sin \beta \right] \quad \ldots \ldots (5)$$

Thus, the received signal shown in equation (2) for the scattered point becomes,

$$S(t) = \exp \left[ -j \frac{4\pi}{\lambda} \left[ R_0 + z_0 \sin \beta \right] \right] \exp \left[ -j 2\pi f t - \frac{4\pi}{\lambda} L \cos \beta \cos (\Omega t + \phi_0) \right] \quad \ldots \ldots (6)$$

where $\beta$ is the elevation angle of the target from the radar and $\Omega$ is the angular rotation rate of the rotor. For a rotor with $N$ blades, there are $N$ different initial rotation angles which can be represented as:

$$\phi(k) = \phi_0 + \frac{2\pi k}{N} \quad \ldots \ldots (7)$$

Here $k=0,1,2,3,\ldots,N-1$. The returns of each blade at an observed interval will appear as the backscattered signal. Then the radar cross section (RCS- $\sigma$) of the blade is given by

$$\sigma = \frac{4\pi a^2 b^2}{\lambda^2} \left( \cos \theta \times \frac{\sin x_k}{x_k} \times \frac{\cos y_k}{y_k} \right)^2 \quad \ldots \ldots (8)$$

III. THE PROPOSED METHOD

Methodology to classify the Helicopters from the radar received signal is shown in Fig 4. Mathematical model of the phase function in the reflected signal from the point scattered helicopter is given in the equation (5). Similarly, the expected received signal magnitude based on the radar range $R$ is given in the equation (8).

![Fig.2. Rotation of rotor blades (courtesy V. C. Chen[1])](image2)

![Fig.3. Rectangular flat plate modelled as the rotor blade (courtesy V. C. Chen[1])](image3)

From Fig.3., we observe that,

$$x_k = ka \sin \theta \sin \Phi \quad \ldots \ldots (9)$$

$$y_k = kb \sin \theta \cos \Phi \quad \ldots \ldots (10)$$

Where $k = \frac{2\pi}{\lambda} \quad \ldots \ldots (11)$

Equation (8) gives the amplitude of the received signal.

![Fig.4. Block diagram representation of mD extraction and helicopter classification process](image4)

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![Fig.4. Block diagram representation of mD extraction and helicopter classification process](image5)

The mD signature from the radar received signal, when it is reflected by a helicopter with 2 blades in its rotor is shown in Fig.5. This is the spectrogram plot of the change in frequency of the signal with respect to time. Next section explains the method using which the parameters are extracted from the spectrogram.

A. Micro-Doppler signature extraction

When the radar returns from the helicopter is viewed in the frequency domain, its mD shifts can be seen from the central frequency. But phase change cannot be identified through simple frequency analysis i.e., FFT. Hence the concept of time frequency analysis is preferred. To analyse the time-varying frequency characteristics of the micro Doppler modulated received signal, basic Short Time Fourier Transform (STFT) is used.

B. Short Time Fourier Transform (STFT):

It is a sequence of Fourier transforms performed on windowed signal which provides the time-localized frequency information. It is usually implemented on signals whose frequency components vary over time. This reveals the Fourier spectrum on each shorter segment. Then the changing spectra is plotted as a function of time. This plot is called the Spectrogram which clearly provides the information needed for the purpose of target identification and further classification.
From the spectrogram one can estimate the following parameters as shown in Fig. 5:

- Number of blades (N)
- Rotation rate \( \Omega = \frac{1}{T_c} \)
- Length of the blade (L)

A. Transmitted signal and received signal plot

To synthesize the transmitted and received signal in time domain using equation (1) and (6), following assumptions are made. The target considered here is a two-blade rotor helicopter whose blade length is of 6.5 m each with a rotation rate of \( \Omega = 4 \text{ revs/s} \) and the nutation angle of \( \theta = 45^\circ \). Here, C-band FMCW radar with the wavelength of \( \lambda = 0.06 \text{ m} \) is assumed for trans receiving the echo signal from the previously mentioned helicopter. Same waveforms are plotted as shown in Fig.6 for ideal scenario. In this plot, it is odd to identify the mD signature from the received signal.

B. Micro-Doppler signatures from the helicopter blades

Fig. 7 shows the spectrogram of the radar received signal. Using these spectrograms the three parameters namely number of blades, length of the blades and the rotation rate are calculated. Each blade rotation will be appearing as a sinusoidal wave form in the spectrogram. Thus the number of symmetric Doppler patterns in the spectrogram indicates the number of blades in the helicopter. Rotor’s rotation rate (\( \Omega \)) is calculated as \( \Omega = 1/t_c \); where \( t_c \) is the time period between two peaks of a sinusoidal waveform in the spectrum. Blade length\( (L) \) is calculated using the following equation [1]

\[
V_{\text{tip}} = 2\pi L \Omega \quad \text{ ...... (12)}
\]

Where \( V_{\text{tip}} \) is obtained from \( \{f_D\}_{\text{max}} = 2V_{\text{tip}} \cos(\theta)/\lambda \).
Tables 2-4 show the comparison between the actual parameters considered to synthesize the received signal and the calculated parameters which were obtained from the spectrogram.

C. Classification Results

The parameters obtained from Tables 2-4 for the three helicopters UN-1N, SH-3H and CH-54B are duplicated using two different \texttt{randn()} function in MATLAB in order to create the dataset as shown in Fig.8(a) and Fig.8(c).

Each parameter has 150 samples. Fig.8(b) and Fig.8(d) represent the dataset after classification using k-means clustering algorithm. It is observed that the created samples in the dataset are assigned to one of the three categories giving rise to 3 clusters each corresponding to one of the three helicopters namely UN-1N, SH-3H and CH-54B.
Fig. 7. Classification using k-means clustering. (a) three dimensional representation of the dataset before classification. (b) the dataset after classification using k-means clustering algorithm. (c) dataset of the helicopter parameters with a slightly lower SNR value. (d) the classified dataset which has some overlap in the classification.

V. CONCLUSION

This paper used one of the existing algorithms for calculating the micro-Doppler signatures. With these extracted features, the concept of machine learning namely k-means clustering is used to classify the different targets. Being one of the simplest and at the same time the effective method for clustering, k-means clustering has provided the clustering of data belonging to three different helicopters with utmost precision. This classification methodology can be used to train the classifier with more dataset which may be collected in actual scenario and can be used for further testing.

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