Legs Components Micro-Doppler Estimation of Human Target Based on Doppler Radar

Chengxi Lei, Yipeng Ding

School of Physics and Electronics, Central South University, Changsha, Hunan Province, 410000, China

Corresponding author’s e-mail: 825947927@qq.com

Abstract. The radar based human micro-motion research is a new technology rapidly developed in recent years. Radar detection of human target has advantages that other sensors do not have. The radar system is not affected by light or weather condition, which makes it possible to achieve detection in various environments. Besides, targets hidden behind obstacles can be detected, because electromagnetic waves can penetrate barriers of a certain thickness. Doppler frequency shift caused by the modulation of electromagnetic waves by the swing of hands and legs during human motion can be obtained by various signal processing methods. Separation and estimation of multi-components signals is a prerequisite for studying micro-motion characteristics of human target. Because there are a lot of aliasing in the time-frequency diagram of component with each other, separation of multi-components signals is a difficult but urgent problem at present. In addition, kinematic parameters of human legs play a key role in distinguishing human and animal targets. Therefore, in order to extract human leg signal and estimate its frequency accurately, a signal separation method based on Bezier curve fitting is proposed in this paper. Because human radar echo signals are often non-stationary time-varying signals, we need to process the collected signals with time-frequency transforms. The accuracy of this method for extracting components of legs is precise, and it has met the accuracy requirement of Micro-Doppler research. The simulation and experimental results prove the effectiveness of this method.

1. Introduction

With the rapid development of modern signal processing technology, semiconductor technology and computer technology, radar function has evolved from single scale information measurement to feature information measurement[1],[2]. That is to say, from the detection and tracking radar which is traditionally used to measure coordinate parameters such as target detection, ranging and angle measurement[3],[4], it has developed into a feature radar which can realize the functions of target fine structure characterization and accurate motion feature extraction[5]. Micro-Doppler method has become popular in current human recognition research, for providing more abundant feature information for human target[6]. Radar detection has been widely used in the field of security and protection due to its advantages of not being affected by light, temperature and humidity, and its ability to penetrate obstacles[7],[8],[9]. With the continuous improvement and refinement of people's demand for security monitoring means, the identification of human targets through micro-motion information is a promising direction in micro-motion research. Because there may be disturbance information such as animals in the scene, human body recognition in complex environment is also a difficult problem[10]. The main centroid translation of radar target or its components is often accompanied by vibration, rotation and accelerated motion which are called Micro-Motion. The Micro-Motion of the target modulates the phase
of radar echo, and then generates corresponding frequency modulation. Additional modulation sideband is introduced near the Doppler frequency shift signal generated by the main translation of the target body. This extra modulation signal is called micro-Doppler signal, and this modulation phenomenon caused by micro-motion is called micro-Doppler effect. In the early stage, when signal processing was carried out, the micro-Doppler signal was usually considered as a side lobe or interference and other disadvantageous factors to be eliminated. In fact, the micro-Doppler effect can be regarded as the result of the interaction among the structural components of the target and the main body of the target. It reflects the instantaneous characteristics of the Doppler frequency shift and represents the instantaneous radial velocity of the micro-motion of the target. It can be seen that the micro-Doppler characteristics of radar echo signal can delicately represent the human motion, and the non-stationary signal analysis method can be used to extract the micro-Doppler characteristics, which can effectively detect and estimate the human motion pattern. The actual target has fine structure and is no longer a simple point target. Usually, the micro-moving target can be regarded as a group of strong scattering points. Radar echo of Micro-Motion target is the result of electromagnetic interaction between these scattering points and radar incident wave. Therefore, the Micro-motion signal is a complex group of multi-component signals, each signal component reflects the physical characteristics of the target Micro-motion structure. In order to extract Micro-motion characteristics, it is necessary to separate Micro-motion signal components. In addition, since the frequency modulation parameters of the Micro-Motion signal directly reflect the dynamic characteristics of the target structure, it is also important to estimate the parameters of the multi-component Micro-Motion signal. However, due to the fact that the multi-component of the Micro-Motion signal usually overlaps and interferes with each other in the time-frequency domain, it poses a challenge to the component separation and parameter estimation of the signal. How to effectively separate the multi-component Micro-Motion signals and estimate the parameters of the multi-component signals has become a focused and difficult topic in the research of Micro-Motion and micro-Doppler.

At present, micro-Doppler signal separation technology can be divided into two categories: time-domain-based and time-frequency-domain-based. According to the different Doppler frequencies of micro-Doppler signal and target main body echo signal, time-domain signal is decomposed into a group of basis functions in different frequency bands, and then the micro-Doppler component is reconstructed using these basis functions. Typical methods include wavelet analysis, chirplet decomposition and EMD[11]. Firstly, the micro-Doppler signal is converted into time-frequency domain, and the instantaneous frequencies of target Micro-Motion parts and target main body are separated from two-dimensional time-frequency plane. These methods include Hough transform and Radon transform. The traditional wavelet analysis and EMD have the problem of insufficient separation accuracy under low SNR, while the Hough transform algorithm has the disadvantage of large amount of calculation[12]. The commonly used methods for parameter estimation of Micro-Motion signals are instantaneous frequency method and Hough transform short-time Fourier frequency estimation method. When the micro-Doppler components are overlapped in time-frequency domain, the instantaneous frequency method can not estimate the parameters well. However, the short-time Fourier transform method can not accurately estimate the frequency because of the shortage of frequency resolution due to the short time window.

In this paper, an effective method is proposed to separate the signal components of human legs based on their distribution characteristics. From the human structure model, we can infer and prove that the signal components of different parts of the human body have their own distribution characteristics in time and frequency domain. The torso component signal obeys the sinusoidal distribution, its frequency is twice that of the whole echo signal and its maximum Doppler shift is small. The leg signal component constitutes the envelope of the echo signal. Therefore, we can use Bezier curve to fit the components of the legs, and achieve effective and accurate micro-Doppler signal separation. By adjusting the movement of the control points of the Bezier curve, we can adjust the slope and shape of the curve arbitrarily. Compared with the traditional linear fitting method, Bezier fitting is more flexible and can more accurately fit the signal components. This micro-Doppler separation technology overcomes the
disadvantages of the above methods and ensures the effectiveness of signal separation. The experimental results show the effectiveness of this method

2. Micro-doppler scattering model for human targets

For a dynamic target, the real-time radial distance $R(t)$ is expressed as

$$R(t) = R_0 + V_R t + x(t)$$  \hspace{1cm} (1)

Where $R_0$ and $V_R$ are the initial range and the radial velocity of target relative to radar, respectively. $x(t)$ is the radial time-varying deviation caused by vibration or rotation of the target or its component. $S_r(t)$ is the transmitting signal of the radar, which can be expressed as

$$s_r(t) = A'(t)e^{i2\pi f_0 t + \psi_0}$$  \hspace{1cm} (2)

Where $f_0$, $\psi_0$, and $A'(t)$ are carrier frequency of the signal, Initial phase and Amplitude of transmitted signal. The transmitted signal returns partially when it encounters the target, and the reflected echo signal received by the radar is $S_R(t)$.

$$S_R(t) = A(t) \cdot e^{i[2\pi f_0 t + 2R(t)/c + \psi_0]}$$
$$= A(t) \cdot e^{i[2\pi f_0 t + 2R(t)/c + \psi_0]}$$  \hspace{1cm} (3)

Where $A(t)$ and $\phi(t)$ are the amplitude and phase of the echo signal. Therefore, the instantaneous frequency $f_D(t)$ is expressed as

$$f_D(t) = \frac{1}{2\pi} \frac{d\phi(t)}{dt} = \frac{d}{dt} \left( f_0 + \frac{2f_0}{c} R(t) + \psi_0 \right)$$
$$= f_0 + \frac{2f_0}{c} V_R + \frac{2f_0}{c} \frac{dx(t)}{dt}$$  \hspace{1cm} (4)

In the coherent radar system, the echo signal is mixed with the local oscillator signal, and then the instantaneous frequency of the output baseband signal is

$$f_D(t) = \frac{2f_0}{c} V_R + \frac{2f_0}{c} \frac{dx(t)}{dt}$$  \hspace{1cm} (5)

In the (5), the first term is the Doppler frequency generated by traditional translation; the second term is the micro Doppler frequency introduced by the target's micro motion.

Unlike rigid object in general, human body is a flexible object with very complex physiological and physical structure. When human body moves, the direction, amplitude and swing frequency of each part relative to radar are different. Therefore, it is almost impossible to give a single and complete description of the micro-Doppler scattering characteristics produced by various parts of the human body. In this part, in order to explain and understand briefly, we use the point scattering model commonly used in electromagnetic field analysis.

As mentioned earlier, when using radar to detect moving or running human targets, the moving speed of the human body (mainly the torso) will produce a traditional Doppler scattering signal, and the human limb swing will also produce additional micro-Doppler scattering. A simpler way of understanding is to assume the human body as five scattering points, namely, torso, left arm, right arm, left leg and right leg. Scattering echo from torso is traditional Doppler scattering, while scattering from arm and leg swing back and forth is defined as micro-Doppler scattering.

$$\varphi(t) = \frac{2f_0}{c} [2\pi \cdot x(t)] = \frac{4\pi}{\lambda} [x_1(t) + x_2(t) + x_3(t) + x_4(t) + x_5(t)]$$  \hspace{1cm} (6)
Where \(x_i(t) (i=1,2,3,4,5)\) represent torso component, hands components, legs components respectively. \(\phi(t)\) is the phase variation caused by these scattering parts. \(f_0\) and \(\lambda\) are the carrier frequency and wavelength. So, the micro-Doppler frequency modulation of the signal can be expressed as below:

\[
f_d(t) = \frac{1}{2\pi} \frac{d\phi(t)}{dt} = \frac{2f_0}{c} \left[ \frac{dx_1(t)}{dt} + \frac{dx_2(t)}{dt} + \frac{dx_3(t)}{dt} + \frac{dx_4(t)}{dt} + \frac{dx_5(t)}{dt} \right]
\]

\[
f_i(t) = \frac{2f_0}{c} \frac{dx_i(t)}{dt} \quad i = 1,2,3,4,5
\]  

(7)

From (7), it can be seen that the micro-Doppler modulation caused by human limb swing is the superposition of the micro-Doppler modulation of the left arm, the right arm, the left leg and the right leg[13].

### 3. Micro-doppler estimation method

Hough transform is a widely-used method for estimating instantaneous frequency of targets. The key part of this method is to select a suitable fitting function model \(F(X,t)\). The selection of fitting model is very flexible. We can adjust the shape of fitting function arbitrarily by setting parameter \(X\). Firstly, the fitting function is used to demodulate the radar received echo signal \(R(t)\), and then the demodulated signal is transformed by Fourier transform. As follows:

\[
S(f,X) = \int [r(t) \cdot e^{-j2\pi \int_0^t f(x,t) dt}] \cdot e^{-j2\pi f dt}
\]

(8)

By substituting the radar echo expression into the above formula, it can be found that when the fitting model function completely fits the original signal, the calculation results in brackets are a constant. The result of Fourier transform of constant is impulse function. That is to say, when the most suitable fitting model is selected, the result of Hough transform is an impulse in frequency domain. Therefore, we can choose the most suitable fitting model function by adjusting parameter \(X\), so that the energy of Hough transform of the original signal can be concentrated in the frequency domain as possible. For example, a traditional Hough transform linear fitting model can be expressed as follows:

\[
F(X,t) = bt + z \quad X = [b, z]
\]

(9)

b and \(z\) in the formula represent the slope and the initial frequency, respectively. By adjusting \(B\) and \(Z\) to form the most appropriate function to achieve the required fitting accuracy.

A n-dimensional Bezier curve is defined by a control polygon, and a group of straight lines constituting the polygon are called control lines. The vertex of the control polygon is \(P0, P1,…., Pn\). Among these points, only the first point \(P0\) and the last point \(Pn\) will be on the Bezier curve, and the remaining points will be used to define the order of the curve. The Bezier curve is represented by a parametric equation as follows:

\[
p(u) = \sum_{i=0}^{n} p_i B_{i,n}(u) \quad (0 \leq u \leq 1)
\]

(10)

\(B(u)\) is the harmonic function, which represents the position vector of points on the curve, as shown below:

\[
B_{i,n}(n) = C_n^i \cdot u^i (1-u)^{n-i}
\]

\[
= \frac{n!}{(n-i)!i!} \cdot u^i (1-u)^{n-i} \quad (i = 0,1,\ldots,n)
\]

(11)

The expression above is a polynomial of order \(n\) with \(n+1\) unknowns, in which \(P_i (i=0,1,2,3\ldots N)\) represents the position vector of the vertex of the control polygon \((n + 1)\). \(i\) denotes the vertex \(i\) and \(u\) is
a parameter. A corresponding Bezier curve is generated when u varies in the range of values in the interval [0, 1].

From the traditional Hough transform algorithm, it can be found that the selection and construction of the fitting model is the key factor to determine the fitting accuracy. At the same time, the traditional Hough transform needs prior knowledge of the target motion. In practice, the motion state of the target is unpredictable and its initial information is insufficient, which makes it difficult to construct an ideal fitting model function for different situations. In order to improve the frequency resolution, the length of frequency window should be as small as possible, but due to the inherent contradiction between time domain and frequency domain resolution, the window length should be selected appropriately. Generally speaking, for real-time human body detection, the optimal time window length is 0.3 to 0.6 seconds. Moreover, the traditional linear Hough transform cannot be accurately fitted when the instantaneous frequency of the target has obvious non-linear characteristics.

The shape of Bezier curve can be changed arbitrarily. For the typical human targets with low speed and large inertia, in order to simplify the description and facilitate understanding, the second Bezier fitting model can be used for Hough transform. When \( n = 2 \), \( P(u) \) is a quadratic curve, which is controlled by three points: starting point, ending point and controlling point. The quadratic Bezier fitting model functions are as follows:

\[
P(u) = \sum_{i=0}^{2} P_i \cdot B_{i,2}(u) = \sum_{i=0}^{2} (1-u)^2 \cdot P_i + 2u(1-u) \cdot P_1 + u^2 \cdot P_2 \quad (0 \leq u \leq 1)
\]

\( P_0 \) is the starting point of the curve, \( P_2 \) is the end point of the curve, \( P_1 \) is the control point of the curve, which can be used to adjust the shape of the curve.

Following is a brief description of the selection of these key points to control the fitting accuracy. Firstly, the radar echo signal is processed by short-time Fourier transform. Then the maximum and minimum points of Doppler frequency in each cycle are selected in the time-frequency map. The method used here is the threshold search method. Specifically, in order to find the maximum value of Doppler frequency in the period, we firstly set a frequency threshold, then search point by point along the frequency axis from top to bottom, and select points larger than the threshold. Then increase the set threshold, and find the points larger than the new threshold in those points. By repeating this, we can get the maximum value. The process of selecting minimum of the frequency is just the opposite. After obtaining the maximum value in a period, the maximum value is regarded as the starting point of Bezier curve and the minimum value as the end point of Bezier curve. Then, within the rectangular range determined by the starting point and the end point, the control points are searched so that the Hough transform energy of the signal can be concentrated as far as possible in the frequency domain. In theory, by increasing the number of control points, we can form a fitting model function of arbitrary shape, which can accurately separate the leg components under various motion conditions. In practical applications, only one control point, i.e. quadratic curve fitting, is needed to obtain a higher fitting accuracy with less calculation burden.

4. Experimental results
To quantitatively evaluate the performance of the proposed method, a Doppler radar prototype system with the carrier frequency of 2.4GHz is constructed in the laboratory. As Fig. 1 shows. In order to demonstrate the performance of the proposed method, both the simulated and measured experiments were carried out respectively. A Hamming window of 0.25 second is applied in this experiment to achieve real time-time processing.
In order to verify the effectiveness of the algorithm in various situations, we set different simulation conditions for human walking and running with constant velocity. Fig. 2 and Fig. 3 show the experimental simulation results of a walking human with the radial speed of 0.5 m/s and a running human with the radial speed of 2 m/s towards the Doppler radar.

From Fig. 2 to Fig. 3, it can be seen that, the human leg component has the largest frequency dynamic range, meanwhile being the weakest echo component. Therefore, it’s very vulnerable to interference from other body components and background noises. The micro-Doppler frequency variation of human leg is relatively complicated because the modulation effect of several interacting joints. The validity of the proposed approach is proven by the simulation results.

In this section, the micro-Doppler frequency estimation performance of the Bezier curve based Hough transform with different models (the traditional linear models) is compared. When traditional linear model is applied, the estimation result is shown in Fig. 4 and Fig. 5. From the figure, it can be seen that, although the traditional linear model can properly extract the foot echo component, there is a great fitting error in the micro-Doppler frequency estimation results, especially in the mid-stance and mid-swing period. This is mainly because that, around these areas, the linearity of the target micro-
Doppler frequency is worse and the linear model is not accurate enough to properly represent the foot IF variation.

![Graphs showing fitting results of a walking human with different models](image)

**Fig. 4.** fitting results of a walking human with different models (a) linear model (b) arc model (c) Bezier model

When the Bezier curve based estimation method is applied, the mid-stance and mid-swing estimation error is reduced, and the fitting frequency (Fig. 4, Fig 5) is almost the same as the practical frequency, especially around the maximum of the curve and can properly represent the asymmetric property of the target micro-Doppler.
The root-mean-square (RMS) error of the target micro-Doppler frequency estimation results have been listed in Table 1, which can further validate the superiority of the proposed new estimation method.

| Linear Model | Arc Model | Bezier Model |
|--------------|-----------|--------------|
| RMS Error (Hz) | 2.18 | 1.07 | 0.51 |

Fig. 6 shows two sets of measured result of walking and running targets respectively. The frequency estimation of the proposed method are close to the practical frequency.
5. Conclusion
In this paper, a human leg micro-Doppler frequency estimation method based on Bezier curve fitting is proposed. The Hough transform with Bezier curve model is used to real-time extract the leg echo components and precisely estimate micro-Doppler frequencies.

Both simulation and experimental results demonstrate the effectiveness and superiority compared with traditional methods. The proposed human leg micro-Doppler frequency estimation approach indicates great potential in various real-time human sensing applications, especially in targets recognition.

Acknowledgments
This work was supported by the Fundamental Research Funds for the Central South University under Grant 2019zzts422.

References
[1] Youngwook Kim et al., "Human Detection Using Doppler Effect on Physical Characteristics of targets", IEEE Geoscience and Remote Sensing Letters., vol. 12, no. 2, pp. 289-293, Feb. 2015.
[2] R.Javier et al., "Application of Linear Predictive Coding for Human Activity Classification based on Micro-Doppler Signatures ", IEEE Geoscience and Remote Sensing Letters,vol.10,no.4,pp.781-785, Jul.2013.
[3] L.Li,W.Zhang et al., "A Novel Autofocusing Approach for Real-Time Through-Wall Imaging Under Unknown Wall Characteristics", IEEE Trans. Geosci. Remote Sens., vol. 48, no. 1, pp. 423–431, Jan. 2010.
[4] X. Lin, Y. Ding, X. Xu, and K. Sun, "Human Target Localization Algorithm Using Energy Operator and Doppler Processing", IEEE Geosci. Remote Sens. Lett., vol. 15, no. 4, pp. 517-521, Apr. 2018.

[5] Yipeng Ding, Chengxi Lei, Ling Wang et al "Human Micro Doppler Frequency Estimation Approach for Doppler Radar", IEEE Access vol. 6, pp.6149-6159, Jan. 2018.

[6] J.A. Nanzer, "A Review of Microwave Wireless Techniques for Human Presence Detection and Classification.", IEEE Trans.Microw. Theory Tech., vol.65, no.5, pp.1780-1794, May. 2017.

[7] S.-K. Lin,"Microwave and Millimeter-wave Remote Sensing for Security Applications",Remote Sens.,vol.5,no1, pp. 367-373, Jan. 2013.

[8] M.Mercuri et al"Analysis of an indoor biomedical radar-based system for health monitoring", IEEE Trans.Microw. TheoryTechn., vol. 61, no. 5, pp. 2061-2068, May, 2013.

[9] A. Tariq, H. Ghafouri-Shiraz, "Vital signs detection using Doppler radar and continuous wavelet transform", Proc. 5th Eur. Conf. Antennas Propag. (EUCAP), pp. 285-288, Apr. 2011.

[10] M.Ritchie, M.Ash, Q.Chen, "Through wall radar classification of human micro-Doppler using singular value decomposition analysis," Sensors, vol. 16, no. 9, p. 1401, Aug. 2016.

[11] D.P. Fairchild and P.M. Narayanan, "Classification of Human motions using empirical mode decomposition of human micro-Doppler signatures", Radar, Sonar Navigat., vol. 8, no. 5, pp. 425-434, Jun. 2014.

[12] H. Benoudnine, A. Meche, A. Ouamri, "Real time Hough transform based track initiators in clutter," Inf. Sci., vols. 337-338, pp. 82-92, Apr. 2016.

[13] P.V. Dorp and F.C.A. Groen, "Feature-based human motion parameter estimation with radar", Radar, Sonar Navigat., vol. 2, pp. 135-145, Aug. 2008.

[14] YS. Wu, XK. Li, Y. Wang, “Extraction and classification of acoustic scattering from underwater target based on Wigner-Ville distribution”, Appl. Acoust, vol. 138, pp. 52-59, Sep. 2018.