Automatic human micro-Doppler signature separation by Hough transform

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ABSTRACT

The micro-Doppler signature is one of the most prominent information for target classification and identification. As Hough transform (HT) is an efficient tool for detecting weak straight target traces in the image, an HT based algorithm is proposed for micro-Doppler signature separation of multiple persons. Few seconds data is processed at one time to ensure human motion traces approximate to straight lines in the radar slow time-range image. Taking HT to the slow time-range image, each human's motion trace can be recovered through recursively searching the peaks in HT space. Applying time-frequency transform to the range cells around each recovered line, the human micro-Doppler signature can be achieved and separated. Experimental results are given to illustrate the validity of the proposed algorithm.

Keywords: Slow time-range image, motion trace, micro-Doppler signature, short time Fourier transform, Ku band radar

1. INTRODUCTION

The target commonly has additional motions relative to the bulk movement. For a moving human, the swing of the limbs and torso will generate sidebands around the center Doppler frequency induced by the human's bulk velocity. This extended frequency is the unique micro-Doppler signature of the moving human. With the micro-Doppler signature, one can separate different motions[1-4] and different targets[5,6] But these researches assume only one person in the scene. A texture-based method to separate different human echoes is proposed[7]. It constructs a pixel-connection map based on the texture angle and separates the target echo through literately executing complex number propagation operation. Its separation process is so complicated and it is hardly to know the iteration number to ensure the echo separated. As we know, the person who has a clear intention always tends to have an appropriate constant velocity. The human moving trace can be considered as a straight line during few seconds time in the radar time-range image. The Hough transform (HT) is an efficient tool for detecting weak straight target traces in the image[8]. We propose to use HT to extract and separate different moving traces in the slow time-range image. As the HT determines a line by the angle and radius[9], it has one more dimension to separate different traces than the texture-based method.

The paper is organized as follows. At first, the radar signal processing procedure for obtaining the slow time-range image is presented in Section 2. Then, the basic of HT and the micro-Doppler signature separation algorithm are introduced in Section 3. In Section 4, the experimental results are given to illustrate the validity of the proposed algorithm. Finally, Section 5 provides some concluding remarks.

2. RADAR SIGNAL PROCESSING

The transmitted signal of our radar system is a linear frequency modulated (LFM) signal

$$s(\hat{t},t_m)=rect(\frac{\hat{t}}{T_p})\exp[j2\pi(f_c t+\frac{1}{2}\gamma\hat{t}^2)]\,, \tag{1}$$

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where $t_m = mT$ $(m = 0,1,\ldots M-1)$ is the slow time, T is the pulse repetition period, $\hat{t}=t-t_m$ is the fast time, $rect(u) = \begin{cases} 1 & |u| \le \frac{1}{2} \\ 0 & |u| > \frac{1}{2} \end{cases}$; f_c is the carrier frequency; γ is the chirp rate and T_p is the pulse duration. The received and transmitted signals are mixed to reduce the sampling rate in the receiver. After removing the intermediate frequency, the final sampling signal is

$$\begin{aligned} s'(\hat{t}, t_m) = \sum_i \delta_i rect(\frac{\hat{t} - 2R_i(t_m)/c}{T_p}) \\ \cdot \exp[-j\frac{4\pi}{c}\gamma(\hat{t} - \frac{2R_{ref}}{c})\Delta R_i(t_m)] \\ \cdot \exp[-j\frac{4\pi}{c} f_c \Delta R_i(t_m)] \exp[j\frac{4\pi\gamma}{c^2}\Delta R_i^2(t_m)] \end{aligned} , \quad (2)$$

where $R_i(t_m)$ is the distance of the scatter point i at slow time t_m, δ_i is the corresponding scatter coefficient, R_{ref} is the reference distance and $\Delta R_i(t_m) = R_i(t_m) - R_{ref}$ is the distance difference.

Applying the Fourier transform to (2) with respect to the fast time, we obtain the range profile:

$$\begin{aligned} s_r'(f, t_m) = \sum_i \delta_i T_p \sin c\left[T_p\left(f + 2\frac{\gamma}{c}\Delta R_i(t_m)\right)\right] \\ \cdot \exp\left[-j\left(\frac{4\pi f_c}{c}\Delta R_i(t_m)\right)\right] \\ \cdot \exp\left[-j\left(\frac{4\pi\gamma}{c^2}\Delta R_i^2(t_m) + \frac{4\pi f}{c}\Delta R_i(t_m)\right)\right] \end{aligned} , \quad (3)$$

where $\sin c(u) = \frac{\sin(\pi u)}{\pi u}$. The range profile will peak at $f = -2\frac{\gamma}{c}\Delta R_i(t_m)$, the phase $-\frac{4\pi f_c}{c}\Delta R_i(t_m)$ is the Doppler term we need and the phase $\Delta\Phi = -\frac{4\pi\gamma}{c^2}\Delta R_i^2(t_m) - \frac{4\pi f}{c}\Delta R_i(t_m)$ is the residual phase which need to be eliminated. Considering $\Delta R_i(t_m) = -\frac{c}{2\gamma} f$, $\Delta\Phi$ can be expressed as $\Delta\Phi = \frac{\pi f^2}{\gamma}$. Multiply (3) by $\exp(-j\frac{\pi f^2}{\gamma})$, $\Delta\Phi$ can be easily removed. The processed range profile is

$$\begin{aligned} s_r(f, t_m) = \sum_i \delta_i T_p \sin c\left[T_p\left(f + 2\frac{\gamma}{c}\Delta R_i(t_m)\right)\right] \\ \cdot \exp\left[\left(-j(\frac{4\pi f_c}{c}\Delta R_i(t_m)\right)\right] \end{aligned} . \quad (4)$$

The discrete expression of (4) is

$$\begin{aligned} s_r(n, m) = \sum_i \delta_i T_p \sin c\left[T_p\left(n f_\Delta + 2\frac{\gamma}{c}\Delta R_i(m)\right)\right] \\ \cdot \exp\left[-j\left(\frac{4\pi f_c}{c}\Delta R_i(m)\right)\right] \end{aligned} , \quad (5)$$

where f_Δ is the frequency sampling interval, $n = 0,1,\cdots N-1$ is the frequency sampling points. We can interpret the frequency coordinate to the range coordinate by the equation $R_n = -\frac{c}{2\gamma} n f_\Delta + R_{ref}$. Therefore the 2-D plane representation of the matrix $|s_r(n,m)|$ is called the slow time-range image.

For human detection, there are a lot of strong stationary scatterers within the beam. We can utilize a notch filter around zero frequency to eliminate most of the static clutter without affecting the human motion signal as long as the extended frequency of micro motion is larger than the notch width[1]. The matrix after clutter suppression is $|s_c(n,m)|$.

3. THE HT BASED MICRO-DOPPLER SEPARATION ALGORITHM

3.1 The basic of HT

A straight line in an image space (x,y) can be expressed as: $y = k_i x + b_i$, which can be rewritten to $b_i = y - k_i x$. Take k as independent variable and b as dependent variable, points on the line map a cluster of straight lines on the space (k,b). The straight lines intersect at the point (k_i, b_i). But there is no space can express the infinite k. An ingenious way to solve this problem is to model the following equation:

$$\rho = x\cos\theta + y\sin\theta . \tag{6}$$

Taken trigonometric identity transform, (6) can be represented as

$$\rho = \sqrt{x^2+y^2}\,\sin(\theta + \arctan\frac{y}{x}) . \tag{7}$$

It is easy to see that any point (x_i, y_i) on the straight line mapped to a sinusoidal curve in (ρ,θ) space. The HT is a point-to-curve mapping. Here the space (ρ,θ) is named as HT space. If there is a straight line existing in (x,y) space, this line corresponds to a cluster of sinusoidal curves intersecting at one point in HT space. The longer the line in the image, the stronger the corresponding peak in the HT space. Therefore, the detection of the line in the image turns into the search of the strongest point in the HT space.

3.2 The proposed HT based micro-Doppler signature separation algorithm

The HT has stable and robust performance for detecting weak straight lines in the image. Apply the HT to the slow time-range image, each line is corresponding to a peak in HT space. Through recursively searching the peaks in HT space, each human's micro-Doppler signature can be achieved by taking time-frequency transform to the range cells around the recovered line. The short time Fourier transform (STFT) is used to micro-Doppler analysis as it is the most conventional time-frequency transform method and easy to implement. The proposed automatic separation algorithm can be described in detail as following:

(i) Applying the HT to the slow time-range image $|s_c(n,m)|$, map the lines to (ρ,θ) space.

(ii) Find the max peak P in HT space, if $P \ge T$, do next step, else exit. Here T is an experiential threshold of the moving human.

(iii) Read the corresponding coordinate (ρ,θ) to the peak P. Recover the trace by the formula:

$$n = \rho\csc\theta - m\cot\theta . \tag{8}$$

(iv) Select the range cells around the recovered trace to form an aligned matrix:

$$s_a(n,m) = \begin{bmatrix} s_c(n+\Delta n, m) \\ \vdots \\ s_c(n,m) \\ \vdots \\ s_c(n-\Delta n, m) \end{bmatrix}, \tag{9}$$

where Δn is an optional range offset between which may contain the human motion information.

(v) Calculate the micro-Doppler spectrum of the moving human:

$$S_{sum}(n,m) = \sum_{i=n-\Delta n}^{n+\Delta n} \left| STFT_m \left[s_a(i,m) \right] \right|^2 \tag{10}$$

Set the peak and the neighborhood around the peak to zero. Return to step (ii).

4. EXPERIMENTAL RESULTS

The radar photograph is shown in Figure 1. It operates at Ku band with center frequency 15GHz and bandwidth 500MHz. The pulse repeat frequency is 1000Hz, which leads to a maximum unambiguous velocity 5 m/s. Key parameters of the radar are listed in Table 1.

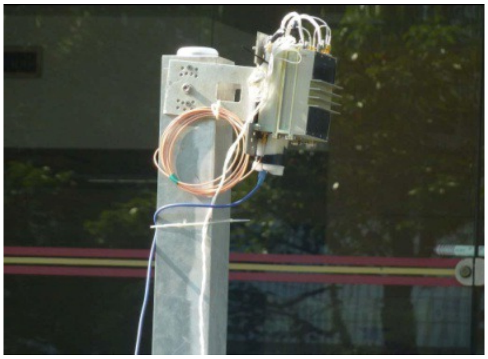


Figure 1. The Ku band radar

Table 1. Parameters of the radar

Parameters	**Value**
LFM bandwidth	500MHz
Wave length	0.02m
Central range	800m
Range swath	400m
Pulse repeat frequency	1000Hz

The experimental setup is in Figure 2. The radar is set on the riverwall. Two people walk towards the radar in an open space on the other side of the river.

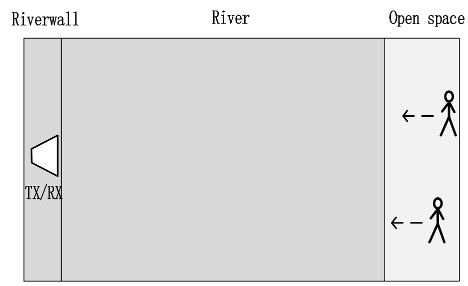
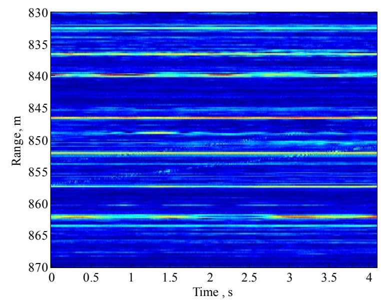
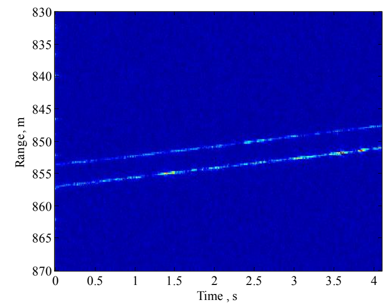


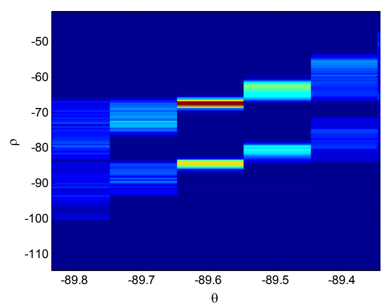
Figure 2. Experimental setup



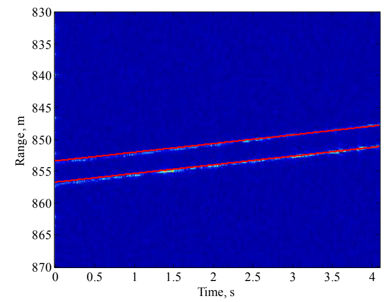
(a) Image before clutter suppression



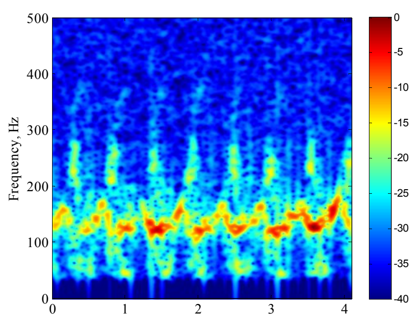
(b) Image after clutter suppression



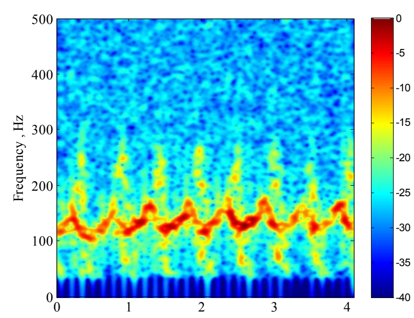
(c) HT space



(d) Recovered traces



(e) Micro-Doppler spectrum of the first person



(f) Micro-Doppler spectrum of the second person

Figure 3. The micro-Doppler separation results of two walking persons

We take the time slice as 4 seconds to ensure human motion traces approximate to straight lines. Figure 3(a) is the slow time-range image before static clutter suppression. There are many strong clutters in the image. The human moving traces are hardly seen. Utilizing a notch filter around zero frequency, Figure 3(b) shows the traces of two walking people. Applying the proposed separation algorithm to Figure 3(b), the two traces are mapped to two peaks in HT pace in Figure 3(c). According to formula (8), the lines are recovered perfectly in Figure 3(d). They agree well with the moving traces. Taking STFT to the aligned matrix composed of the range cells around the recovered line, the human micro-Doppler spectrums are separated automatically in Figure 3(e) and Figure 3(f). The sinusoidal frequency variation with the amplitude 40Hz and frequency 0.5Hz corresponds to the micro-Doppler of the humans' torso. The center Doppler frequency 135Hz corresponds to the humans' bulk motion velocity 1.35m/s. The stride circle is 1Hz which is the double of the torso's micro-motion period. The estimate parameters from the spectrums are consistent with the testing persons.

5. CONCLUSION

An automatic human micro-Doppler signature separation algorithm is presented. It maps the lines in the slow time-range image to the peaks in the HT space. Through recursively searching the peaks, each person's moving trace can be recovered. By analyzing the range cells around the trace, each person's micro-Doppler spectrum can be obtained. The proposed method works well when the targets move at a constant speed. The experimental results demonstrate the effectiveness of the algorithm. The proposed method has a great potential to be applied in actual radar surveillance systems.

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