Analysis of microDopplers from human gait using reassigned joint time-frequency transform

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2 authors:

Shobha Sundar Ram
Indraprastha Institute of Information Technology

Hao Ling
University of Texas at Austin

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S.S. Ram and H. Ling

The Doppler spectrogram of a moving human is characterised by microDoppler returns due to the dynamic movements of the different body parts. The reassigned joint time-frequency transform is applied to study these distinct microDoppler features. Reassigned spectrograms generated from a simulation model and measured data are presented and analysed.

Introduction: The radar return from human gait has been studied in a number of publications [1–3]. It was reported that microDoppler returns due to non-rigid body motions of arms and legs are quite unique and may be useful in varied applications such as computer animation, physical security and surveillance. The microDoppler features are most easily observed by the application of the short-time Fourier transform (STFT) on the time domain radar signal. The resulting spectrogram is characterised by time-varying Doppler tracks due to the torso returns, along with weaker microDoppler features arising from the swinging arms and legs. However, a well-known limitation of the STFT is that it is not possible to obtain optimal precision or localisation of the signal energy in the spectrogram. If the time extent of the window function used in the STFT is σ, the 'thickness' of the signal feature in the spectrogram is σ in the time domain and $1/\sigma$ in the frequency domain. This issue becomes a limiting factor for discriminating the microDoppler features when the radar operating frequency is lowered to enhance penetration of electromagnetic waves for through-wall applications [4]. As a result of the lower operating frequency, the Doppler sensitivity is reduced and it becomes increasingly difficult to discern the various microDoppler components in the spectrogram.

In this Letter, we apply the reassigned joint time-frequency transform for the analysis of radar microDopplers from human gait. The reassigned spectrogram (also called the time-corrected instantaneous frequency spectrogram) was first developed by Kodera *et al.* [5], and has recently been adopted in the acoustics community [6–8]. The derivatives of the phase of the traditional STFT spectrogram are used to derive the instantaneous time, t_{ins}, and instantaneous frequency, f_{ins}, of the signal. Each point in the STFT spectrogram is then *reassigned* to the co-ordinate positions (t_{ins}, f_{ins}). This causes the signal energy to be localised in the spectrogram to thin lines of high precision and can lead to significantly improved readability of the traditional spectrogram. There are various implementations of the phase derivatives. In this work, we utilise the form proposed in [8] and apply this transform to the human microDoppler tracking problem.

Reassigned joint time-frequency transform: The analytical method for computing the reassigned spectrogram proposed in [8] is summarised here. Given a signal $x(t)$, its standard STFT, $\chi(t,f)$, using a Gaussian window is given by:

$$\chi(t,f) = \int x(t')e^{-((t-t')^2/2\sigma^2)}e^{+j2\pi f(t-t')}dt' = |\chi|e^{j\varphi} \tag{1}$$

Also needed is the spectrogram, $\eta(t,f)$, due to a time-product form of the Gaussian window:

$$\eta(t,f) = \frac{1}{\sigma}\int (t'-t)x(t')e^{-((t-t')^2/2\sigma^2)}e^{+j2\pi f(t-t')}dt' \tag{2}$$

Then, the instantaneous frequency and the instantaneous time can be computed from χ and η as follows:

$$f_{ins} = \frac{1}{2\pi}\frac{\partial\varphi}{\partial t} = f + \frac{1}{2\pi\sigma}\mathrm{Im}\left\{\frac{\eta}{\chi}\right\} \tag{3}$$

$$t_{ins} = t - \frac{1}{2\pi}\frac{\partial\varphi}{\partial f} = t + \sigma\mathrm{Re}\left\{\frac{\eta}{\chi}\right\} \tag{4}$$

To form the reassigned spectrogram, a two-dimensional grid is created on the (t_{ins}, f_{ins}) plane. Each pixel in the grid is weighted by the number of points within the pixel and by the sum of the strength of the distribution, $|\chi|$, within that pixel. This results in the reassigned distribution in the (t_{ins}, f_{ins}) plane.

The reassigned transform is generated for a test signal comprising the sum of three signals: a click ($\delta(t-t_o)$), a ramp ($e^{j\alpha t^2}$) and white Gaussian noise. The STFT spectrogram of the signal is shown in Fig. 1*a*. As expected, the thickness of the signal along the time and frequency axes is defined by the time window (0.1s) and its inverse (10 Hz). The reassigned transform is then applied to the signal, and the reassigned spectrogram is presented in Fig. 1*b*. The click and the ramp in the reassigned spectrogram have nearly infinitesimal thickness, being limited mainly by the plotting pixel size of the image and not by σ. The white noise likewise transforms to thin veins [8]. However, it is important to point out that the reassigned transform can resolve two signals only if they are farther apart than σ in the time domain and $1/\sigma$ in the frequency domain, i.e. outside the Fourier uncertainty bounds. Indeed, some slight distortions can be observed at the crossing point between the click and the ramp.

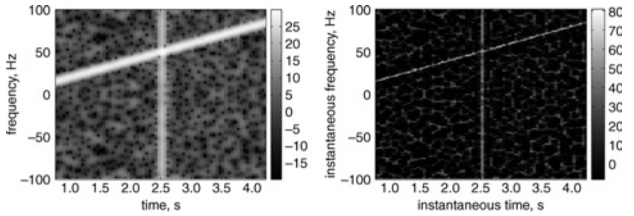

Fig. 1 *Spectrogram of signal comprising click, ramp and white Gaussian noise*

a STFT
b Reassigned transform

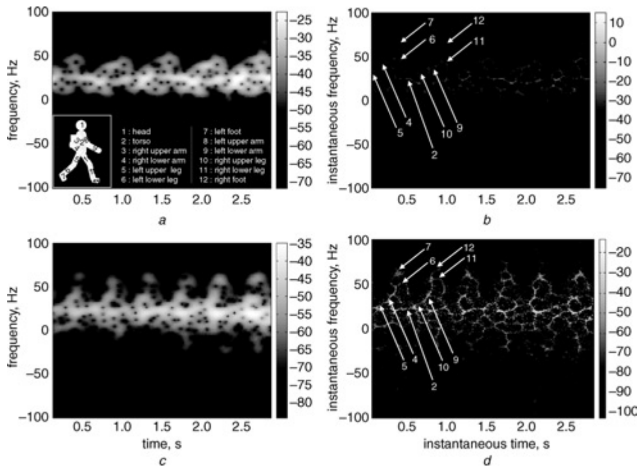

Fig. 2 *Spectrogram of human gait obtained by processing simulated data at 2.4 GHz and measured data from 2.4 GHz Doppler radar*

a STFT
b Reassigned transform
c STFT
d Reassigned transform

MicroDoppler from human gait: The microDoppler phenomenon is first studied using simulation. The human body is modelled as a target with 12 body parts as shown in the inset of Fig. 2*a*. The Thalmann model [2, 9] is used to describe human gait. The kinematics of each body part, i.e. the position of the body part against time, is given by the model as a function of the velocity of the human. The time-varying radar cross-section (RCS) of the human target is then obtained by the complex sum of the RCS of the individual body parts modelled as perfectly conducting spheres, cylinders and ellipsoids. We assume the human subject approaches a continuous-wave radar of 2.4 GHz at a velocity of 1.3 m/s. The radar return is obtained using the radar range equation. The STFT of the radar return from the simulated human gait data is presented in Fig. 2*a*. Here a Gaussian time window of 0.25 s is used. The strongest Doppler return is due to the torso where the centre of gravity is located. The front and back swings of the arms and legs cause positive and negative Doppler spread with respect to the torso return. It is possible to discern the microDoppler tracks due to some body parts such as the torso (**2**) and the feet (**7**, **12**). However, by and large, the different tracks appear vague and indistinct. Fig. 2*b* shows the reassigned spectrogram of the same data. It is observed that the precision of the signals in the spectrogram have been greatly improved. It is now possible to discern up to nine distinct microDoppler tracks (labelled as **2**, **4**, **5**, **6**, **7**, **9**, **10**, **11** and **12**). The highest Doppler returns are caused by the motion of the feet (**7**, **12**) and the lower legs (**6**, **11**). In a typical walking pattern, the motion of the left leg (**5**, **6**, **7**) is accompanied by that of the right arm (**4**) and vice versa. The weaker returns due to the upper arms (**3**, **8**) cannot be distinguished from the stronger torso return (**2**).

Next, actual measurements are conducted using a Doppler radar operating at a continuous-wave mode of 2.4 GHz [4]. A human subject approaches the radar at the steady speed of approximately 1.3 m/s. Figs. 2*c* and *d* show, respectively, the STFT spectrogram and the reassigned spectrogram. Again, the reassigned spectrogram shows better precision and thus improved readability for identifying the various Doppler tracks. Distinct microDoppler features from the feet, lower legs, lower arms, upper legs and torso are identified. By comparing Figs. 2*b* (simulated) and *d* (measured), it is observed that they differ somewhat in the detailed Doppler tracks. Some of the possible factors that may contribute to this difference include: (i) the simulated motions were derived from an 'averaged' kinematic model, (ii) the point scatterer model may not be an accurate model for a complex target such as a human, (iii) some parts of the body may be shadowed from the radar by other parts, (iv) the observation angle of the different body parts constantly changes during motion, and (v) human targets are not perfectly conducting. The reassigned spectrogram makes possible such a detailed feature-by-feature comparison.

Conclusion: The reassigned joint time-frequency transform was applied to the Doppler spectrogram of a walking human. The results were compared with the standard spectrogram. It was demonstrated that this transform enabled the discernment of distinct microDoppler features that arise from the motions of specific parts of the body.

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S.S. Ram and H. Ling (*Department of Electrical and Computer Engineering, The University of Texas at Austin, Austin, TX 78712-1084, USA*)

E-mail: shobhasram@mail.utexas.edu

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