Vignaud, L., Ghaleb, A., Le Kernec, J., and Nicolas, J.-M. (2009) Radar High Resolution Range & Micro-Doppler Analysis of Human Motions. In: International Radar Conference - Surveillance for a Safer World, 2009, Bordeaux, 12-16 Oct. 2009, ISBN 9782912328557.

RADAR HIGH RESOLUTION RANGE & MICRO-DOPPLER ANALYSIS OF HUMAN MOTIONS

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Abstract — **In radar imaging it is well known that relative motion or deformation of parts of illuminated objects induce additional features in the Doppler frequency spectra. These features are called micro-Doppler effect and appear as sidebands around the central Doppler frequency. They can provide valuable information about the structure of the moving parts and may be used for identification purposes [1].**

Previous papers have mostly focused on 1D micro-Doppler analysis [2-4]. In this paper, we propose to emphasize the analysis of such "non stationary targets" using a 2D imaging space, using both the micro-Doppler and a high range resolution analysis. As in 2D-ISAR imaging, range separation enables us to better discriminate the various effects caused by the time varying reflectors.

We will focus our study on human motion. We will see how micro-Doppler signature can be used to extract information on pedestrians gait. We will show examples on simulated and experimental data.

Keywords --- ISAR imaging, micro-Doppler, gait analysis

I. INTRODUCTION

Most of studies relative to the human motion analysis have been made using optical systems. They have shown that the human gait is unique and can be used for identification. Though the task is more difficult in radar, previous studies proved that radar signature can reveal information on the human's behaviour.

When a human moves, the different parts of his body (torso, arms, legs) have a particular motion that produces characteristic Doppler signatures. That's why most of methods are based on the spectral analysis of the received signal [6-10]. Considering the distribution and the evolution of the velocities with time, Doppler spectrum can be seen as a unique signature. As the evolution of the Doppler spectrum is mostly periodic, a time Doppler variation analysis permits to extract features of the pedestrian's gait.

In most of the paper relative to the subject, detection and recognition of pedestrians are only based on the motion's rhythm analysis. Fourier transform and more recently time-frequency transforms (STFT) are used to analyse the Doppler and identify the different parts of the human body playing part during the motion. Spectrograms which are time-Doppler representations permit to retrieve some motion features such as velocity or gait cycle frequency.

However analysing the time-Doppler variations usually requires to observe the phenomenon during a long time, at least long enough to retrieve the gait cycle frequency. But motion features could vary during this period, particularly the pace, the velocity or the motion direction. In such cases, the analysis would become more delicate. Moreover, the presence of several people simultaneously in the radar field of sight could involve interferences. Doppler frequencies would thus be mixed and the received signal could not be easily separated anymore.

Introducing the range dimension in the analysis shortens the time needed to observe the pedestrian, in order to detect him and distinguish the different parts of his body at a given time. A trained observer could in deed detect pedestrian characteristic features from a single image. A micro-Doppler analysis combined with a high range resolution enables a more accurate analysis of a moving pedestrian radar signature with a better separation of the different parts of his body. It also permits to localise and analyse simultaneously the gait of several peoples.

The experimental system we have used to acquire data from moving targets is a high range resolution radar, named HYCAM [5], developed by ONERA. This device is able to measure targets with small Radar Cross Section such as pedestrians with a resolution less than 20 cm. It's then possible to take into account the spatial dimension of the different pedestrian's parts.

To better understand and validate experimental data, we have also worked with synthetic data provided by a motion capture system. These data have permitted to compute simulated radar backscattering of every part of the human body in order to perform spectrograms and range-Doppler images of pedestrians.

This paper aims to emphasize the 3D interaction between a radar signal and a pedestrian (walking or running) by analysing the phenomenon in three dimensions (range, Doppler and time). We will use both simulated and experimental data and will take into consideration the angle between the pedestrian's direction and the radar's line of sight. This analyse shows to be very useful to improve our knowledge in human recognition and gait analysis in radar imaging.

II. DESCRIPTION OF THE DATA

A. *Experimental data*

The experiment has been made at ONERA with the HYCAM radar. This system has a wide frequency bandwidth (800 MHz), which means a slant distance resolution less than 20 cm. It uses an OFDM waveform permitting to emit all the frequencies simultaneously in a very short time. The Doppler sampling is fixed at 1 ms : that gives a Doppler ambiguity of 1 KHz, which is enough to measure a pedestrian moving at a regular speed.

The radar is positioned on a top of a building (18 m high). It illuminates a flat scene which center is 25 m away from the radar, as illustrated in Fig.1.

The experiment objective is to measure the motion of a pedestrian walking/running with/without arms at different directions (0°, 45°, 90°). We also have measured the motion of several people moving at the same time.

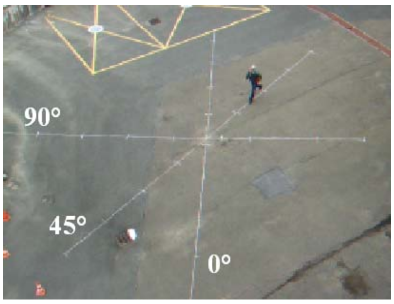

Figure 1. Scene photography from the radar

Let's define the 2 angles between the pedestrian's direction and the radar Line Of Sight (LOS):

- The azimuth θ which is the angle between the pedestrian's direction and the LOS's projection on the ground plan (O,X,Y) (Fig 3). When θ=0°, the pedestrian is moving in front of the radar.
- The elevation φ which is the angle between the pedestrian's direction and the LOS's projection on the plan (O,X,Z). In the experiment φ is comprised between 40° and 50°. To simplify, we will assume it's about 45° for the rest of this paper.

We will see that direction of observation (θ, φ) is crucial when we analyse the interaction between the radar signal and the different parts of the body.

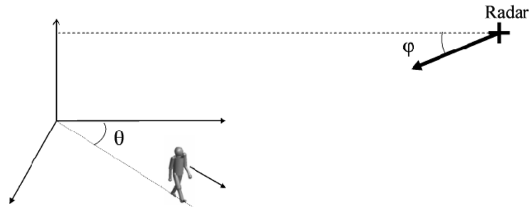

Figure 2. Angles between pedestrian's direction and radar LOS

B. *Simulated data*

The human gait is a complex mechanism where body and limbs move in precise coordination to create human locomotion. The swinging motion of arms and legs is not obvious and it is hard to build an analytic model. That's why we have chosen a pedestrian's model provided by a motion capture system called VICON [11]. It provides a data file with time samples of the three-dimensional coordinates of 41 markers distributed all over the pedestrian's body, as shown in Fig. 3. We have used motion simulation data files available on the Carnegie Mellon University website [12]. Among several scenarios available on the website, we have focused our study in analysing simple motions: walking and running on a straight line at constant velocity.

This solution gives a really smooth motion of every part of the body and permits to obtain quite realistic simulations. We have thus been able to decompose the human motion in order to better understand the interaction between the transmitted signal and the different parts of the human body.

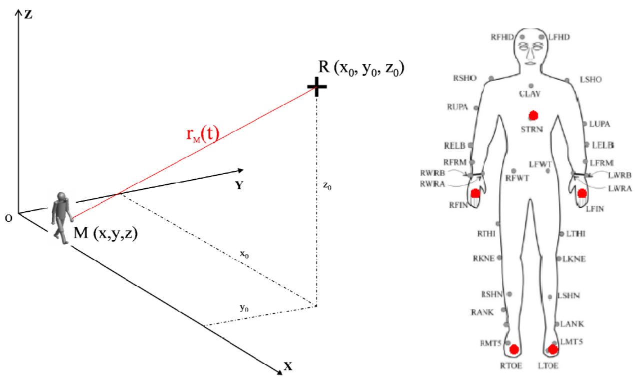

Figure 3. Pedestrian's model

We have developed a radar simulation tool to build spectrograms and range-Doppler images using data extracted from the chosen models. The objective is to faithfully reproduce the experiment in order to compare images performed with experimental and simulated data.

As illustrated in Fig. 3, we have positioned the pedestrian in the scene and put the radar at the desired coordinates (x_0, y_0, z_0), according to the distance of observation and the angles θ and φ (set by the user) between the radar LOS and the pedestrian's direction.

We have focused our study on the motion of 5 reflectors: torso, left hand, right hand, left foot and right foot (marked with red points on Fig. 3).

C. Image processing

We have achieved two analyses:

- A time-frequency analysis using spectrograms, in order to visualize the Doppler's evolution with time and extract motion's periodicity. It's been done using a STFT.
- A range-Doppler "movie" analysis ("image by image") in order to obtain information on the relative reflector's position.

Every image has been computed with an integration time $\Delta T = 0.1$ s which gives a 10Hz Doppler resolution. For a better understanding we have displayed the velocity instead of the Doppler since the two are linearly linked.

Range-Doppler images are more striking the eye if they can be viewed successively, like a movie, to emphasize the variation of the phenomenon with time. We have only presented here selected images.

III. Walking

The gait cycle extends from heel strike to heel strike of one leg and includes the stance and swing phases of both legs. In the basic gait cycle the movements are divided into the times when the foot is on the ground (stance phase) and when the foot is off the ground (swing phase). The time period when both feet are on the ground will be referred to as double support. The stride length is defined as the distance between two consecutive contacts of the same foot.

In simulated data walking velocity is Vo = 1.18 m/s; in the experiment Vo = 1.53 m/s

A. Simulated data

1) Time-frequency analysis

For the simulated spectrogram (Fig. 4) we have displayed the time-velocity of the 5 markers described before. We can observe the evolution of the velocity during the gait cycle, in function of the relative orientation between the pedestrian's direction and the radar LOS.

The person is moving with a constant velocity Vo. The sternum's velocity has slight variations. We can see that the legs, arms and torso all move at different velocities during the gait cycle.

One foot remains still while the other successively accelerates to reach it maximal velocity and decelerates to be still. It reaches a peak of velocity (which can be about 3Vo when the pedestrian is walking in front of the radar) in a very short time. These brutal variations have to be considered when imaging. Points will be not focused if the integration time is too long.

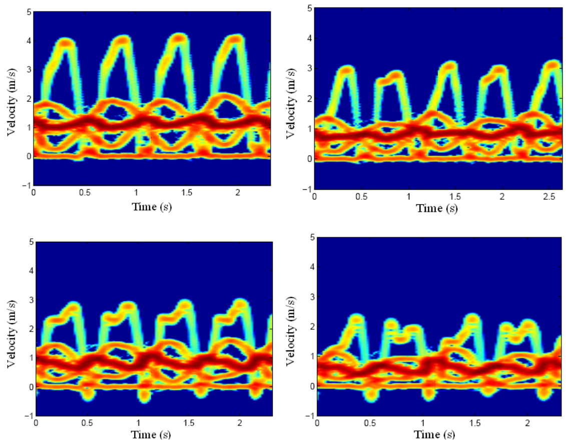

Figure 4. Simulated spectrograms of the walk. From up left to down right: (θ=0°, φ=0°), (θ=45°, φ=0°), (θ=0°, φ=45°), (θ=45°, φ=45°).

Doppler frequencies can differ if the radar is not in the pedestrian's direction. Depending on the pedestrian's relative orientation, the Doppler frequencies will be induced by different parts of the body. When the pedestrian is in front of the radar, Doppler is induced by the horizontal velocity's component. Considering this component is preponderant in the motion, the Doppler spreading will be maximum in this configuration. When the pedestrian is not in front of the radar, the amplitude of the velocities decreases with θ because of the projection of the velocity vector.

When the radar is above the pedestrian, the Doppler is partly induced by the motion's vertical component (especially the limbs). That's why negative Doppler can appear. If the radar was just above the pedestrian, the Doppler would only be induced by arms and legs' vertical motion.

2) Range-Doppler analysis

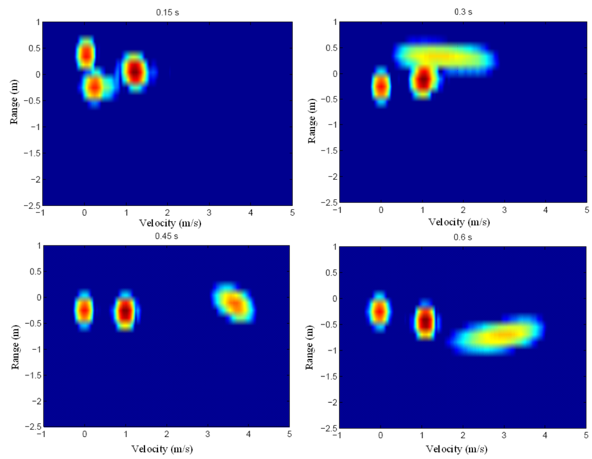

Figure 5. Simulated range-Doppler images at different instant of the walking gait (θ=0°, φ=0°).

If the reflectors can be distinguished by their various Doppler frequencies, they also have various ranges. If the range resolution can be accurate enough, the Doppler analysis can be coupled with a range analysis to improve the possibilities of identification by gait analysis.

We have focused our attention on the body and the 2 feet (Fig. 5). In this case the pedestrian is walking in the direction of the radar LOS (θ=0°, φ=0°). We have decomposed the walking cycle in 4 images. On the first image, both feet have a velocity close to zero. The first foot (at the top) is already still while the second (at the bottom) is ready to stop. It is called the double support phase. On the second image the back foot accelerates to reach it maximum velocity on the third image and decelerates on the fourth image. During this phase, the second foot remains still and the body has a quite constant velocity.

B. *Experimental data*

1) Time-frequency analysis

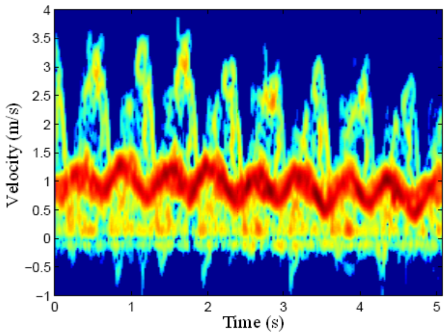

Figure 6. Experimental spectrogramm of the walk (θ=45°, φ=45°).

The main difference between simulated (Fig. 4) and experimental spectrogram (Fig. 6) is the Doppler's spreading between 0 and the maximum. Indeed we have simulated the Doppler effect for reflectors positioned at the extremities of the body (hands and feet). In reality, reflectors' distribution is continuous.

2) Range-Doppler analysis

Thanks to this analyse, we show it's possible to discriminate the different parts of the body. Fig 7 emphasizes the walk's swinging phase when the leg moves, visible by the Doppler spreading of its reflectors. Fig 8 emphasizes the stance phase because both feet have a zero Doppler. On this case it's possible to assess the step length by measuring the number of range cell between the two reflectors (step=60cm).

IV. RUNNING

The running cycle shows major differences with the walking cycle. The stance phase is shortened, while the swing phase is lengthened. There is no time of double support but a non-support phase in which neither leg is weight bearing (double float).

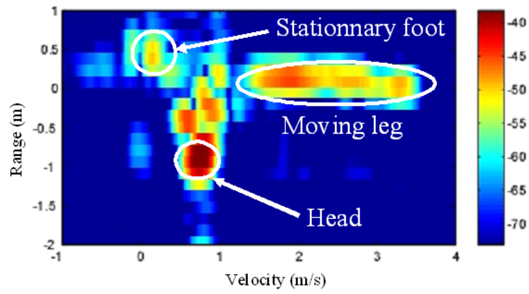

Figure 7. Experimental range-Doppler image of the walk (θ=45°, φ=45°): swinging phase

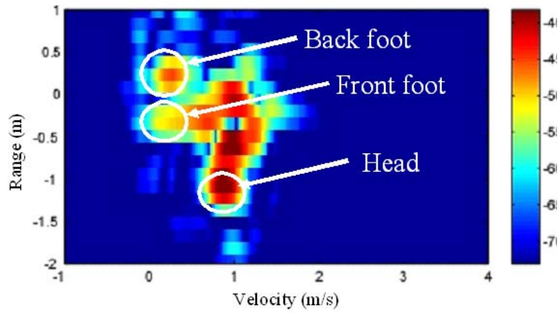

Figure 8. Experimental range-Doppler image of the walk (θ=45°, φ=45°): double support phase

In simulated data running velocity is Vo = 3.5 m/s; in the experiment Vo = 3.3 m/s.

A. *Simulated data*

1) Time-frequency analysis

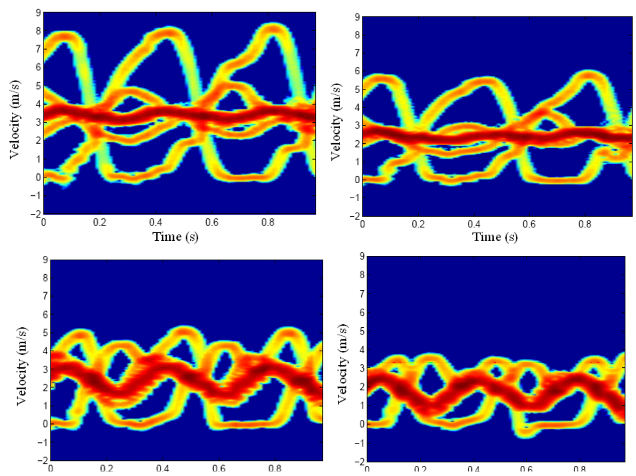

Figure 9. Simulated spectrogram of the running gait. From up left to down right: (θ=0°, φ=0°), (θ=45°, φ=0°), (θ=0°, φ=45°), (θ=45°, φ=45°).

2) Range-Doppler analysis

Like for the walk, we have focused our attention on the body and the 2 feet (Fig. 10) for a pedestrian running in the direction of the radar LOS (θ=0°, φ=0°). We have decomposed the running cycle in 4 images. On the first image, the first foot is standing while the second is reaching its maximal velocity. When the second is decelerating, the first one leaves the ground and its velocity increases. Contrary to the walk, there is no double support phase. There is a floating phase we can see in the second image where both feet have a positive Doppler.

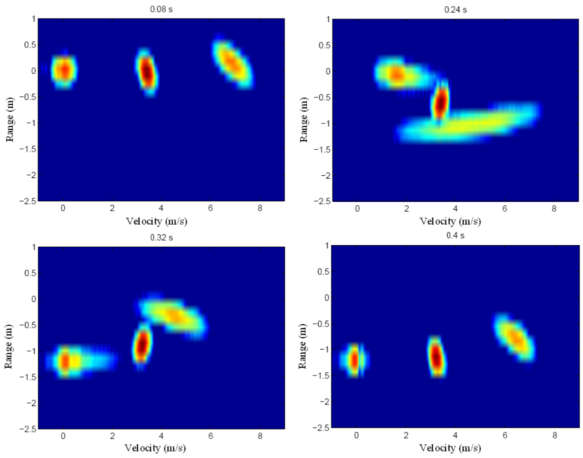

Figure 10. Simulated range-Doppler images at different instant of the running gait (θ=0°, φ=0°).

B. Experimental data

1) Time-frequency analysis

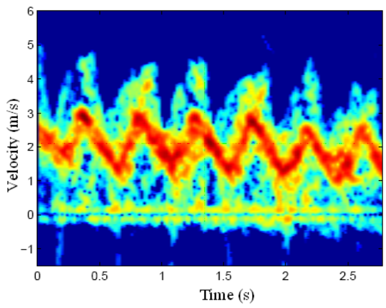

Figure 11. Experimental spectrogram of the running gait (θ=45°, φ=45°).

2) Range-Doppler analysis

Fig. 12 shows the moment where one foot is on the ground while the other is reaching its maximum velocity. Fig. 13 shows the phase of double float where no foot touch the ground. Legs are crossing which means that all the points have almost the same velocity. Contrary to the walk it's not obvious to assess the step length because both feet are not on the ground at the same moment.

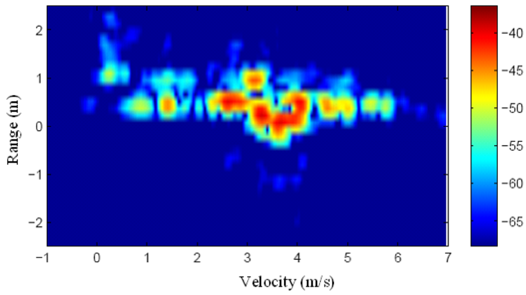

Figure 12. Experimental range-Doppler image of the running (θ=45°, φ=45°) : swinging phase

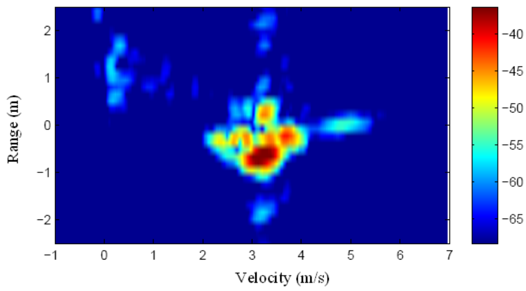

Figure 13. Experimental range-Doppler image of the running (θ=45°, φ=45°) : double floating phase

V. SEVERAL PEDESTRIANS

In this acquisition, two people are walking in opposite direction at constant velocity (Fig. 14).

Figure 14. Scene picture seen from the radar with 2 people walking

1) Time-frequency analysis

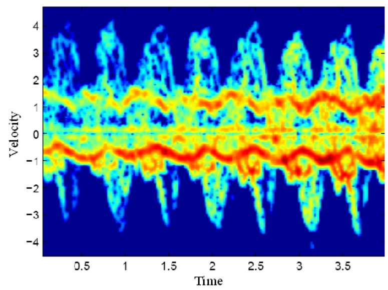

Figure 15. Two people on a spectrogram

Radar studies only analyze the Doppler's variation. They don't take into account the motion's range component. When several people move in the radar field of view, there are interferences between Doppler frequencies and it's not possible anymore to interpret the received signal (Fig. 15).

2) *Range-Doppler analysis*

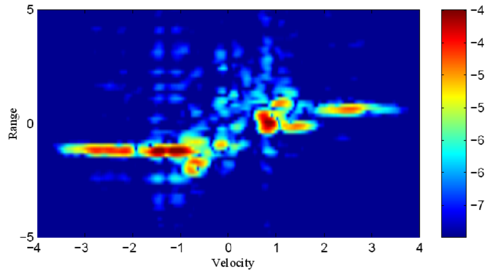

Figure 16. Two people on a range-Doppler image

Thanks to the resolution, it's possible to observe several people simultaneously, to localize them in range and to distinguish the evolution of the different parts of the body both in range and Doppler (Fig. 16).

VI. Conclusion

The human gait is a complex motion of swinging arms and legs. To better understand and analyse the range and Doppler's evolution of the different body's parts, we have used a pedestrian's model provided by a motion capture system. It was thus possible to obtain the three-dimensional coordinates of reflectors distributed on the pedestrian. This model has permitted to isolate and analyse independently the motion of each part. This model has then been injected in a range Doppler imaging simulator. Knowing the kinematic of every part, it has been possible to understand the composition of a range-Doppler image resulting from the interaction between a pedestrian and a microwave signal.

Images from simulated data have been compared with images from experimental data and results are particularly satisfying. They first show that HYCAM is a device capable to detect micro-Doppler induced by the pedestrian's limbs. Images performed with experimental data are coherent with simulated data even if it is not always obvious to fit exactly both results. Thanks to the high range resolution we are able to discriminate in range and Doppler the different parts of the body and even several people moving in a scene.

The investigation field on human motion analysis is very wide and offers many perspectives. HYCAM will soon raise its bandwidth from 800 MHz to 1.6 GHz, in order to observe more accurately pedestrians' micro-motions.

Acknowledgment

The authors would like to thank ONERA for giving us the opportunity to use HYCAM and especially J. Le Kernec who has developed the last version of the radar and helped us for the experiment.

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