Analysis of Radar Doppler Signature from Human Data

Milenko ANDRIĆ [1], *Dimitrije BUJAKOVIĆ* [1], *Boban BONDŽULIĆ* [1],
Slobodan SIMIĆ [1], *Bojan ZRNIĆ* [2]

[1] Military Academy, University of Defense, Generala Pavla Jurišića Šturma 33, 11000 Belgrade, Serbia
[2] Defense Technologies Department, Ministry of Defense, Nemanjina 15, 11000 Belgrade, Serbia

asmilenko@beotel.net, dbujakovic@verat.net, bondzulici@yahoo.com, simasimic01@gmail.com, bojan.zrnic@vs.rs

Abstract. *This paper presents the results of time (autocorrelation) and time-frequency (spectrogram) analyses of radar signals returned from the moving human targets. When a radar signal falls on the human target which is moving toward or from the radar, the signals reflected from different parts of his body produce a Doppler shift that is proportional to the velocity of those parts. Moving parts of the body causes the characteristic Doppler signature. The main contribution comes from the torso which causes the central Doppler frequency of target. The motion of arms and legs induces modulation on the returned radar signal and generates sidebands around the central Doppler frequency, referred to as micro-Doppler signatures. It was demonstrated that the human motion signature extraction is better using spectrogram analysis. While the central Doppler frequency can be determined using the autocorrelation and the spectrogram, the extraction of the fundamental cadence frequency using the autocorrelation is unreliable when the target is in the clutter presence. It was demonstrated that the value of the fundamental cadence frequency increases with increasing dynamic movement of people and simultaneously the possibility of its extraction is proportional to the degree of synchronization movements of persons in the group.*

Keywords

Human gait, Doppler signature, cadence frequency, spectrogram, autocorrelation.

1. Introduction

The main tasks of ground surveillance radars for security and perimeter protection are detection and classification of moving ground targets. Radar operates by emitting electromagnetic waves and receiving echoes of that signal. In typical radar systems, target detection is fully automated, but the target classification requires human involvement. If the target is moving, there is a slight change in the frequency of the radio signal due to the Doppler effect. Typically, the radar produces an audio signal from the Doppler frequency of moving target to the operator.

An algorithm for moving object detection using the information entropy is proposed and analyzed in [1]. The proposed algorithm is applied on Doppler radar signal and it represents an alternative approach to Doppler radar signal analysis using the Fourier transform. In [2] an information theoretic approach is used to compute the importance ranking of features prior to classification for the specific problem of discriminating between human walking and running.

Some researchers in their studies proved that spectrogram based features could be used for discrimination purposes either between humans and other moving objects or between different persons [3]-[7]. Human spectrograms can be used to reveal information on the human's behavior and to determine features about the human target being observed, such as size, gender, action, and speed, too. Research done by Geisheimer and others [3] showed that the human spectrogram is the sum of Doppler shifted signals reflected from the various parts of the moving body. Using Short Time Fourier Transform (STFT) and the chirplet transform, they extracted various parameters of the human gait from the signal. Research done by van Dorp and others [4] showed that the radar Doppler signatures, observed in the spectrogram, give detailed information about the movements of the human body parts. The authors focused on the extraction of parameters and described a method for estimating human walking parameters from radar measurements. The application of continuous-wave radar for the detection and classification of people based on their motion was demonstrated in [5]. Spectral analysis of the output from the radar using a sequence of STFTs was used to extract and identify key features of the human walking motion, and to differentiate humans from dogs. Using human gait analysis Greneker [6] designed and tested a suicide bomber detection system based on variations in the spectrogram caused by the presence of a bomb. Authors in [7] used the wavelet transform with time-frequency analysis to extract Doppler features from radar signal returns of helicopter and human targets; additionally, the wavelet transform is combined with autocorrelation to measure motions parameters such as the vibration/rotation rate.

A target classification algorithms using Doppler signature were presented in [8]-[12]. In [8] a Hidden Markov

Model (HMM) classifier was implemented for classification between three classes of targets: personnel, tracked vehicles and wheeled vehicles. A fuzzy logic approach to the automatic classification was presented in [9]. Bilik [10] developed a Greedy Gaussian Mixture Model (GMM) based classification technique, applicable in classification for low resolution ground surveillance radars. The problem of classification between a walking person, pair of walking persons and slowly moving vehicle was studied in [11]. They used time varying velocities and biomechanical human locomotion models for target classification. Using joint time-frequency analysis Molchanov [12] classified eight different classes of ground moving targets.

The main goal of this paper is analysis of radar Doppler signature of different human classes: walking person, running person, group of persons walking and group of persons running. The Doppler signature of human data is analyzed using the spectrogram and the autocorrelation where the data used in this analysis were collected through trials in the field. There have been studies of the Doppler signatures in the past few years; however, there is just a few experimental trials performed in order to analyze human targets. As such, this paper contributes additional experimental data and analysis which should help in developing a better understanding of the Doppler effect in radar remote sensing of walking personnel in the future.

The rest of the paper is organized as follows: Section 2 describes the database, which was obtained using records of ground surveillance radar; in Section 3 the analysis is done on Doppler signature that is derived from human movement using STFT and autocorrelation; the conclusion is given in Section 4.

2. Real-World Data Acquisition

The real-world data set used herein is acquired by Ku-band short-range ground surveillance coherent pulse Doppler radar [13], [14]. The radar parameters were: frequency 16.8 GHz, average power 5 mW, pulse width 14.63 μs, frequency repetition pulse 34.18 kHz, average range resolution 150 m, elevation resolution 7.5° and azimuth resolution 5°. For the purpose of this research monostatic radar configuration with the parabolic antenna (vertical polarization and antenna gain 32 ± 2 dB) was used.

This radar has so-called audio output, which can be used by the operator to detect and classify targets. When a radar signal falls on a target moving towards or from the radar, the signals reflected from different parts of the target have a Doppler shift that is proportional to the radial velocity of those parts. Doppler frequencies are in the audio band, being in the order of a kilohertz, and the radar operator can listen to them through headphones. When listening to this tone, one can note that ground moving targets produce a very distinct and characteristic sound that, upon hearing only a few times, one can learn to recognize easily.

For the recording procedure, the moving target was detected and tracked automatically by the radar, allowing continuous target echo records. The range between the radar and the target was adjusted from 100 m to 1000 m. The moving targets were within the line-of-sight, in the presence of ground clutter with low vegetation and without any interference. The target motions were fully controlled, where only direct motion (toward or away from the radar) was conducted. Each person in a group contributes to the radar returned signal equally due to frontal marching. One human class at a time was recorded in each trial.

The amplitude of the raw Doppler radar data is in the range ±1 V. Audio output signal from the radar was connected to computer sound card microphone input and recorded onto it, where the data was then saved as digitized WAV files, with the sampling rate of 4 kHz. To avoid Nyquist sampling aliasing effect, analog signal is band-limited by adequate filter (40 Hz – 1900 Hz). The digitized data can be easily processed using MATLAB^{TM}. We analyzed a portion of radar echoes records from various human classes that lasts for 4 s and consists of 16 000 samples. The backscattered radar signals were recorded in two different radar environments. The first one is the road of 4 m width, and 800 m length. The second one is the rough terrain with barriers (slews, woods) and small vegetation. Detailed description of the scenarios and collected human data can be found in [13].

3. Human Motion Signature in Doppler Signal

3.1 Spectrogram of Human Data

The human gait is a complex motion that comprised the many movements of individual body parts, [7]. The movements of these parts produce micro-Doppler effect suitable for target recognition and which can be clearly determined using time-frequency representations. For a 1-D discrete signal $x[n]$, the STFT is defined as

$$X[n,k]=\sum_{r=-\infty}^{\infty}x[r]w[r-n]e^{-j2\pi rk/N},\ k=0,1,\ldots,N-1 \quad (1)$$

where n is the discrete time index, k is the discrete frequency index, N is the number of points used to calculate the discrete Fourier transform (DFT) and $w[n]$ is the window function. The resolution of STFT is determined by the window size N_W. A shorter $w[n]$ has higher time resolution but poor frequency resolution. The windows could be overlapped or disjointed. A bigger windows overlap leads to a smoothed spectrogram with higher time resolution.

The spectrogram $S[n,k]$ of discrete signal $x[n]$ is computed by taking the squared magnitude of its STFT,

$$S[n,k]=\left|X[n,k]\right|^2. \quad (2)$$

In this research, for spectrogram computations the following parameters are used: $N = 1024$, Kaiser window function with 256 samples and parameter $\beta = 3\pi$, and 50% overlapping. The Kaiser β parameter can be interpreted as 1/4 of the 'time-bandwidth product' of the window in radians. It provides a control over the fundamental window trade-off between side-lobe level and main-lobe width. Larger values of β give lower side-lobe levels, at the cost of wider main lobe. Since the signal sampling frequency is 4 kHz, the Doppler frequency resolution is 3.9 Hz.

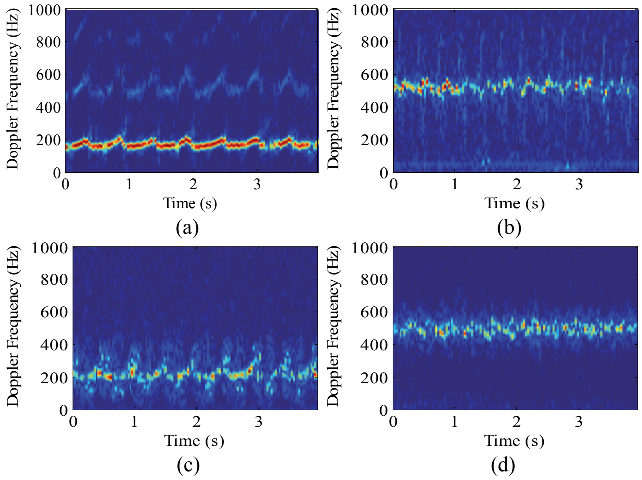


Fig. 1. Spectrograms (the asphalt road): (a) person walking, (b) person running, (c) group of persons walking, (d) group of persons running.

Fig. 1 shows the spectrograms of person and group of persons (five persons) walking or running on the asphalt road where the distance between the targets and the radar is approximately 600 m. The Doppler frequency is displayed on the vertical axis and time is on the horizontal. The amplitude of the reflected signal is color coded with red being the highest intensity and blue the lowest (as in the following illustrations). When humans walk, the motion of various components of the body including the torso, arms, and legs produce a very characteristic Doppler signature, Fig. 1(a). Doppler spectrogram from a running person is presented in Fig. 1(b). From these, we can see a specific person signature which is characterized with component that oscillates in frequency (characteristic quasi-periodic signal). The comparative analysis of spectral characteristics of these two target classes shows the difference in central Doppler frequency and the width of spectral line around central Doppler frequency. The presence of group of persons simultaneously in the radar field of sight, irrespective of motion type, involve interferences, Fig. 1(c) and Fig. 1(d). Moreover, asynchronous motion of persons in a group causes the distortion of quasi-periodic signal on spectrogram.

Doppler spectrograms of the person and groups of persons (five persons) walking or running on the rough terrain, which contains barriers and a low vegetation, are shown in Fig. 2. Here the distance between the targets and the radar is also 600 m. Since the lower extremities are mainly masked by it, the spectrogram significantly reduces visible oscillations around the central Doppler frequency. It can be noticed the significant spread of the Doppler component caused by the varying motion from the appendages.

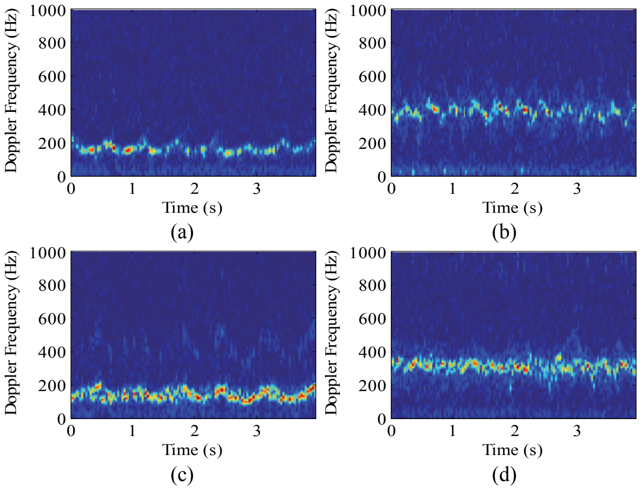


Fig. 2. Spectrograms (the rough terrain): (a) person walking, (b) person running, (c) group of persons walking, (d) group of persons running.

The spectral amplitude corresponds to RCS of the moving parts, where the main contribution is from the torso. The motion of arms and legs induces modulation on the returned radar signal and generates sidebands about the Doppler frequency. This can provide valuable information about the structure of the moving parts and it can be used for classification purposes. Since the motion of the legs and arms of a walking person is periodic, Otero in [5] used the DFT to extract basic information such as the cadence frequency from the spectral image, which is the step rate. For each Doppler bin on the spectrogram vertical axis, a DFT was applied over the entire time frame. The result is preserving the vertical scale and transforming the horizontal time axis to the frequency domain. The cadence frequency plot highlights the periodic signals present in the spectrogram [5], and this notice is studied here in details.

Within this analysis (described with above-used parameters), spectrogram contains 124 time frames (for 4 s signal duration), so the maximum cadence frequency is 15.5 Hz. For each Doppler bin, the DFT is calculated in 1024 points. According to this, the cadence frequency resolution is 0.03 Hz.

Fig. 3-6 show the cadence frequency plots, followed with horizontal and vertical projections, from real human data acquired on the asphalt road. The horizontal and vertical projections of cadence frequency plots were normalized from 0 to 1. The two dominant parameters which characterize the human gait (mean velocity and step rate) can be extracted from suitable portions of the cadence plot. The peak at about zero cadence frequency corresponds to the motion of the torso, with the value of the Doppler frequency f_d. It can be simply extracted as the maximum of the cadence frequency plot projection on the Doppler frequency axis.

The next peak in cadence frequency plot corresponds to the fundamental frequency, f_c. Forming the projections of values from cadence frequency plot into cadence frequency domain, f_c can be extracted. Subsequent peaks (gait harmonics) result from the motion of the other appendages, such as the arms and legs.

Main velocity v is proportional to the measured Doppler frequency f_d,

$$v = \frac{\lambda f_d}{2} \tag{3}$$

where λ is the wavelength of the transmitted signal. The main velocity and fundamental frequency yields the length of the stride l_s,

$$l_s = \frac{v}{f_c}. \tag{4}$$

In Fig. 3 the torso component has a Doppler frequency of 169 Hz that indicates the person was moving with a speed of about 1.51 m/s, (3). The spectral spread around central Doppler frequency can cause errors in main velocity and stride length extraction. The modulation of the legs has a fundamental cadence frequency of 1.9 Hz and the stride length, using (4), is 0.8 m. Because of known dependencies between step frequency and velocity of human gait, it is expected to be useful to combine these both features for target classification.

The value of the fundamental cadence frequency increases with increasing dynamics movement of people (Fig. 4 where f_c = 3 Hz and Fig. 6 where f_c = 2.9 Hz) and simultaneously the possibility of its extraction is proportional to the degree of synchronization movements of persons in the group.

Otero considered the amplitudes of the cadence plot peaks to be indicative of RCS, [5]. He determined the RCS of the appendages by summing the amplitudes of the peaks of the fundamental and 2nd and 3rd harmonics that are associated with the periodic motion of the arms and legs. This is then divided by the amplitude of the torso peak in the spectrum. This feature is referred to as the appendage/torso ratio. Noise and clutter have detrimental effect on the estimate values of fundamental cadence frequency and appendage/torso ratio. Clutter is due to unwanted reflections of objects in the environment that are not targets, such as trees, asphalt roads, buildings, and multi-path target reflections.

Fig. 7-10 shows that environment has a great impact in appendage/torso ratio estimation. If the legs swings are hidden with vegetation, higher order harmonics are significantly reduced at cadence frequency plots. This is evident in the comparative analysis of Fig. 3-4 with Fig. 7-8. Moreover, valid fundamental cadence frequency can be estimated for analyzed situations.

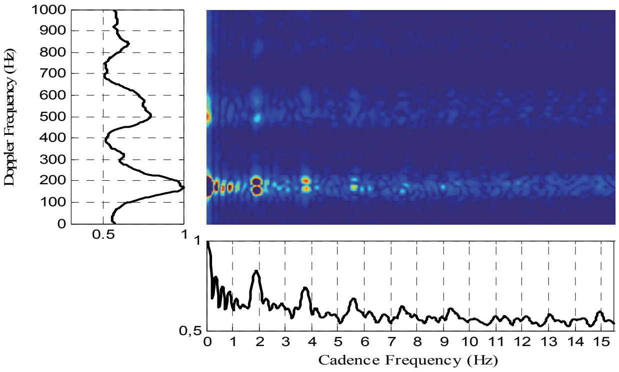


Fig. 3. Person walking on the asphalt road (f_d = 169 Hz, f_c = 1.9 Hz).

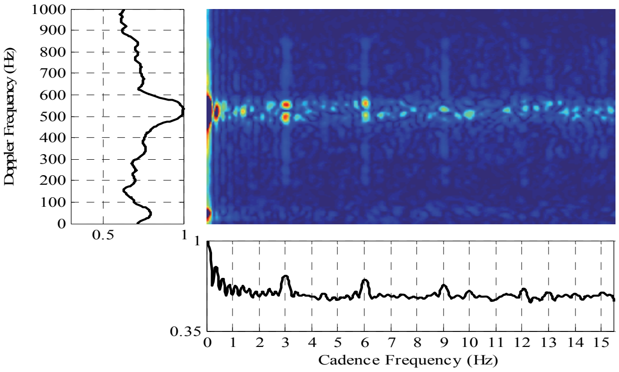


Fig. 4. Person running on the asphalt road (f_d = 535 Hz, f_c = 3 Hz).

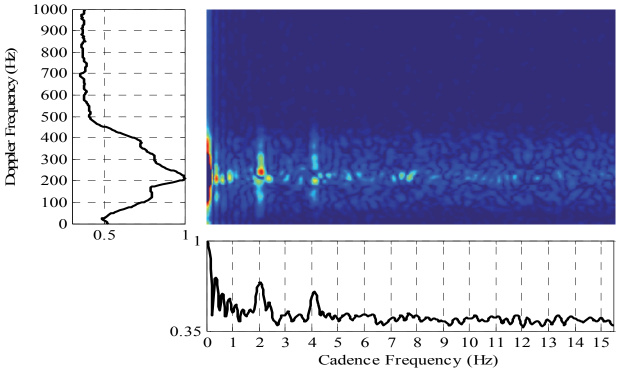


Fig. 5. Group of persons walking on the asphalt road (f_d = 211 Hz, f_c = 2 Hz).

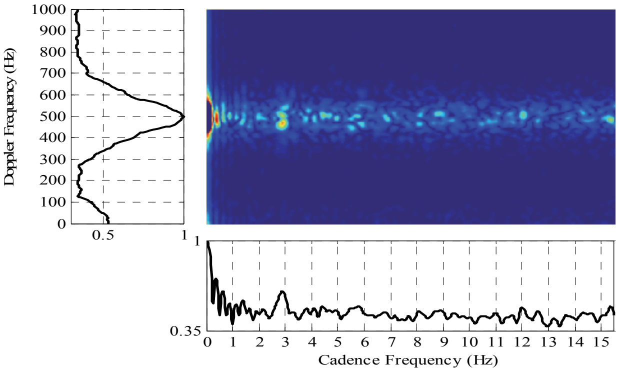


Fig. 6. Group of persons running on the asphalt road (f_d = 500 Hz, f_c = 2.9 Hz).

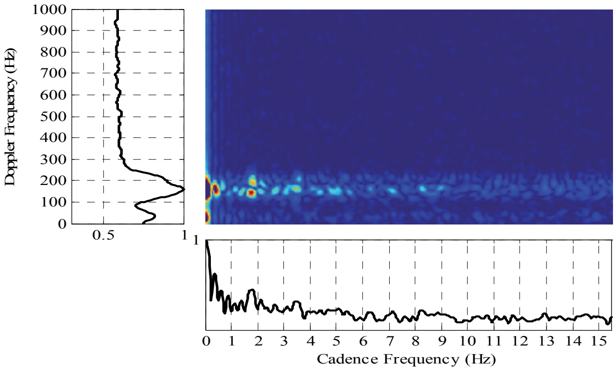


Fig. 7. Person walking on the rough terrain (f_d = 160 Hz, f_c = 1.8 Hz).

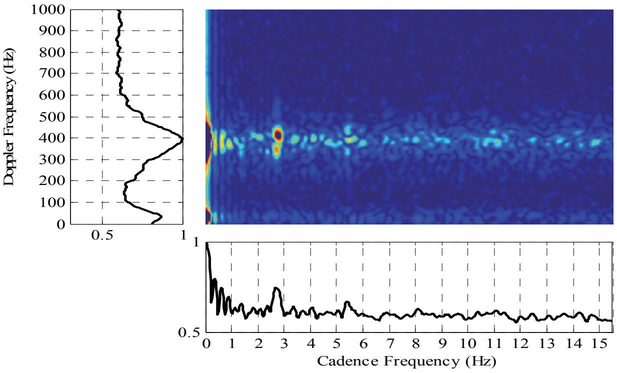


Fig. 8. Person running on the rough terrain (f_d = 400 Hz, f_c = 2.8 Hz).

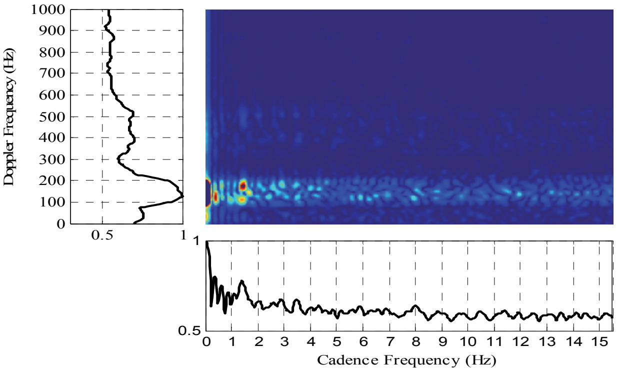


Fig. 9. Group of persons walking on the rough terrain (f_d = 123 Hz, f_c = 1.4 Hz).

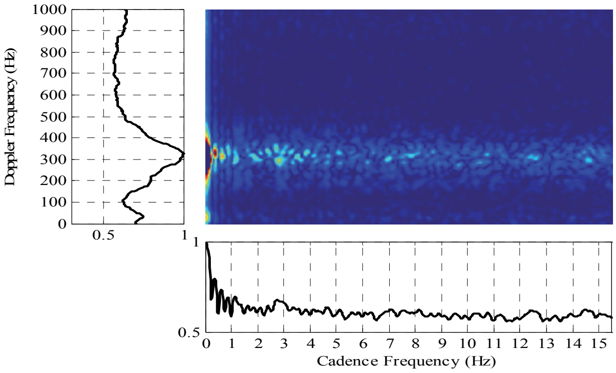


Fig. 10. Group of persons running on the rough terrain (f_d = 324 Hz, f_c = 2.7 Hz).

Unfortunately, estimates of parameters derived from the cadence frequency plot tend to be quite unreliable in the presence of group persons simultaneously in the radar field of sight (Fig. 5-6 and Fig. 9-10). In some cases fundamental cadence frequency peak appear since group of persons have higher degree of synchronization movement (Fig. 5 and Fig. 9).

Finally, fundamental cadence frequency provides additional information to differentiate persons' class from the others. The length of the time window must be chosen to provide enough gait cycles to resolve the cadence frequency for a typical walking/running subject.

3.2 Autocorrelation of Human Data

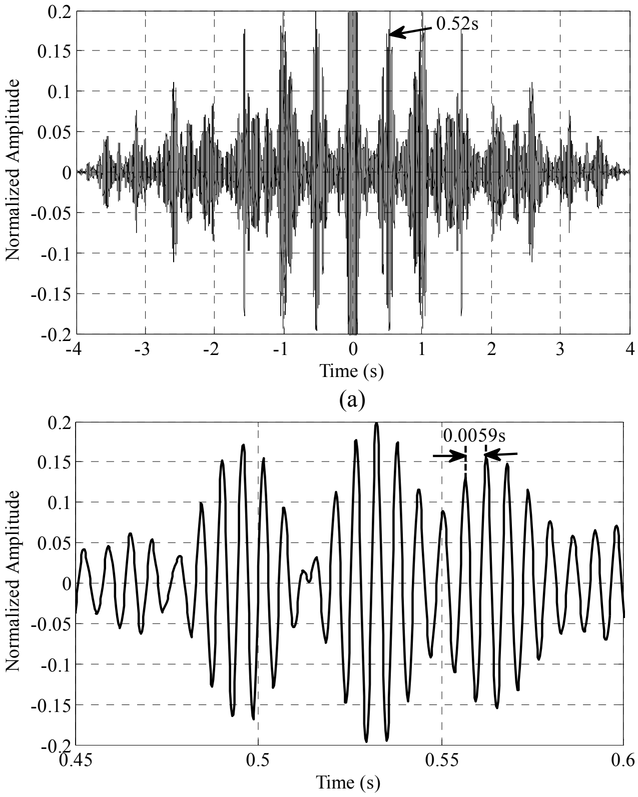
Autocorrelation of discrete-time signal $x[n]$ is defined as:

$$R[n]=\sum_{k=-\infty}^{\infty}x[k]x[k+n],\; n=-(M-1),\ldots,M-1 \qquad (5)$$

where M is the signal length. Autocorrelation is performed on the same sequences used in analysis above. Fig. 11(a)-14(a) show the autocorrelation of time-sequence data collected as human classes moving on asphalt road. Normalized values of autocorrelation are displayed on the vertical axis, while time is on the horizontal. Fig. 11(b)-14(b) show a zoomed version of autocorrelation sequence over the time interval that will be considered in the central Doppler frequency analysis.

The conducted analysis shows that autocorrelation sequence can be considered as a modulated signal with the carrier frequency equal to central Doppler frequency, while envelope is low-frequency part that is caused by swinging parts of human body. The central Doppler frequency can be estimated by taking the autocorrelation of the time sequence data, Fig. 11(b)-14(b). The distances between the peaks describe fundamental gait frequency. For example, using Fig. 11, the central Doppler frequency is calculated to be 169 Hz, while the fundamental cadence frequency is calculated to be 1.9 Hz, which is consistent with the values from the time-frequency (spectrogram) analysis, Fig. 3. Similar results are obtained for person running class (Fig. 12). Note that with asynchronous motion within group of person class, it is more difficult to estimate fundamental cadence frequency from the autocorrelation of the original data, Fig. 13-14. The peaks are much less prominent because of higher interference. Comparing these results to the results obtained using spectrogram (Fig. 5-6), it can be concluded that spectrogram is more suitable technique for fundamental gait frequency determination than autocorrelation.

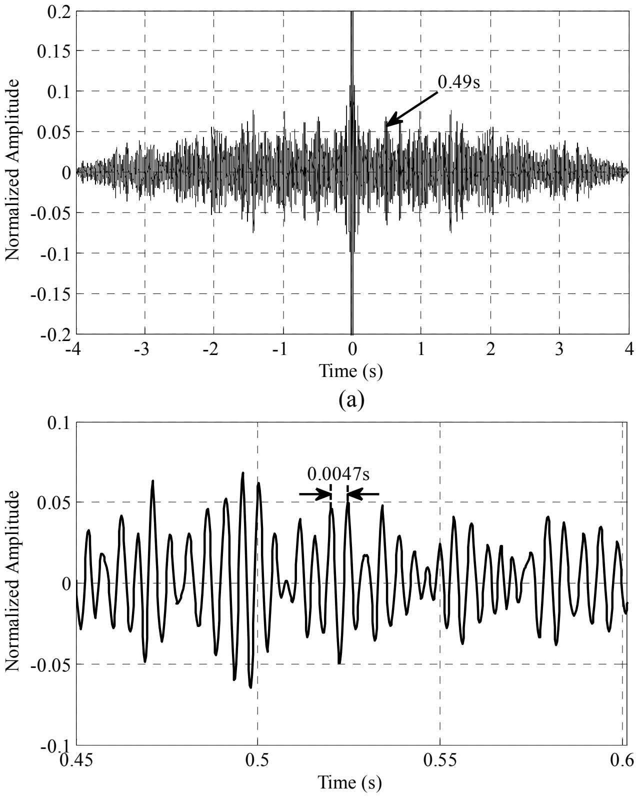
Now consider the autocorrelation plots in Fig. 15-18. Legs swings are hidden with vegetation and this can be considered as clutter presence. In these cases both features of the human target are the best observed for person walking class (Fig. 15). However, the amplitude of the



(a)

(b)

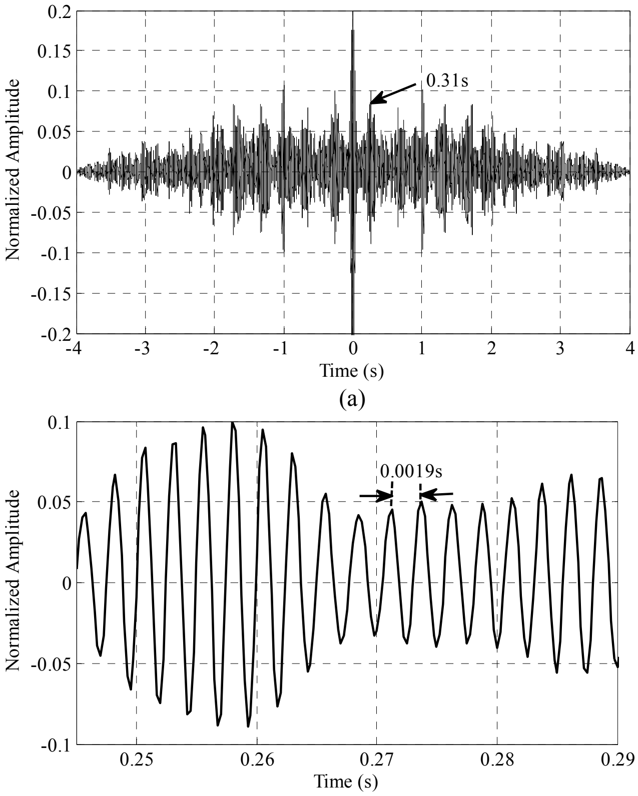
Fig. 11. Person walking on the asphalt road: (a) autocorrelation, (b) autocorrelation segment.



(a)

(b)

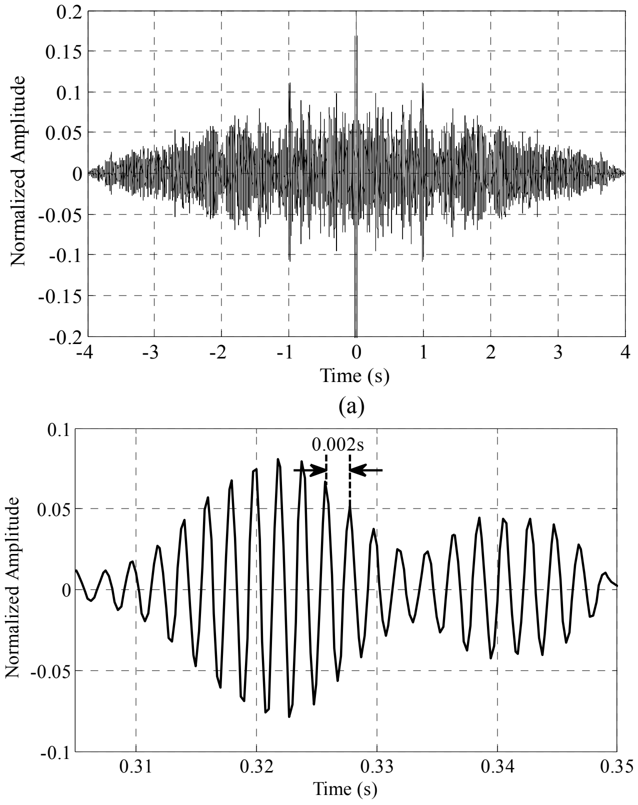
Fig. 13. Group of persons walking on the asphalt road: (a) autocorrelation, (b) autocorrelation segment.



(a)

(b)

Fig. 12. Person running on the asphalt road: (a) autocorrelation, (b) autocorrelation segment.



(a)

(b)

Fig. 14. Group of persons running on the asphalt road: (a) autocorrelation, (b) autocorrelation segment.

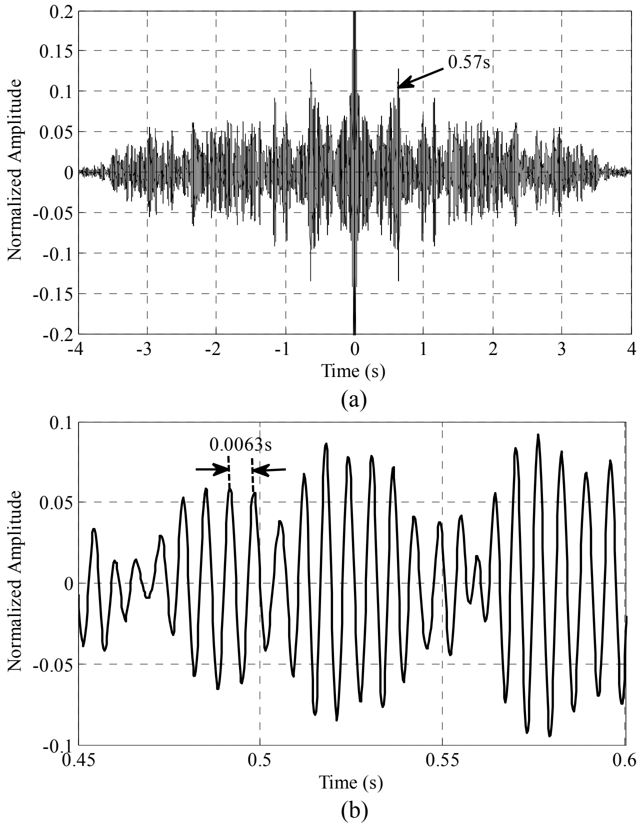


Fig. 15. Person walking on the rough terrain:
(a) autocorrelation, (b) autocorrelation segment.

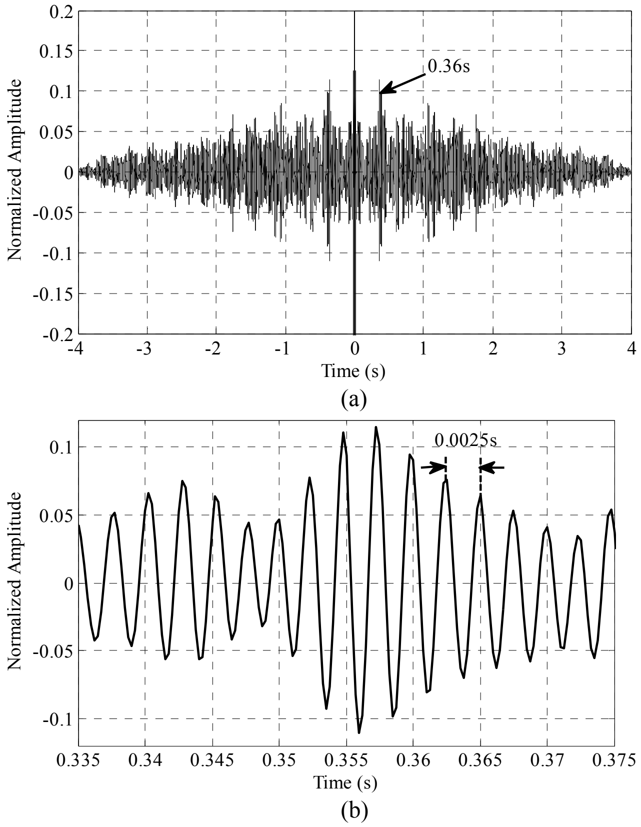


Fig. 16. Person running on the rough terrain:
(a) autocorrelation, (b) autocorrelation segment.

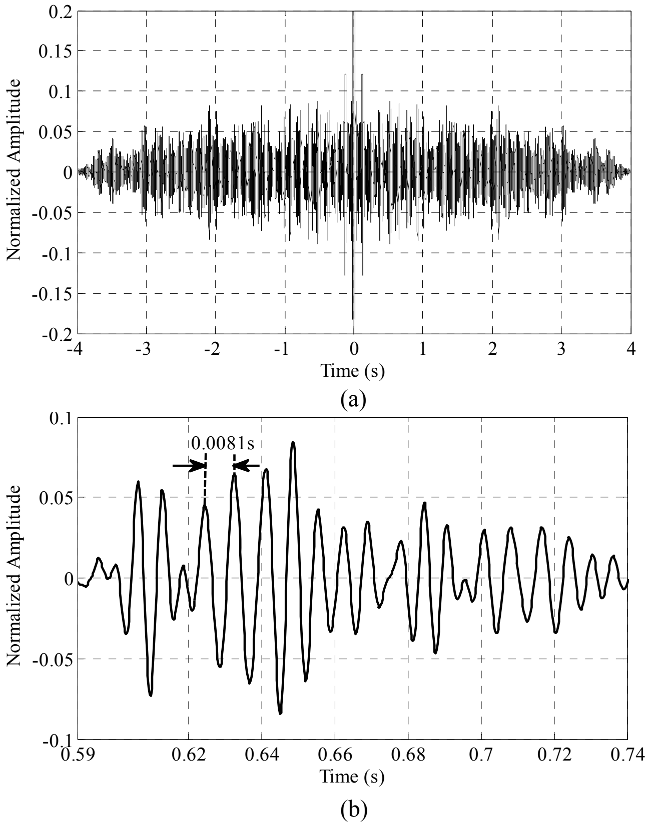


Fig. 17. Group of persons walking on the rough terrain:
(a) autocorrelation, (b) autocorrelation segment.

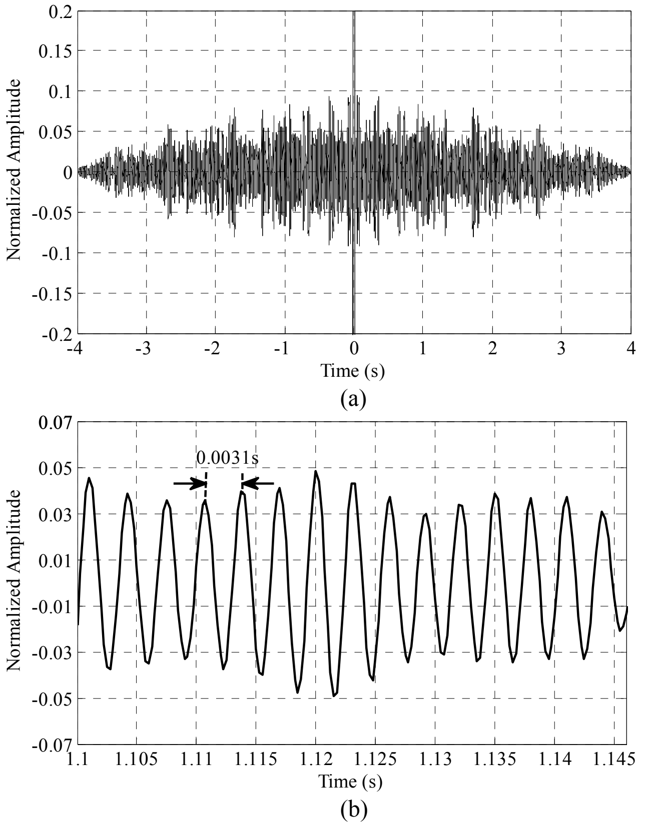


Fig. 18. Group of persons running on the rough terrain:
(a) autocorrelation, (b) autocorrelation segment.

sidelobes in this figure is much lower than those for the same class on the asphalt road (Fig. 11). Fig. 17-18 with group of persons classes additionally confirm results derived above according to Fig. 13-14, i.e. fundamental cadence frequency cannot be easily determined using the autocorrelation. Proper spectrogram plots, Fig. 5-6 and Fig. 9-10, highlight the time-frequency analysis advantages.

It should be emphasized that central Doppler frequency can be extracted using autocorrelation. Extraction of fundamental frequency suffers same problems independently from used tool. However, it could be noticed that extraction of this frequency using spectrogram appears to be more robust.

4. Conclusion

This paper highlights the extraction of Doppler signatures from radar signal returns of moving human targets. Human data are real-world data acquired by ground surveillance Doppler radar operating in Ku-band. Time-frequency analysis (spectrogram) is used to estimate the human's motion features - central Doppler frequency and fundamental gait cadence frequency. The autocorrelation of the time sequence data is also used to measure motion parameters.

Human gait is quite complex with contributions to the velocity from each of the upper and lower parts of the extremities. The main contribution comes from the torso which causes the central Doppler frequency of target. This frequency can be determined using both the autocorrelation and spectrogram.

The presented findings show that the results of human motion signature extraction are better within spectrogram analysis, therefore spectrogram is an effective tool for human motion signature extraction. If the group of persons moves in clutter, determination of the fundamental cadence frequency cannot be achieved using autocorrelation. According to this, the extraction of the fundamental cadence frequency using the autocorrelation is unreliable when the target is in the clutter presence.

It was demonstrated that the value of the fundamental cadence frequency increases with increasing dynamic movement of people and simultaneously the possibility of its extraction is proportional to the degree of synchronization movements of persons in the group.

In this paper it is shown that the feature referred as the appendage/torso ratio is not reliable in the case of multiple persons in the scene. Generally speaking, determination of this feature cannot be achieved in the clutter.

The analysis of micro-Doppler features and extraction using time-frequency techniques has to be explored further. Therefore new time-frequency distributions and methods will be investigated in purpose of feature extraction and target recognition. This would be investigated in order to determine the possible feature vectors for proper classification of human classes (one person or group) and behavior (walking or running).

As stated in the paper, only direct movement toward or away from the radar was investigated. In future work we will consider influence of aspect angle between radar line of sight and target direction. Observing walking persons in non-radial direction can skew the results and their interpretation a lot. For example, torso reflection may not always be strong for monostatic radar configuration. Moreover, the micro-motion of the body parts cannot be easily extracted in Doppler signature.

Acknowledgements

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About Authors ...

Milenko ANDRIĆ was born in Pljevlja in 1972, Montenegro. He received the B.Sc. degree in Electronics Engineering from the Military Technical Academy, Serbia in 1995. He received M.Sc. and Ph.D. in Electrical Engineering in 2001 and 2006, respectively. He is an associate professor at the Department of Military Electronics Engineering and he also works as scientific researcher at the Electronic Systems Laboratory of the Military Academy in Belgrade. His main research interests are in the fields of stochastically process in telecommunication and radar engineering, pattern recognition, methods for signals analysis and digital signal processing. He has published more than 50 papers in national and international conferences and journals.

Dimitrije BUJAKOVIĆ was born in Kragujevac, Serbia in 1980. He received the B.Sc. degree in Electronics Engineering from the Military Technical Academy, Serbia in 2004. He received his M.Sc. in Control Systems from the School of Electrical Engineering of University of Belgrade in 2008. He works as a research assistant at the Department of Military Electronics Engineering, Military Academy in Belgrade. His research interests include methods for signal analysis and digital signal processing. He has published more than 20 papers in national and international conferences and journals.

Boban BONDŽULIĆ was born in Požega in 1976, Serbia. He received the B.Sc. degree in Electronics Engineering from the Military Technical Academy, Serbia in 2000. He received his M.Sc. degree in 2005 from the Faculty of Electrical Engineering, University of Belgrade, Serbia. He works as a research assistant at the Department of Telecommunications and Informatics, University of Defense in Belgrade, Serbia. His research interests include information fusion, image and video quality evaluation, detection and tracking of moving objects, pattern recognition. He has published more than 40 papers in national and international conferences and journals.

Slobodan SIMIĆ was born in Krupanj in 1976, Serbia. He received his B.Sc. in Electrical Engineering from the Military Technical Academy, Serbia in 2000, M.Sc. degree from the Faculty of Electrical Engineering, University of Belgrade, Serbia in 2006, Ph.D. degree from the Faculty of Technical Sciences, University of Novi Sad, Serbia in 2013. He is a teaching assistant at the Department of the Military Electronics Engineering, Military Academy, University of Defense in Belgrade. His research interests include digital signal processing and embedded system design. He has published over 40 papers in national and international conferences and journals.

Bojan ZRNIĆ graduated in 1992 on the Military Technical Academy in Belgrade with B.Sc. degree in Electrical Engineering. He received M.Sc. and Ph.D. in Electrical Engineering in 1998 and 2001, respectively. He is a Head of the Defense Technology Department in Serbian MOD. He is also visiting professor at the Serbian Military Academy on the radar and EW subjects. His research work includes radar signals and systems. He has published over 70 papers in national and international conferences and journals.