The Radar Application of Micro Doppler Features from Human Motions

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Abstract— **This study aims to experimentally investigate the feasibility of discriminating human motions with the help of micro Doppler features by using radar. In the first phase of the work, the synthetic data is generated through the human walking simulator by V. Chen and different time-frequency transformations are applied on the data and the results of the simulator are compared with field experiments. In the following phase, several field experiments which are in the scope of the simulator are conducted and the experimental data for running, crawling, creeping and walking with the aspect angles of 0°, 30°, 60° are collected. Signal processing steps and micro Doppler processing steps are applied to the collected data and spectrograms are obtained. Lastly, six features, which are torso frequency, bandwidth of the signal, offset of the signal, bandwidth without micro Dopplers, the standard deviation of the signal strength, the period of the arms or legs motions are extracted from the spectrograms and the efficiency of the features in motion classification is compared.**

Index Terms— **Micro Doppler; Human Motion Classification; Feature Extraction**

I. Introduction

Classifying human motions by using radars has become an important emerging research field for both civilian and military applications. Radar has some important advantages over other sensors for detecting human motion. First of all, radar can work in both daytime and nighttime with full performance, because it does not depend on additional external light sources for its operation. Furthermore, radar is affected only slightly by weather conditions such as smoke, dust and fog, and radar can operate behind walls or at very long distances from the targets. These features make the radar usage superior for security and surveillance in many applications. In another aspect, human intention can be anticipated from the motions, therefore, the classification of human motions can be important in several security applications. Thus, discriminating the human motions and detecting abnormal activities by radar are useful for physical security, urban military operations and law enforcement.

Micro Doppler classification studies in the literature are investigated. First of all, time-frequency transformations are examined and it is seen that Short Time Fourier Transform (STFT), Wigner Ville Distribution (WVD), Cohen Class transformations become prominent for micro Doppler studies [1]. In addition, feature extraction methods from the motion spectrograms are investigated. Otero applied FFT for every Doppler bins on the vertical axis to obtain cadence frequency and accepted that the first feature is stride which is the division of velocity to the cadence frequency and the second feature is appendage/torso ratio which is the division of the summation of the RCS of the arms and legs to the RCS of the torso [2]. In [3], a new algorithm named as empirical mode decomposition (EMD) which provides an efficient way of extracting micro Doppler signatures is proposed in addition to the known feature algorithms. In [4] and [5], the micro Doppler characteristics of human walking are examined to find out the distinctive signatures to distinguish genders. In [6], the stride rate, which is used as biometric, is extracted as feature from the spectrograms and the torso is extracted from the spectrogram with the isolation of the maximum signals at each time. Youngwook and Kim provide one of the efficient and applicable methods; their method provides the extraction of the torso frequency, the bandwidth of the signal, the offset of the signal, the bandwidth without micro Dopplers, the standard deviation of the signal strength, the period of the arms and legs [7], [8].

The main aim of this study is to investigate the feature extraction methods from the human motion spectrograms for ground surveillance radar systems. First of all, a human walking simulator is investigated. After that the collection of experimental human data for different motions by using a ground surveillance radar, the steps of processing signals, and feature extraction methods are presented. In addition, the comparison between the features is given in this study.

II. Human Motion Spectrograms

In this part, V. Chen's human walking simulator is presented [9]. In addition, another time-frequency transformation is applied on the simulator.

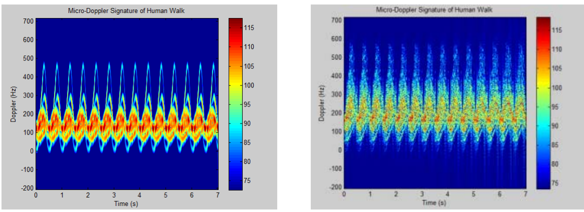
A. Human Walking Simulator

The human walking simulator consists of 17 human points such head, hands, arms, knees, feet, etc. V. Chen uses Boulic, Thalmann and Thalmman's human segmentation and walking model.

In the first part of the study, the human walking simulator is examined and the different time-frequency transformations are applied on the simulator. The purpose of this part is to get an idea about the field data before collecting and obtain an infrastructure to compare the simulator with the real data.

1) Applying Time-Frequency Transformations on Human Walking Simulator

The time-frequency transformations of Short Time Fourier Transform (STFT) and Wigner Ville Distribution (WVD) are applied on the human walking simulator. The spectrograms in Figure 1 are obtained. It is seen from the spectrograms that the envelope of the spectrogram with WVD is similar to the envelope of STFT; on the other hand, there are interferences on the spectrogram of WVD. It is an understandable result that the nature of the WVD causes cross term interferences for multicomponent signals [10]. Because radar return signal of human walking is a multicomponent signal which contains torso, limb motions, WVD causes cross terms. Therefore, use of STFT seems more appropriate than WVD for human motion spectrograms.



(a) STFT (b) WVD

Figure 1. The spectrograms of human walking simulator with different time-frequency transformations

B. Experiments for Collecting Human Walking Data

After simulation studies, real human motion data is collected in an outdoor test facility, by using a ground surveillance radar, which is a pulsed Doppler radar operating at Ku-band. For the data collection, fixed antenna position mode of radar is used, in which radar operates at selected azimuth angle without rotation. The test facility can be described as a concrete, rectangular area, whose dimensions are approximately 200 meters of length, 150 meters of width, and is surrounded by steppe.

The experimental data consists of 3 human subjects with 7 realizations for different human motions as walking, running, crawling, creeping and for different walking azimuth angles of 0°, 30°, 60°. The range of the 3 human subjects is adjusted to approximately 150 meters from the radar.

1) Signal Processing Steps

After experimental data collection part, the collected data is processed through the radar signal processing steps of matched filtering, moving target indicator filtering, windowing, Fast Fourier Transform (FFT) and Constant False Alarm Rate (CFAR); at the end of these steps, the range of the target is obtained. After that micro Doppler processing steps are applied. A high pass filter is designed to suppress the clutter. The matched filtered matrix is passed through this high pass filter and Hamming window. After windowing, the range columns of the targets are extracted from the matrices and combined. By applying STFT on the range column matrix, the human motion spectrograms are obtained.

2) Feature Extraction Methods

Youngwook and Kim's feature extraction methods consist of six features which are the torso Doppler frequency, the total bandwidth of the Doppler signal, the offset of the total Doppler, the bandwidth without micro Doppler, the normalized standard deviation of the Doppler signal strength, and the period of the limb motions [7], [8]. These features are extracted from the collected data and the features can be seen in Figure 3.

The first feature is the torso frequency. The strongest return on the spectrograms belongs to torso; therefore, the torso frequency is calculated by dividing the frequencies of strongest signals to time bins. For 2nd, 3rd and 6th features, high and low envelopes are extracted. The bandwidth of the signal is the difference between the highest frequency of high envelope and lowest frequency of low envelope. The offset value is the average of the mean values of the high and low envelopes. The bandwidth without micro Doppler is the difference between the highest and lowest points of the torso envelopes. For the fifth feature, the standard deviation above noise is calculated. For the period feature, the time difference between two consecutive peaks of high envelope is calculated.

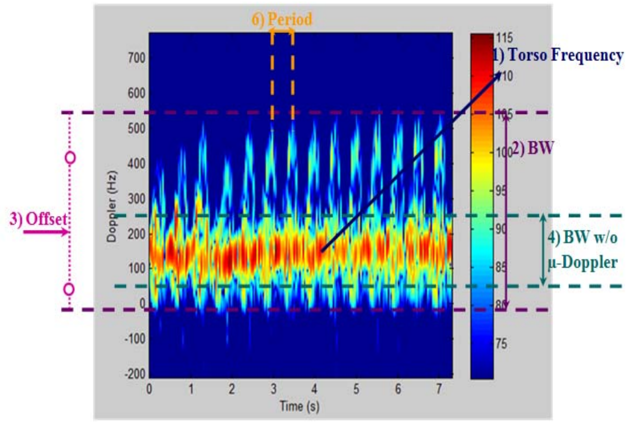


Figure 2. Demonstration of features on the experimental spectrogram

3) Comparison between Simulated Human Walking Model and Experimental Human Walking Result

In Figure 3, the spectrograms of V. Chen's human walking simulator and real human walking data are given. It is seen that two spectrograms seem quite similar. The shape of swinging foot is very consistent with simulated and experimental data. The shape and the amount of extension of fixed foot are also similar on both spectrograms. Even the torso seems spread in the experimental data, the general form and position of torso resembles the torso part of the simulator. Although knee is more distinctive for simulator than experimental spectrogram, the position and the shape of knee are again similar in both spectrograms.

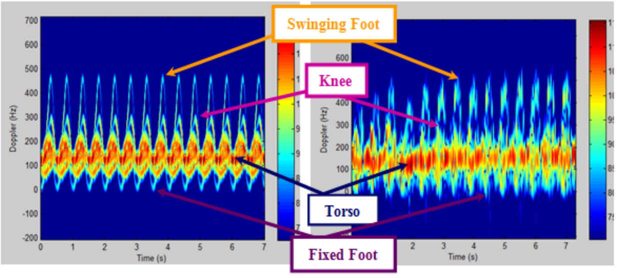


Figure 3. Spectrograms of human walking

In order to see the effectiveness of the simulator in the generation of selected micro Doppler features quantitively, the extracted feature values of human walking simulator by STFT and the average values of experimental human walking with azimuth angle of 0° are listed at Table 1.

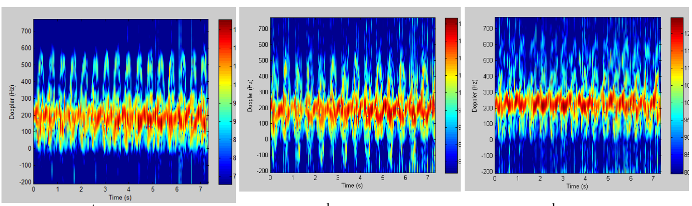
Table 1. Comparison between human walking simulator by STFT and experimental human walking result by means of micro Doppler features

	Comparison of Simulator and Experimental Human Walking					
	Torso Freq (Hz)	Bandwidth (Hz)	Offset (Hz)	Bandwidth w/o Micro Doppler (Hz)	Standard Deviation	Period (sec)
Human Walking Simulator with STFT	144.7	497.9	169.7	227.9	7.20	0.50
Experimental Human Walking with Azimuth Angle of 0°	150.0	492.5	168.1	183.7	7.43	0.46

When quantitative results are investigated, it can be seen that the results of human walking simulator by using STFT is very similar to experimental human walking with azimuth angle of 0°; therefore, the given simulator is a beneficial tool to study human characteristics on radar.

4) Analysis of Different Human Subjects

In order to see whether every person has different walking characteristics and can be distinguished by using micro Doppler features, spectrograms of 3 human subjects' walking with azimuth angle of 0° are given in Figure 4 and extracted feature values of 1st person's, 2nd person's and 3rd person's walking spectrograms are listed at Table 2.



(a) 1st person (b) 2nd person (b) 3rd person

Figure 4. The spectrograms of 3 human subjects' walking with azimuth angle of 0°

Table 2. Micro Doppler features of walking of 1st person, 2nd person and 3rd person

Walking with Azimuth Angle of 0°	Characteristics of 3 Persons' Walking with 0°					
	Torso Freq. (Hz)	BW (Hz)	Offset (Hz)	BW w/o Micro Doppler (Hz)	STD	Period (sec)
Average Values for 1st Person	188.6	557.5	196.3	235.1	7.32	0.46
Average Values for 2nd Person	177.3	547.7	193.7	211.3	7.56	0.47
Average Values for 3rd Person	223.7	528.8	219.6	185.9	7.91	0.49

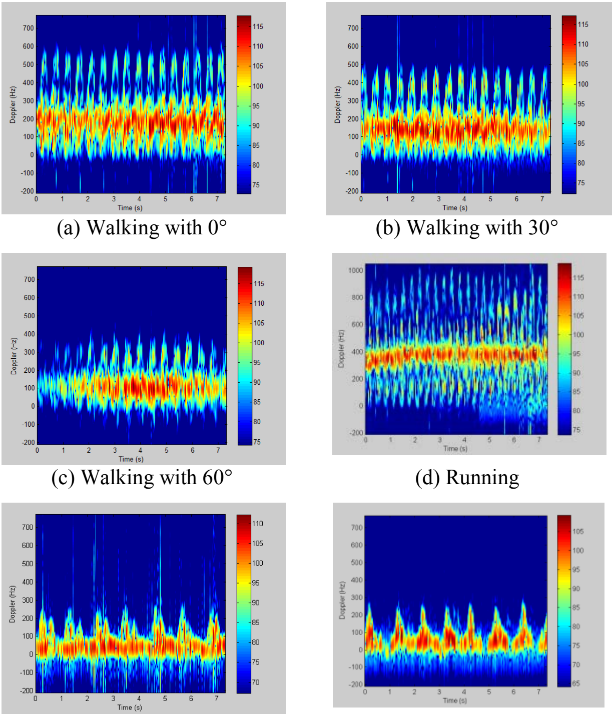
The followings can be extracted from Table 2:

- 3rd person has the largest torso frequency, which means that this person has the largest speed of walking.
- 1st person has the largest BW value, which can be explained that this person has the highest velocity of limb motions of walking.
- 3rd person has the largest offset value, which can be deduced that the forward and backward limb motions are more asymmetric than other persons' limb motions while walking.
- 1st person has the largest BW without micro Doppler value, which can be concluded that this person has the largest bobbing motion of torso while walking.
- 3rd person has the largest standard deviation value, which means that dynamic range of the motion is bigger than others'; in other words, the signal strength bar consists of larger range of numbers.
- 3rd person has the largest period values, which means that the swing rate of limbs is smaller than others', which means that this person swings arms slowly.

In brief, when extracted features of walking spectrograms of the targets are taken into consideration, it is seen that each person has distinctive walking features, in other words each person has signatures of walking and identification of walking person could be done by looking at the walking spectrograms and from the numerical values of extracted features.

5) Analysis of Different Types of Human Motions

Signal processing steps and micro Doppler processing steps are applied on the experimental radar data of walking with azimuth angles of 0°, 30°, 60°, and running, crawling, creeping. The spectrograms of these motions are given in Figure 5.



(a) Walking with 0° (b) Walking with 30°

(c) Walking with 60° (d) Running

(e) Crawling (f) Creeping

Figure 5. Spectrogram of different types of human motions

The Doppler signatures provide distinguishing the type of motions by only looking at them. It is known that the torso produces the strongest return in each spectrogram, while arm and leg movements surround the torso with the periodic micro-Doppler modulations. Walking and running spectrograms are discriminated from crawling and creeping spectrograms at first look because of several reasons. First of all, torso frequency of crawling and creeping signatures are positioned around 0 Hz. Secondly, due to the fact that there is no back swing in these motions, negative Doppler signatures do not occur; therefore, micro Dopplers skew towards the positive with respect to the torso frequency. Thirdly, these motions have narrower Doppler signal spread. Lastly, the period of these motions are longer. With the help of these deductions, crawling and creeping signatures are discriminated from others. Even crawling and creeping are very close to each other, they can also be distinguished. In crawling, there are two consecutive positive modulations for each micro Doppler peak; on the other hand, there is only one positive modulation for each micro Doppler peak in creeping. This can be explained with the difference of arm and knee motions. In crawling, there are two consecutive positive modulations for each peak in the spectrogram; however, in creeping, the arm movements are dominant motions, which produce only one positive modulations for each peak. Walking and running signatures can be discriminated from the spectrograms by using the following method. Firstly, torso frequency of running is positioned around 400 Hz, which is higher than the frequency of walking. Secondly, running has a wider Doppler spread compared to walking. Lastly, the period of running is shorter than walking period. These three features are sufficient to discriminate running from walking.

Walking with the different azimuth angles are compared; the followings are the comparison results:

- When azimuth angle increases from 0° to 60°, the resolution of the limb motions on the spectrograms decreases. The limb motions that are very clear for the azimuth angle of 0° are blurred for the azimuth angle of 60°. In addition, the time intervals 0-2 sec and 6-7 sec can be assumed as transition parts, where the person starts walking into the coverage of the azimuth beam width of the radar.
- The torso frequency, which depends on the human speed, decreases with the increasing azimuth angles. It is known that if the azimuth angle is bigger than 0°, the human speed according to the radar becomes the related component of the human speed. Therefore, it is reasonable that human speed becomes smaller for bigger azimuth angles than 0° and this makes the torso frequency values decrease while the azimuth angles are increasing.
- The bandwidth also decreases while azimuth angle increases from 0° to 60°. If there is an azimuth angle bigger than 0°, the limbs speed according to the radar is calculated as the related components of the limbs speed; therefore, for the larger azimuth angles, smaller bandwidth values are obtained.

The feature extraction methods, explained in II.B, are applied on the experimental motion data set. In order to compare different types of human motions quantitively, average values for walking with azimuth angles of 0°, 30°, 60°, running, crawling and creeping are presented at Table 3.

Table 3. Average values of the spectrograms of different human motions

	Comparison of Different Human Motions					
	Torso Freq (Hz)	BW (Hz)	Offset (Hz)	BW w/o Micro Doppler (Hz)	STD	Period (sec)
Running	418.7	918.3	437.8	254.4	7.82	0.26
Walking with 0°	196.5	544.7	203.2	210.7	7.60	0.48
Walking with 30°	152.2	492.5	168.1	183.7	7.42	0.46
Walking with 60°	88.1	282.0	79.5	162.2	7.17	0.44
Crawling	75.7	337.9	91.7	93.4	7.15	0.79
Creeping	72.2	361.4	78.7	74.4	7.01	0.86

The results extracted from the spectrograms and the numerical results of extracted features of different human motions are followings:

- Among all motions running has the largest torso frequency of 418.7 Hz; which makes sense because torso frequency depends on the human speed and the human speed is the highest for running. Torso frequency values of walking 196.5 Hz, 152.2 Hz and 88 Hz are lower than running, higher than crawling and creeping values as expected; because the human speed is lower than running, but higher than crawling and creeping. When the torso frequency values of crawling and creeping are compared, it is seen that these values are close to each other; which means that average human speed is similar for crawling and creeping. The torso frequency of crawling is slightly higher than creeping as expected.

- Among all motions, running has the largest bandwidth value of 918.3 Hz; which makes sense because bandwidth depends on the limbs speed and the limbs speed is the highest for running. Bandwidth values of walking 544.7 Hz, 492.5 Hz and 282.0 Hz are lower than running; because limbs speed is lower than running. The bandwidth value for walking with azimuth angle of 60° is narrower than bandwidth values of crawling and creeping. In fact, the expectation is opposite because walking must have wider bandwidth than crawling and creeping; however, when the spectrograms of walking with azimuth angle of 60° are examined, it is seen that these spectrograms are blurred. Therefore, because of the unclear spectrograms of walking with 60°, the feature extraction from these spectrograms might have some deviations. Moreover, when the bandwidth value of crawling of 337.9 Hz and the bandwidth value of creeping of 361.4 Hz are compared, it is seen that creeping bandwidth value is higher than crawling value; while the opposite is expected. Different creeping styles of human subjects can cause this result.

- It is known that if the motion is symmetric, the offset value converges to the torso frequency. Because walking is more symmetric motion than others, the offset value of walking of 203.2 Hz is very close to torso frequency of 196.5 Hz. It is seen that crawling is more asymmetric motion than others, there is approximately 20 Hz of difference between the offset value of crawling of 91.7 Hz and the torso frequency of 72.2 Hz. It is also realized the offset values of walking with azimuth angle of 60° of 79.5 Hz are smaller than the torso frequency of 88.1 Hz; the unclear spectrograms of walking with 60°, the feature extraction from these spectrograms might cause these deviations. In the light of these explanations, it is seen that running has the largest offset value of 437.8 Hz. After running, walking offset values are higher than others, except the walking with 60° because of the deviations of features from blurred spectrograms. Lastly, it is seen that crawling offset is bigger than creeping value. Actually, creeping is an asymmetric motion and it is expected that the offset value is much different than 5.6 Hz; however, it can be said that different creeping styles of human subjects may cause this result.

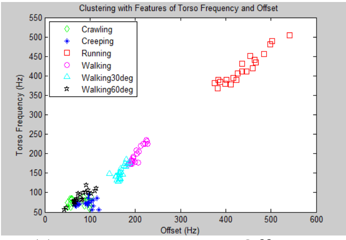
- Among all motions, running has the largest value of bandwidth without micro Doppler 254.4 Hz; because this feature depends on the bobbing motion of the human and bobbing motion is the highest for running. Bandwidth without micro Doppler values of walking of 210.7 Hz, 183.7 Hz and 162.2 Hz are lower than running, higher than crawling and creeping values, as expected; the bobbing motion is smaller than running but larger than crawling and creeping. The bandwidth without micro Doppler value is 93.4 Hz for crawling. Among all motions, creeping has the smallest bandwidth without micro Doppler value of 74.4 Hz; which makes sense as bobbing motion is very small for the creeping. When the bandwidth without micro Doppler values are taken into account, it is seen that these values are disjoint; which means that bandwidth without micro Doppler values is one of the efficient discriminative features.

- Among all motions, running has the largest standard deviation of 7.82; because the standard deviation depends on the dynamic range of the motion and it is obvious that dynamic range has the highest value for running; in other words, the signal strength bar of running consists of largest range of numbers. Standard deviation values of walking of 7.60, 7.42 and 7.17 are lower than running, and higher than crawling and creeping values as expected; because the dynamic range is lower than running but higher than crawling and creeping. The standard deviation value is 7.15 for crawling. Among all motions, creeping has the smallest standard deviation value of 7.01; which can be seen from the spectrograms that creeping has the smallest dynamic range, in other words the smallest range numbers for signal strength. When the standard deviation values are taken into account, it is seen that the standard deviation values are very close to each other; which means that standard deviation is not a very discriminative feature.

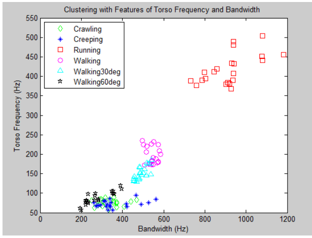
- Among all motions, creeping has the longest period of 0.86 sec; which makes sense because period depends on the swing rate of human limbs and it is obvious that human subject has the smallest swing rate for creeping. The swing rate for crawling is higher than creeping, which makes the period of the crawling as 0.79 sec, which is shorter than creeping period. Period values of walking of 0.48 sec, 0.46 sec and 0.44 sec are shorter than crawling but longer than running as expected; the limbs walking swing rate is higher than crawling but smaller than running. Running has the shortest period value of 0.26 sec, because the swing rate is very high for running. Although there is a logic between the period values; the feature of period is not a very efficient feature for classification of motions. One reason for this fact is that while searching the peaks from the complex spectrograms, there can be errors on the calculation of the peak numbers. In addition, the period values are very close to each other; which means that period is not a very discriminative feature.

C. *Efficiencies of Features*

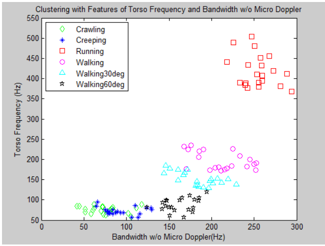
When the features are examined, it is seen that the efficiencies of these features for discriminating human motions are not same. While some features are quite distinctive, some features are not able to make distinctive the human motions. In order to visualize the efficiency of extracted features, the experimental data for a pair of features is plotted in Figure 6.



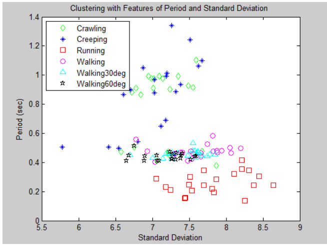
(a) Torso Frequency vs. Offset



(b) Torso Frequency vs. BW



(c) Torso Frequency vs. BW w/o micro Doppler



(d) Standard Deviation vs. Period

Figure 6. Clustering of features

In Figure 6, the clustering figures of feature pairs are seen. When these figures are examined, several observations can be made:

- The effectiveness of torso frequency is obvious from the first three graphs; because nearly all motions can be separated with the help of their torso frequencies; thus, the most discriminative feature is torso frequency.
- For the symmetric motions, offset values approach the torso frequency; for the asymmetric ones, the difference becomes bigger. However, for both case, it is very distinctive. It can be assumed that the offset value is second efficient feature for classification.
- Running and walking with 0°, 30° are separated; however, walking with 60°, crawling and creeping cannot be discriminated. In brief, the bandwidth value can be considered at the third place; because three classes mixed too much for this feature.
- Bandwidth width without micro Doppler values are similar for running and walking data and also crawling and creeping cannot be discriminated; therefore, it can be assumed as it has the fourth place in the list of classification performance of features.
- Period is the feature at the fifth place; at least running, group of walking and pair of crawling and creeping can be discriminated.
- The least effective feature seems standard deviation; whose values are similar for nearly all classes.

III. Conclusions

The followings are the conclusions derived from the study:

- The human walking simulator by V. Chen is examined and it is deduced that this simulator is consistent with experimental human walking data, and it can be a beneficial tool for human walking studies.
- The time-frequency transformations on human walking simulator are examined and it is seen that STFT is a more appropriate time-frequency distribution for human walking than WVD.
- Each person has Doppler signatures for motions and identification of person could be done by Doppler features.
- The effects of azimuth angles on human walking spectrogram are analyzed. When the azimuth angle is approaching to 90°, the micro Doppler effects are hard to discriminate from the spectrograms.
- Six features are extracted from the human motion spectrograms and when the efficiencies of features are ordered, the most discriminative feature is torso frequency, the offset value seems that it is the second efficient feature for classification, the bandwidth value can be considered at the third place, bandwidth width without micro Doppler has the fourth place of the list of classification performance of features, period is the feature at the fifth place, the least effective feature seems standard deviation.

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