Abstract—Single-sensor Doppler radar faces many challenges in elderly fall detection. The similarities of the Doppler signatures between falls and other motions of fast time transitions render CW-based EM sensing insufficient for proper motion discriminator. Further, motion articulations in the directions of a small or zero projections along the line-of-sight generate noisy Doppler signatures and greatly contribute to the confusion matrix. In this paper, the benefit from the range information is used to distinguish between fall and non-fall motions with similar Doppler features. We also examine the effects of the aspect angle on fall detection. Simulation results using Kinect-based radar simulator and 24 GHz UWB radar sensing system, demonstrate the merits of the proposed platform for indoor motion monitoring serving assisted living applications.

Index Terms—Assisted Living; Range-Doppler Radar; Fall Detection, Support Vector Machine

I. INTRODUCTION

Radar can be used to recognize targets and their activities by analysis of the target’s micro-Doppler signatures [1]–[10]. The role of radars in assisted living and in-home monitoring of elderly predicated on its ability to perform motion detection, classification, and localization [11]–[13]. Successful detection of a fall, locating its occurrence to, at least, room accuracy, and determining its type with high classification rates would provide critical information to the first responders [14]–[21]. One key factor hindering the application of the radar sensing modality in assisted living is confusing falls with other human gross-motor activities [18]. In this paper, we consider two different range-Doppler radars and show their significance in reducing false alarms, especially those associated with the motion of sitting, under different aspect angles.

A Doppler radar for in-home monitoring obtains target Doppler information by observing the phase variation of the return signal over time [1]. The ability to effectively suppress clutter is an important property of Doppler radar, represented by strong scatterings of the electromagnetic waves from room furniture, floors, ceiling, or from interior walls [22]. Radars have also the capability to separate motions of animate and inanimate targets, like fans and pendulums. Radar units in homes can be low cost, low power, small size, and can be mounted on walls and ceilings in different rooms, depending on logistic needs and signal strength. In addition to high false alarm rates stemming from confusion of falls with similar motions, like sitting and kneeling, other main challenges in fall detection using Doppler-only radars are a) presence of scatterers caused by interior walls which create clutter and ghost targets; b) similar Doppler signatures of pets jumping off tables and chairs to those of a human falling; and c) the orthogonality between the motion direction and the line-of-sight.

In this paper, we demonstrate the offering of the range information under different aspect angles for distinguishing between sitting and falling. Both motions cause a high Doppler frequency, albeit, falling typically exhibits higher frequency due to accelerating motion of the body towards to the ground. However, the maximum frequency differences can prove insignificant, depending on how slow or fast falling and sitting are. In other words, a situation may arise where the Doppler signatures of these two motions appear similar or identical to the classifier.

It is shown that, though the time-frequency (TF) Doppler signatures can be highly overlapping, the range extent of a fall along the line-of-sight is considerably higher than that of a sit. The latter is influenced by the type and the depth of the base of the chair or the sofa. Two verification approaches are adopted to underscore the key role of the range information in the underlying problem. The first approach is using Kinect, the software technology that enables advanced gesture recognition. The Kinect time varying output is converted to an equivalent range-Doppler information and used to reveal the inter-relation between range and Doppler. The second approach utilizes a 24 GHz UWB radar to construct both Doppler signatures and range information. The main reason of using the Kinect simulator together with the real radar data is to underscore their agreements and output similarities. Kinect can help generating a much needed repository of fall and non-fall data necessary for proper classifier training and testing. From Kinect, a model based on bio-mechanics and kinematics of different motions can be generated. Possible scenarios of the same motion assumed by a generic elderly can be obtained from variants of the model parameters. The above two approaches are described in details and found to confirm the distinction in range spread of the two motions considered. These results are important in reducing fall false alarms and, as such, moving the radar forward as a preferred fall detection technology and a viable alternative to both intrusive wearable

Effects of Range Spread and Aspect Angle on Radar Fall Detection

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This paper also highlights the role of the aspect angle and the "look" direction on fall detection. Based on the obtained unsatisfactory single unit fall results, we argue that the deployment of two or more radar units provides multiple radar eyes and is key to achieving a high fall detection performance. The data corresponding to multiple radar units can be preprocessed to generate TF spectrograms, range vs. time, and range vs Doppler plots, which are then fused for reliable fall detection. The existing literature only reported data fusion based on decision level, whereby the data from each radar unit is separately processed for fall detection, and a fall is declared when fall is detected by at least one unit [23]. However, data fusion can also be made in the raw-data level, which stacks the data or preprocessed plots for all active-mode radar units as an extended observation data, and in the feature-level, which makes a joint fall decision based on the features extracted from all radar unit data [24].

The paper is organized as follows. In section II, we describe the Kinect-based UWB pulse Doppler radar simulator and experiments. Section III introduces the 24 GHz UWB radar sensing system. Experimental results are presented to emphasize the importance of the range information and effects of the aspect angle in Section IV. Conclusions are drawn in Section V.

II. KINECT-BASED UWB PULSE DOPPLER RADAR SIMULATOR

Kinect-based radar UWB pulse-Doppler radar simulator is originally proposed in [25]. The 3D position measurements obtained from the Kinect sensor are used in lieu of the time-varying range measurements typically obtained by using radar. The Kinect data for a given activity (falling or sitting) was first captured by the developed software and stored in memory to create a database. Then, the Kinect-derived 3D position measurements were used in a mathematical model for radar returns to simulate the response expected from a human motion. A smoothing function with low-pass filter characteristics is applied to the Kinect skeleton data to remove high frequency components associated with the Kinect’s tracking errors of some body joints. Especially at the end of the fall motion, these tracking errors cause spiky-type data where the front view of the human body is relatively obscured. Details of the Kinect-based simulation system can be found in [25].

The range-slow time and the micro-Doppler signature can be obtained after computation of the human radar for a given activity. The micro-Doppler signatures may be simply derived by adding all radar returns in overall range bins during the observation period, and then applying short-time Fourier transform (STFT) and its energetic representation, i.e., spectrograms.

The Kinect-based skeleton tracking data were collected at Villanova University Radar Imaging Laboratory, PA, USA. Kinect was placed at approximately 2.5 meters above ground to capture the complete human body joints and the entire falling and sitting motions. We conducted two different experiments. First, two subjects performed a falling motion at two different speeds: slow and fast. An example of the simulation output of falling can be seen in Fig. 1 (left). The second experiment involved the same two subjects who performed a sitting motion, described in Fig. 1 (right), also at two different speeds. Kinect was tilted to capture the entire motions. This tilt angle due to Kinects elevated position was compensated by applying a 3D rotation matrix, results in generating the correct skeletal data. Another 3D rotation matrix is also applied to rotate the direction of the target motion for any desired aspect angle.

The aspect angle between the radar line-of-sight and the direction of target motion greatly influences the micro-Doppler signatures and range-slow time maps. The most distinctive signatures appear when target is moving towards or away from the radar, leading to the maximum Doppler spread. As the aspect angle increases, the Doppler effect also lessens. The resulting signatures have a compressed structure in frequency domain which causes classification results to dramatically worsen. To investigate the effect of the aspect angle, micro-Doppler signatures and range-slow time maps were computed for both falling and non-fall motions which are shown in Fig. 2. It is evident from Fig. 2 (top left) that the extreme Doppler frequency when target is falling away from the radar, appears around -300 Hz, whereas when motion direction is orthogonal to the radar line-of-sight, the Doppler signature does not contain any micro and macro components of the motion in Fig. 2 (top right). Same condition is also valid for the range-slow time map. We observe that when target is falling away from the radar, range spread, shown in Fig. 2 (bottom left), is 1.76 m, whereas the range spread is considerably compressed when the target is orthogonal to the line-of-sight, as depicted in Fig. 2 (bottom right). Since there are no guarantees on motion orientations, it becomes necessary to deploy multi radar monitoring system where blind spots due to transversal motions can be eliminated.

III. 24 GHZ UWB RADAR SENSING SYSTEM

The UWB system used in the experiments, named SDR-KIT 2500B, is developed by Ancortek, Inc. This system has built in compact-size, light weight, low-power software defined RF modules and field programmable gate array (FPGA) - based processor module operating in K band (24 GHz). The UWB radar system parameters are: transmitting frequency 25 GHz, PRF 1000 Hz, bandwidth 2 GHz which provides 0.075 cm range resolution.
The micro-Doppler signatures and the range maps of the data measurements are provided in Fig. 3 for both falling and sitting motions for two different aspect angles. The most easily distinguishable signatures are obtained when the target is directly moving towards or away from the radar, resulting in maximum Doppler and range spread which is shown in Fig. 3 (top and bottom left). Examination of the micro-Doppler signatures in Fig. 3 (top left and right), reveals the aspect angle has a crucial importance on the micro-Doppler signatures. Range spread is also visually compressed which can be seen in Fig. 3 (bottom left and right). Consisted with the results obtained by Kinect, micro-Doppler signatures and the range maps are squished in frequency and range when the direction of the target motion is orthogonal to the line-of-sight. Visually, the 90° falling spectrogram is similar to the sitting spectrogram at 90°. Thus, motion is skewed relative to the aspect angle which results in poorer estimates of the extreme Doppler frequency and range spread features. These uncertainty effects lead to increased confusion between fall and non-fall classes.

IV. EXPERIMENTAL RESULTS

Database for different human motion articulations was constructed by using Kinect-based UWB radar simulator. Specification of the simulated mono-static pulse Doppler radar properties can be written as: center frequency is 25 GHz, range resolution is 0.075 m, pulse repetition frequency (PRF) is 1000 Hz pulse Doppler. The database contains 13 total samples of falling and 13 non-fall motions. Support vector machine (SVM) is applied to discriminate fall from non-fall events. The data is first separated into training and test sets. In the scope of this work, training and test sizes are defined as 60% and 40%, respectively. Samples for the training and test sets were randomly selected. The random selection process was repeated 1000 times to follow the Monte Carlo approach and characterize the classifier. The effect of the aspect angle can be seen in Table I and II, where aspect angles are, 0° and 90°, respectively.

The two tables demonstrate the effect of the aspect angle by exploiting the two different features: the extreme Doppler frequency and range spread. The average classification rate is found 96% when the aspect angle equals to 0° in Table I, whereas classification rate decreases dramatically to 44% when the aspect angle is equal to 90° in Table II. Consistent with the earlier discussions, the aspect angle is a critical factor affecting the classification rate. Therefore, multi-sensor system plays an important role to increase fall detection rates.

<table>
<thead>
<tr>
<th>Activity-Class</th>
<th>Fall</th>
<th>Non-Fall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fall</td>
<td>0.93</td>
<td>0.07</td>
</tr>
<tr>
<td>Non-Fall</td>
<td>0.01</td>
<td>0.99</td>
</tr>
</tbody>
</table>

TABLE II: Confusion matrix where the aspect angle is 90°

<table>
<thead>
<tr>
<th>Activity-Class</th>
<th>Fall</th>
<th>Non-Fall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fall</td>
<td>0.59</td>
<td>0.41</td>
</tr>
<tr>
<td>Non-Fall</td>
<td>0.71</td>
<td>0.29</td>
</tr>
</tbody>
</table>
Fig. 3: 24 GHz UWB system, micro-Doppler signatures of falling where aspect angle is 0° (top left), 90° (top right), range-slow time maps of falling where aspect angle is 0° (bottom left), 90° (bottom right).

To further assess the impact of the aspect angle on fall detection, a database is generated for 7 different aspect angles. Classification performance of the extreme Doppler frequency and range spread features, is given as a function of the aspect angle in Fig. 4. As expected, the average classification performance is increasingly degraded towards 90° proving the detrimental effect of the higher aspect angles. The best classification performance is achieved 96% at 0°, whereas at 60°, performance drops below 85% and finally at 90° classification performance degrades to as low as 45%.

V. CONCLUSION

Towards advancing radar in-home monitoring and its use in assisted living, this paper demonstrated the significance of using the range information, and showed the effects of the aspect angle, in distinguishing falls from sitting motions. This distinction leads to reduced false alarms and showed the detrimental effects of the aspect, which remain the leading obstacle in final developments and marketing of this technology. Two approaches were used to establish both the importance of using the range for fall detection and multiple aspect angle. One approach is based on Kinect simulator system where the output is transformed to equivalent radar returns, whereas the other approach used UWB radars. Both approaches showed that the fall exhibits approximately twice the range extent as that of sitting when the motion direction is along the line-of-sight and revealed the effect of the aspect angle.

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