A Feasibility Study on Human Gait Monitoring Using a Wearable K-band Radar

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***Abstract*—Falling is a primary public problem which will cause serious injuries, especially for senior people aged over 65. Therefore, various fall detection systems are designed and developed. However, in existing researches, very few researchers use wearable radio frequency device to monitor the signature of human leg and detect fall event. In this paper, a feasibility study of all-time gait monitoring using wearable K-band Doppler radar is presented. In the experiment, a radar sensor was mounted on the subject's right ankle or right knee to capture the Doppler frequency. Experiment results are compared to show different features of Doppler information in different movements. Measurement results demonstrate the feasibility of fall detection using wearable onboard radar system.**

I. Introduction

According to world population prospects, the population of senior people will experience a explosive increase within next several decades. Taking U.S. as an example, by 2050, the population over age 65 is predicted to double in 2012 [1]. As a result, medical and health-care applications with emphasis on senior people has become one of the most promising topic in industrial and academic fields. As a primary elderly health problem, fall is the dominant cause of unintentional injuries. It is reported that about one third of senior adults aged over 65 falls every year, some of them even suffer from serious injuries as bone fracture, brain injury and limb injury [2]. As a result, fall detection technology has kept gaining interests, and attracted a large number of researchers to devote into this topic.

Camera-based systems and Kinect-style depth sensors are popular solutions to this problem[3][4]. Algorithms were designed for capturing features during a fall event. However, these sensors have various limitations. Kinect-style depth sensor has limited operational range and is sensitive to ambient light. Both camera-based and Kinect-style depth sensors need a complicated environment to capture surrounding features for data processing, which means the data will be inaccurate if the surrounding environment is monotonous.

Inertial measurement unit (IMU)-based system is another popular technology for human fall detection. Some researchers used the accelerator built-in smart phone to capture the acceleration at three axes. Falls were recognized by comparing acceleration magnitude thresholds between collected data and a database [5][6]. However, a typical problem is that this technology highly depends on predefined data, thus it is very hard to cover all cases of falls.

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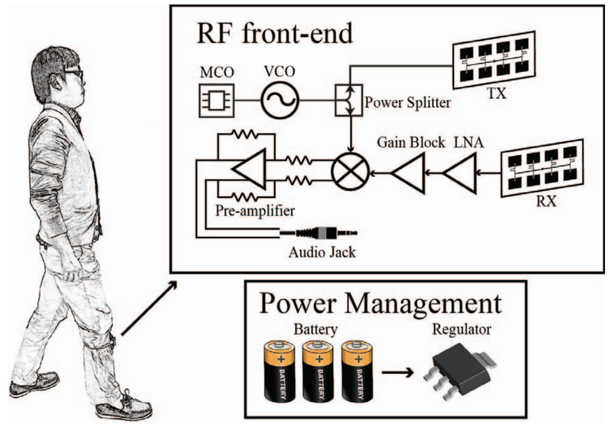

Fig. 1. Block diagram of the K-band radar sensor used in the experiment

As a non-contact high accuracy solution, radar-based systems have shown its unique advantages in many fields. Many researches have been carried out using Doppler radar and stepped-frequency continuous-wave radar for fall detection [7]-[12]. However, in these researches, radar sensor were placed at a fixed location. Although antenna can be designed to steer its beam, the operation range was still limited. On the other hand, those radar-based fall detection researches were mainly focused on extracting unique Doppler signature when fall happens. Very few researches used radar sensor to capture the signature of human leg when human perform a normal motion. Moreover, to the authors' knowledge, no wearable radar-based systems were implemented on human gait monitoring and fall detection.

In our previous work, we proved the feasibility of indoor position tracking using a wearable K-band Doppler radar [13]. This paper presents an initial study on all-time gait monitoring using a K-band Doppler radar, which is wearable by the human subjects. In our experiments, a radar sensor was mounted on the subject's right ankle or right knee to capture the Doppler information produced by legs in different movements. Experiment results were analyzed to demonstrate the feasibility of fall detection using wearable onboard radar system.

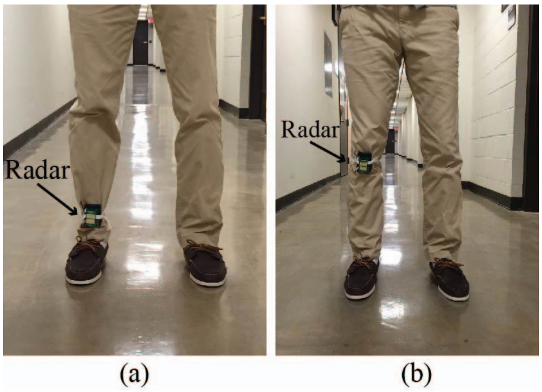

Fig. 2. Experiment setup with radar mounted on the right ankle (a) and right knee (b).

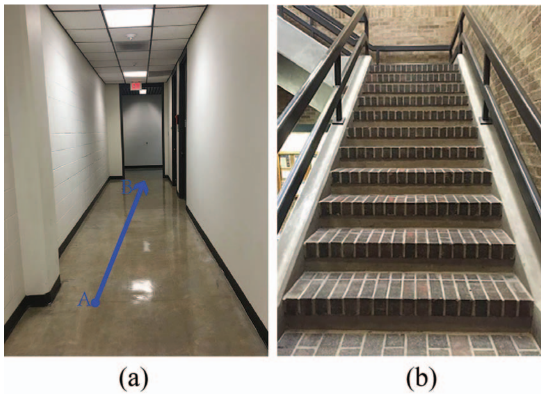

Fig. 3. (a) Environment in normal walking experiment (b) Environment in climbing stairs experiment.

II. Gait Monitoring using Wearable Radar

Fig. 1 shows the block diagram of the K-band radar. The radar transceivers operate at a typical frequency of 24.125 GHz at room temperature. The radar transceiver uses a 2×4 patch antenna array, which has 45-degree horizontal and 38-degree vertical full beam width. After the transmitted continous-wave signals are reflected by surrounding objects, the received I/Q signal at baseband can be used to obtain the motion signal $x(t)$ of the the subject. Different movement produces different Doppler shifts, which can be recovered through short-time Fourier transform algorithm. Moreover, the Doppler shift Δf is directly proportional to the moving velocity of the the subject as $\Delta f = v \times 2f_c/(c - v)$, where f_c is transceiver carrier frequency, c is light speed. If v is much smaller than c, then the velocity of the the subject is $v = \Delta f \times c/2f$.

By constantly measuring Doppler frequency generated by human legs, all-time monitoring can be realized. For typical indoor moving speed from 0.3 m/s to 3 m/s, the corresponding Doppler frequency for a 24-GHz carrier ranges from 48 Hz to 480 Hz. This frequency can be easily collected by audio device such as a laptop sound card, which usually provides at least two channels of 16-bit resolution. As the carrier frequency increases, shorter wavelength will result in larger Doppler frequency. Therefore, to alleviate the requirement on high-speed ADC, it is more reasonable to use K-band radar instead of millimeter-wave radar.

It should be noted that an microcontroller was embedded in the system. The microcontroller makes our radar sensor possible to work in frequency-modulated continuous-wave(FMCW) mode, which has the ability to detect absolute distance between radar and its surrounding objects. Therefore, our system has a great potential for further study on novel all-time fall detection and prevention system.

III. Experiment Scenario

The Radar sensor used in this research is a commercial product InnoSent IPS-154, which was designed for automatic door opener. Experiments were performed in a department building. The radar sensor was mounted on a subject's right ankle and right knee, respectively, as shown in Fig. 2. (a) and (b). The subject was asked to perform the following experiments:

1) Normal walking: In this experiment, the subject was instructed to walk across a short distance in the corridor towards a wall. The experiment environment was shown in Fig. 3. (a), the subject started at point A, stopped at point B. To make the experiment close to practical situation, the subject was walking at his comfortable pace. It should be noted that the subject's walking velocity may vary. However, the subject's walking steps and walking pattern was precisely controlled to be the same. Therefore, results can be compared to illustrate the difference in Doppler shift produced by radar sensor.

2) Climbing stairs: In this experiment, the subject was instructed to climb a 1.95m staircase with 11 steps. The staircase is shown in Fig. 3. (b). The subject's climbing speed was self-controlled, but climbing pattern was fixed with right foot stepping on the first stair. It should be noted that to precisely control the climbing pattern, the subject rehearsed experiment for a number of times before data was collected.

3) Foot slip during climbing stairs: This experiment was implemented in the same staircase as the second one, the subject was asked to climb the staircase with the same moving pattern. However, a foot slip is simulated at the eighth stair with the subject's right foot landing in the stair.

IV. Experiment results

A. Normal walking

Human movement is a complicated swing of legs and arms. Fig. 4. (a) shows a complete walking cycle when a normal walking is performed. To separately analyze the walking character during the whole process, a complete walking cycle can be divided in five phases, each of them represent a different pose of right leg. As the radar sensor was mounted on the right ankle and right knee, respectively, positions of knee and ankle were labeled in the figure as K and A. During phase 1 and phase 2, K1 and A1 moved forward to K2 and A2 at a regular speed, corresponding to a smooth increase in Doppler frequency. In this process, the ankle experienced a larger movement than the knee, thus a larger peak reading of Doppler frequency was presented in Fig. 5 (a). In the next phase, while the ankle was still experiencing a smooth movement from

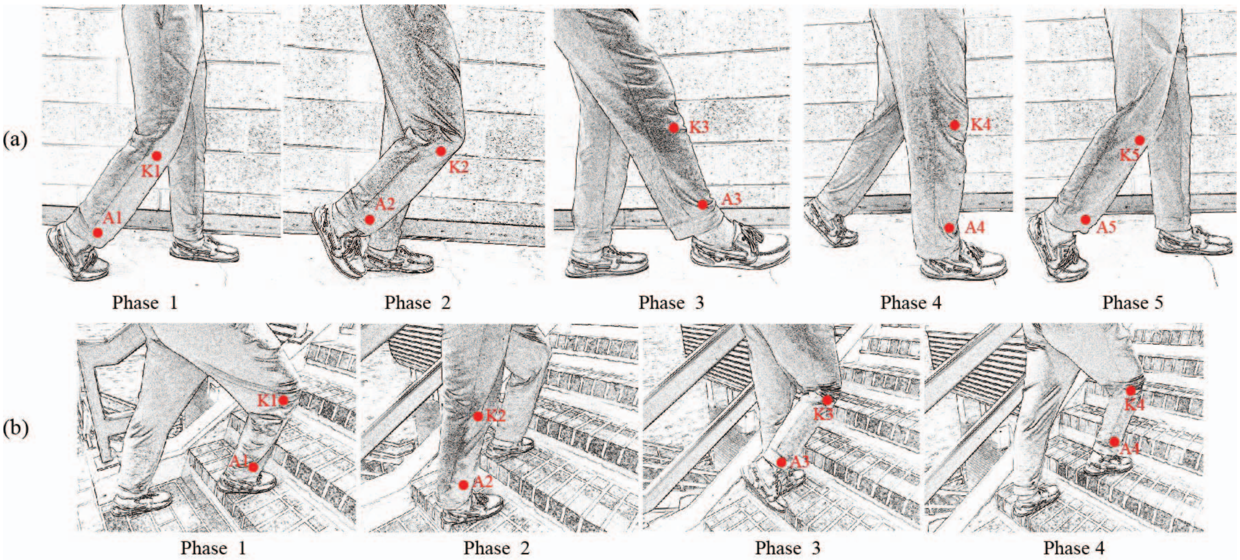

Fig. 4. (a) Five phases of a complete walking cycle in normal walking experiment (b) Four phases of a complete walking cycle in climbing stairs experiment

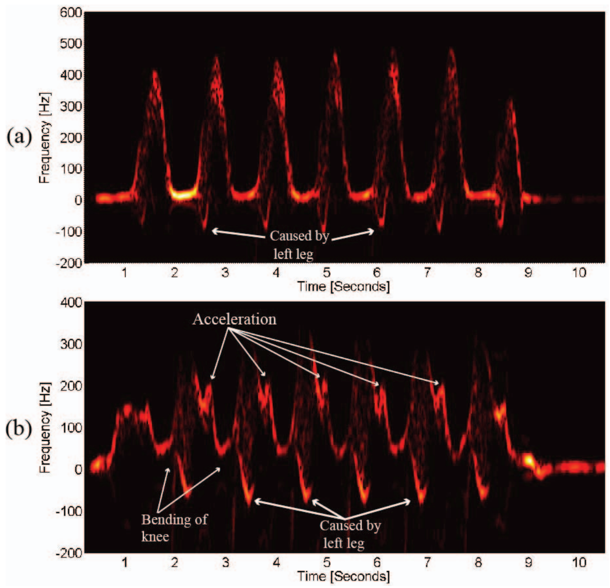

Fig. 5. Measured Doppler spectrum with K-band radar mounted on the ankle (a) and knee(b) in experiment A.

A2 to A3, the bouncing of the knee joint from K2 to K3 resulted in a sudden acceleration. This sudden acceleration was clearly shown in Fig. 5 (b). In phase 4, as right leg movement gradually stopped, the decreasing speed will lead to a decreasing Doppler frequency in the spectra. When the left leg passed the right leg in phase 5, the position of the ankle was almost fixed. However, as the body center moving forward, the right knee joint will naturally bend forward to K5/K1 at a low speed. This natural bending caused the Doppler frequency of knee joint never approaching zero during normal walking. It should be noted that the negative Doppler frequency shown in Fig. 5 was caused by the passing of the left leg in phase 5.

B. Climbing stairs

Fig. 4 (b) depicts a complete walking cycle when the subject climbed stairs. In order to separately analyze the subject's gaits in this experiment, the entire movement was divided in four phases. Positions of the right knee and the right ankle were also labeled as K and A. Between phase 1 and phase 2, right knee has a obvious bounce back from K1 to K2. This bounce back presented a clear negative Doppler frequency as shown in Fig. 6 (b). At the same time, the right ankle performed a tiny movement from A1 to A2, thus the Doppler frequency produced was close to zero as shown in Fig. 6 (a). When the right leg gradually approached the next stair in phase 3, the radar sensor experienced a sudden distance increase, which happened when the radar detecting area suddenly changed from one stair to the next one. This sudden distance change resulted in a decreasing in Doppler frequency, which was presented in Figs. 6 (a) and (b). After phase 3, the moving velocity of the right leg gradually decreased, resulting a decreasing Doppler frequency. Finally, the entire movement transited into the next walking cycle.

C. Foot slip during climbing stairs

Foot slip will probably happen when people step on the edge of the stair. Fig. 7 shows a general scenario of foot slip when the subject climbed the staircase. Positions of knee and ankle were labeled as K and A. In phase 1, when foot slip happened, the subject's right foot stepped back rapidly to the previous stair as labeled in phase 2. During this process, K1 and A1 were subsequently moved backward to K2 and A2 at a rapid speed. This rapid speed, corresponds to a large negative Doppler shift, was clearly presented in Fig. 8. Once the subject's foot landed in the previous stair, due to the descending of body center, an instinctive behavior of human will perform a back and forth bouncing on the leg to stabilize the subject's body. At this time, human legs worked as a bumper to reduce vibration. And the back and forth movement

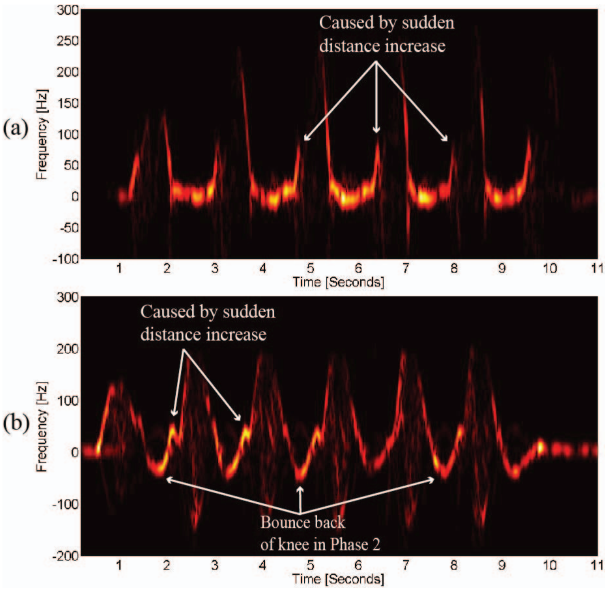

Fig. 6. Measured Doppler spectrum with K-band radar mounted on the ankle (a) and knee(b) in experiment B.

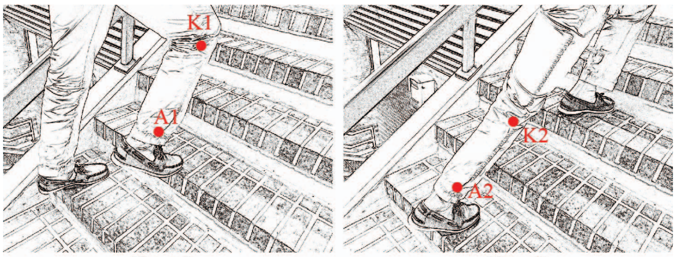

Fig. 7. Scenario of foot slip when the subject performed a normal stair ascending.

of K2 and A2 caused an oscillation of Doppler frequency, which is indicated in Fig. 8. It should be noted that foot slip happened at the eighth stair. Therefore, the spectra shown in Fig. 8 have the same features as presented in Fig. 7 in the first seven steps.

V. Conclusion

A wearable radar-based all-time human gait monitoring system was implemented and tested. A K-band radar was mounted on the subject's right ankle and right knee, respectively, to capture Doppler information when the subject performed different movements. Measurement results show that spectra measured at the ankle have different features from that measured at the knee, which indicates ankle and knee have different gait when human walks. Furthermore, our study has demonstrated the feasibility of fall detection using wearable radar.

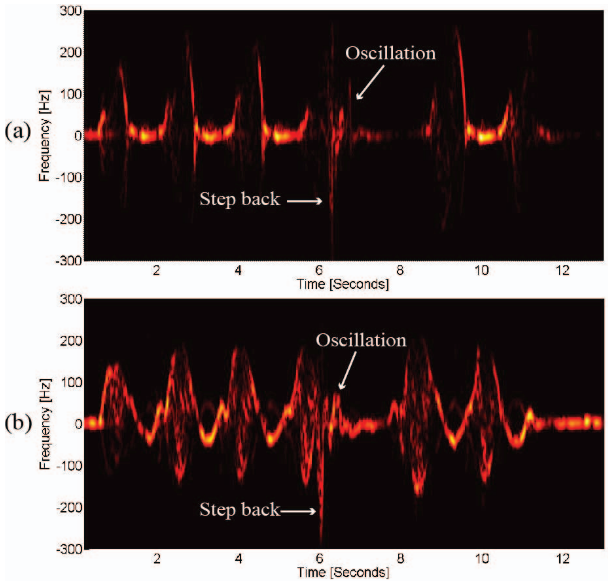

Fig. 8. Measured Doppler spectrum with K-band radar mounted on the ankle (a) and knee(b) in experiment C.

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