FMCW Radar Fall Detection based on ISAR Processing Utilizing the Properties of RCS, Range, and Doppler

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Abstract — Falls are among the leading causes of fatal and non-fatal injuries for seniors. For long-term non-contact detection of falls in home and nursing environments, a coherent frequency-modulated continuous-wave (FMCW) radar sensor is designed and tested. The coherence property of the developed FMCW radar helps to preserve the phase history of the signal detected from human subjects, and can thus obtain Doppler information based on inverse synthetic aperture radar (ISAR) imaging. By analyzing the changes of the radar cross-section (RCS), range, and Doppler on ISAR images during the movement of a subject, falls can be distinguished from normal activities. Experiments have been carried out to demonstrate and analyze the ISAR signature of actual fall incidents, which has been compared with that of an abrupt movement. Preliminary results have confirmed the ability of an FMCW radar to successfully detect fall events using ISAR imaging.

Index Terms — Doppler, fall detection, FMCW radar, health monitoring, ISAR, RCS.

I. Introduction

The health of seniors is a major concern in the society with population aging. Among various factors that threat the health of seniors, accidental fall is one of the most dangerous. Studies of fall detection based on different techniques can be found in the technical literature, including accelerometer-based solutions [1], camera-based solutions [2], [3] and Doppler-radar-based systems [4], [5]. Accelerometer-based techniques require subjects to carry or wear sensors. They also need for charging or replacing batteries frequently. Camera-based solutions implement algorithms to extract motion dynamic features, such as velocity and intensity gradient of human subjects, which require intensive computation and does not have sufficient accuracy. Though a recently-reported technique [6] tried to reduce the computational intensity and improve accuracy, camera-based solutions still suffer from several critical problems. One is that the views of cameras can be easily blocked by obstacles. Moreover, privacy concerns limit practical use of camera in seniors' daily life.

Moving targets, such as walking persons and different parts of the body, will introduce frequency modulation to a microwave continuous-wave signal, which is commonly referred to as "Doppler effect" and enables radars for fall detection. Unlike accelerometers, radar sensors do not need subjects to wear anything, which makes them more user-friendly. In addition, compared with camera-based solutions, radar systems can be used in all types of environments and can also penetrate obstacles. However, current radar-based fall detection systems only utilize Doppler information [5]. They may trigger false alarm because the Doppler signature produced by other life activities may be similar to that caused by a fall event. Examples of activities that may trigger a false alarm include jumping, abruptly stepping forward, or quickly moving a hand in one direction.

In this work, a custom-designed coherent FMCW radar sensor is used to mitigate the shortages of purely Doppler-based detection. In comparison with existing works, this paper utilizes multiple properties of the radar cross-section (RCS), range, and Doppler information of a subject to identify fall incidents. The coherence of an FMCW radar helps to preserve phase histories of the signal detected from human subjects. Thus, Doppler information can be derived using the inverse synthetic aperture radar (ISAR) imaging algorithm. Experiments will be carried out to demonstrate and analyze the ISAR signatures of actual fall events, as well as similar normal activities. Frames of ISAR images corresponding to different states of a fall event will be illustrated and compared with those of other motions. The obtained results will confirm the ability of an FMCW radar to properly detect and identify fall accidents with ISAR imaging.

II. Theory of ISAR-Based Fall Detection

FMCW radars can continuously track the range history of a human target [7]. Furthermore, if an FMCW radar is coherent, a series of ISAR images can be obtained by deriving the speed of a human subject and plotting it with the range information simultaneously. In this section, the theory of ISAR-based fall detection with a custom-designed FMCW radar prototype will be presented. Three different cases of body motions are illustrated in Fig. 1, along with their corresponding ISAR image evolution also depicted.

Figure 1(a) illustrates the case when the human subject falls toward the radar. The falling event is divided into four phases depending on the changes of the velocity, RCS, and range of the human subject. At time P1, the human subject starts to fall with relatively low speed, which appears as low Doppler frequency in the ISAR image. Then, at P2, the signature of the human subject has a sudden Doppler change due to the acceleration during the fall event. In the meantime, the tilt angle of the human subject is small, so that the RCS of the human subject does not change too much. Thus, the human signature is still quite strong in the ISAR evolution figure. When the human subject continues to fall, the RCS keeps decreasing as indicated by P3 in Fig. 1(a), which makes the

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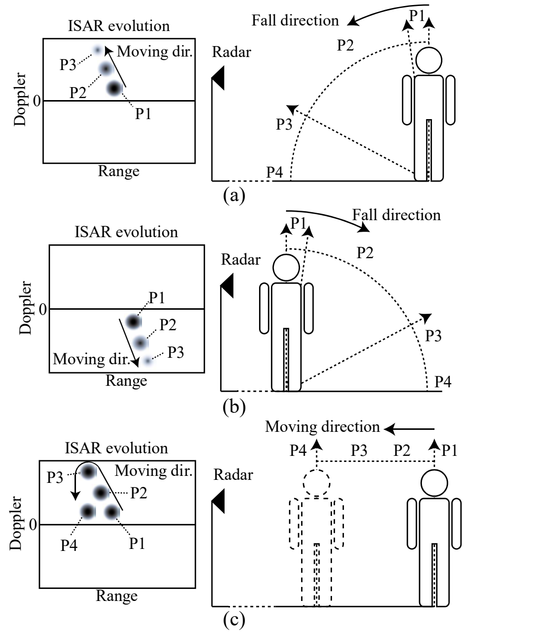

Fig. 1. Illustration of the actions of a human subject and the corresponding ISAR image evolutions. (a) The human subject falls toward the radar. (b) The human subject falls away from the radar. (c) The human subject makes an abrupt movement toward the radar.

ISAR signature to fade along the marked direction. The moving direction of the signature is affected by the changes of both the target velocity (i.e., Doppler frequency) and the target range. As soon as the human target hits the ground, the human signature disappears since both the RCS and Doppler are minimized.

Similar to the scenario when a subject falls toward the radar, falling away from the radar can also be divided into four phases, as shown in Fig. 1(b). At P1, the human subject starts to fall, producing a strong signature below the zero Doppler line. At P2, the human subject starts to accelerate without a significant change of the RCS. Thus, the Doppler frequency of the human signature increases while the strength does not change much. When the human subject is close to ground, indicated as P3 in Fig. 1(b), the ISAR signature fades away in the marked direction due to the decrease of the RCS. Finally, as the human subject hits the ground, its signature disappears.

A fall event can be divided into a series action of start, acceleration, and stop, based on which, one of the most similar events is an abrupt movement toward or away from the radar. Such an event can also be divided into four phases as shown in Fig. 1(c). At P1, when the human subject starts to move, the signature appears with low Doppler frequency above the zero Doppler line. During the acceleration phases P3 and P4 of Fig. 1(c), in which the Doppler frequency of the signature increases and the range slightly decreases, it can be observed that the signature moves towards the marked direction similar to the fall case in Fig. 1(a). However, as the RCS of the human subject does not change much during the abrupt movement action, the signature does not fade in P3, which is different from fall incidents. Finally, in P4, as the human subject stops,

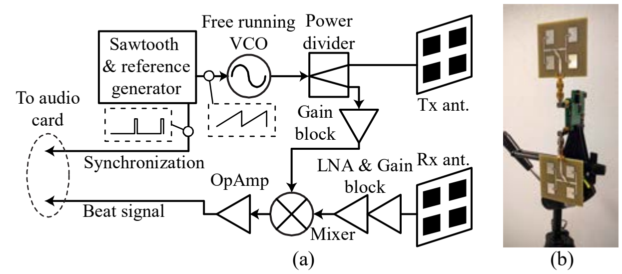

Fig. 2. (a) Schematic of the FMCW radar prototype. (b) Photograph of the FMCW radar prototype mounted on a tripod.

TABLE I
PARAMETERS OF THE RADAR PROTOTYPE

Center frequency f_c	5.8 GHz	Sampling frequency f_s	44.1 KHz
Transmitted bandwidth B	320 MHz	Frequency ramp repetition period T	10 ms
Average transmitted power	8 dBm		

a strong signature returning to zero Doppler will be observed in the ISAR image in Fig. 1(c), which is also different from fall events.

It should be noted that for other common human activities, such as walking, sitting, and running, their actions are very different from fall incidents, so that they can be easily identified. For example, the signature of a waking person in ISAR images has a periodically-changing Doppler frequency with a continuous increase or decrease in the target range. If the person stops, the Doppler of the signature will move to zero.

III. Radar Prototype and Experiments

The radar prototype used in the experiments was designed with a center frequency of 5.8 GHz. Fig. 2 shows the block diagram and photograph of the radar prototype. To minimize its complexity and cost, an operational-amplifier-based circuit was implemented to generate a “sawtooth” voltage to control a free running voltage-controlled oscillator (VCO). A pair of 2 × 2 patch antennas were used to transmit and receive signal. The audio card of a laptop is employed for signal acquisition, facilitating real-time signal processing in the laptop. The coherence property of the system is achieved by simultaneously sampling the beat signal and the synchronization signal, which is locked to the “sawtooth” voltage signal. The phases of the beat signals are aligned to the falling edge of the synchronization signal during signal processing. The basic parameters of the radar prototype are listed in Table I.

Preliminary experiments were carried out to show the capability of the developed FMCW radar for fall detection. The ISAR images (ISAR imaging does not respect the usual convention for the sign of the Doppler frequency) shown in Fig. 3(a)-(d) correspond to the 4 different phases of the fall event in Fig. 1(a), i.e., P1 to P4. It should be noted that the ISAR signature of the human subject experienced an

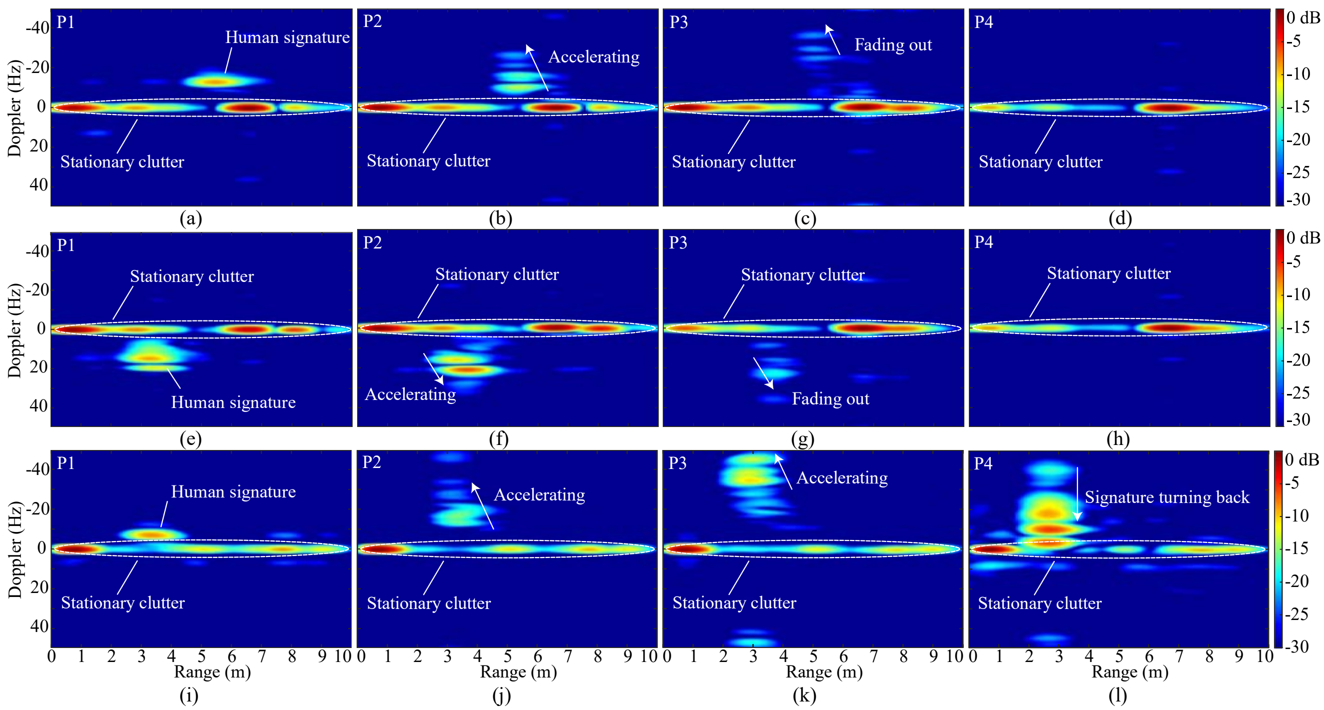

Fig. 3. Different frames of ISAR images during fall incidents and an abrupt body movement. (a)-(d): falling toward the radar; (e)-(h): falling away from the radar; (i)-(l): an abrupt movement toward the radar.

acceleration and a fading period, before it disappeared as the human subject hit the ground.

Similarly, Fig. 3(e)-(h) correspond to the fall event shown in Fig. 1(b). The phases of P1 (start), P2 (acceleration), P3 (fading), and P4 (disappearing) in the detected human signature can be clearly identified in these ISAR images, which is consistent with the theoretical analysis in Section II.

As a comparison, the results of an abrupt movement toward the radar are shown in Fig. 3(i)-(l), which also correspond to the four phases in Fig. 1(c). As discussed in Section II, P1 and P2 of the abrupt movement are similar to those of a fall event, but P3 and P4 of the abrupt movement are significantly different.

IV. Conclusion

This work has demonstrated the ability of an FMCW radar to detect fall events based on real-time ISAR imaging. A 5.8-GHz custom-designed prototype of portable coherent FMCW radar was used in the experiments. ISAR images measured from different human motions show that with an FMCW radar, it is possible to detect falls based on Doppler frequency, range information, and the RCS. This may enable long-term remote fall detection without requiring seniors to wear any sensing device in home and nursing environments.

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