Investigation of a wireless sensor network for improving in-door fall detection and tag-less localization

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Abstract

Fall incidents and sustained injuries are the most dangerous causes of accidents for elderly people, and represent also the third cause of chronic disability. The rapid detection of a fall event can reduce the mortality risk and increases the chance to survive the incident and to return to independent living. A variety of fall detection methods have been published in recent scientific literature. However, they suffer from critical limitations and the number of "false positives" is still unacceptably high. In this paper, the use of a Stepped-Frequency Continuous Wave (SFCW) radar is proposed for non-invasive fall detection and tag-less localization. A fall in principle involves changes both in position and in speed. Measurements have been performed with the radar fixed both on the wall and on the ceiling. In both situations, absolute distance and speed of a target have been measured with good accuracy. By combining these two physical quantities, a fall can be properly detected, distinguishing the fall from both walking and sitting movements. The results show the feasibility of this approach. Moreover, to increase the accuracy of the system and to minimize the number of false positives, next step is to integrate multiple SFCW radars in a wireless sensor network.
Keywords: *fall detection, wireless sensor network, health monitoring, radar remote sensing, SFCW radar, Zigbee.*

1 Introduction

The elderly population of 60 years and older has been steadily increasing worldwide. The situation has resulted in a growing need for healthcare approaches that emphasize routine long-term monitoring. Monitoring is of primary interest in the home situation [1]. There is a natural desire to stay at home, combined with a general shortage of nursing homes. However, elderly people who live alone are usually exposed to health risks which in some cases may cause fatality. In fact, fall incidents among the elderly are a major problem worldwide, and often result in serious physical and psychological consequences [2]. Research pointed out that 30% to 45% of the persons older that 60 years fall at least once a year. People who experience a fall event at home, and remain on the ground for an hour or more, may suffer from many medical complications, such as dehydration, internal bleeding, and cooling, and half of them die within six months [3]. The delay in hospitalization increases mortality risk. Studies have shown that the longer the persons lie on the floor, the poorer is the outcome of medical intervention [4-5]. To address the problem of medical intervention delay, it is imperative to detect the falls as soon as they occur such that immediate assistance may be provided. Currently, health monitoring is achieved through active patient communication through pressing a button worn as a necklace, for example. However, in many situations, this imposes an important risk factor. At any time, a person may forget to put on the necklace, or may not be able to press the button in an emergency situation. A lack of significant innovation in this system persists, despite the need for reliable health monitoring. Thus, the ideal solution of a contactless health monitoring system is considered here which avoids the need for human action. Current systems under investigation for contactless fall detection are based on video cameras, floor vibration, and acoustic sensors. For the video camera method, people are currently trying to address challenges related to low light, field of view, and image processing as the number of false positives is still unacceptably high, but also privacy is a concern [6]. Floor vibration and acoustic sensors have limited success due to the environmental interference and background noise [7]. Moreover, they are not good in case of a “soft” human fall in which the individual collides with an object (table, dresser, chair, carpet, ect.). In this paper we show the feasibility of using SFCW radar working in the lower microwave frequency range for fall incident detection and tag-less localization. To the authors’ knowledge, the use of radars has not been explored yet for in-door fall detection. The goal of a fall detection system is to minimize the number of false alarms. In order to achieve this, we believe that several sensors have to be integrated in a smart wireless sensor network. For that reason, four different wireless communication technologies have been compared in order to determine the most suitable candidate for the Homecare WSN. In Section 2 the radar architecture that was employed is introduced. The experimental results will be discussed in Section 3. In section 4 we propose a wireless sensor network to reduce the number of false alarms. Conclusions are discussed in Section 5.

2 SFCW radar architecture

The block diagram of the quadrature SFCW radar is shown in Figure 1. The radar is constructed using a wideband antenna, a power splitter, a wideband LNA and an IQ demodulator. In order to demonstrate the functionality, the radar is realised as a board design using off-the-shelf circuits. An SFCW radar transmits a group of N coherent pulses whose frequencies are increased from pulse to pulse by a fixed frequency increment Δf as indicated in Figure 1. The frequency of the n-th pulse can be written as:

$$f_n = f_0 + n\Delta f \qquad (1)$$

where f_0 is the starting carrier frequency, and Δf is the frequency step size, that is, the change in frequency from pulse to pulse. Each pulse is τ seconds long, and the time interval T between the pulses is adjusted to obtain an unambiguous range. For this kind of application, an SFCW radar presents several advantages compared to both CW and UWB IR radars: the former is unable to detect distance, and the hardware of the latter is highly complex.

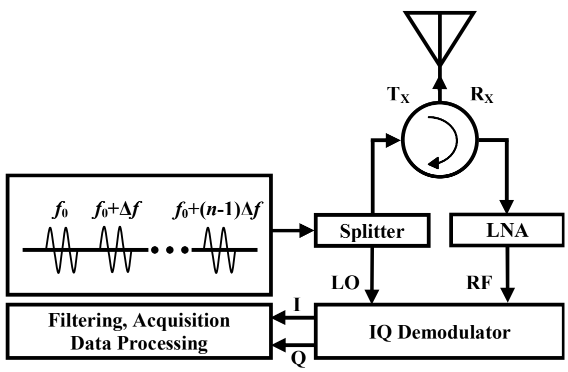

Fig. 1 – SFCW radar system

3 Experimental Results

The radar setup that is used in the experiments is based on above SFCW architecture. N=100 pulses are transmitted starting from 1.0 GHz to 2.0 GHz with Δf=10 MHz. This involves an unambiguous range of 15 m and a range resolution of 15 cm that can be considered a proper value to establish if a person has fallen or not. A transmitted power of -10 dBm is sent to the antenna. The echo reflected off the target is mixed with the transmitted signal to produce the I and Q components. In particular, the echo reflected from the n-th pulse should return to the receiver and then be mixed with the n-th transmitted pulse before a new f_{n+1} pulse is sent.

Since both transmitted and received *n*-th pulse are close in frequency, and the dwell time of the pulses is very short, mixing will produce *I* and *Q* DC levels. Since the downconverted signals are at DC, the typical sampling rate is one complex sample per pulse width, making the sample rate lower compared to other ultra wideband radars. The *I* and *Q* samples are related as:

$$C_n = I_n + jQ_n \qquad (2)$$

where *n* is the index of the *n*-th frequency in the burst. Applying eq. (2) improves the signal-to-noise ratio by 3 dB. In order to determine absolute distance, the entire burst should be received and processed. Moreover, the burst interval (*N**T*) should be such that the target may be assumed static during a burst. Due to this reason, for *N*=100, τ and *T* have been chosen to be respectively 50 μs and 80 μs. This involves a burst interval *N**T* of 8 ms which is sufficiently small to fulfil the above condition. The first step in data processing of a step-frequency burst is to organize the C_n samples of *M* bursts in a matrix as shown in Table I.

Table 1: Complex samples of different bursts in a matrix

burst	f_0	$f_0+\Delta f$	$f_0+2\Delta f$	…	$f_0+(N-1)\Delta f$
1	C_{11}	C_{12}	C_{13}	…	C_{1N}
2	C_{21}	C_{22}	C_{23}	…	C_{2N}
…	…	…	…	…	…
M	C_{M1}	C_{M2}	C_{M3}	…	C_{MN}

Each row represents the *N* (=100) complex samples of a burst. By IFFT compression to each row of the matrix, the range profile is obtained. It determines the absolute distance of the target each *N**T* seconds. This is true if the assumption of a static target during burst interval (*N**T*) is valid.

In order to detect the position of a person, different measurements have been performed by fixing the radar both on the ceiling and on the wall. Figure 2 shows the range profile of a standing person when the radar is fixed on the wall. The peak corresponding to the standing person is very clear. This result clearly shows how the SFCW radar can determine the absolute distance of a target. Moreover it is possible to see that the radar is able to separate the target peak from the static reflections, corresponding to clutter.

Regarding the speed of the target, just one frequency among the *N* pulses is considered and the Doppler principle is exploited. This means that just one column of the matrix should be considered. In our case the first column, that is the one of the 1 GHz frequency, has been chosen. This operation is equivalent to having a pure CW Doppler radar working at 1 GHz. Also in this case, measurements were performed with the radar fixed both on the wall and on the ceiling. The results show clearly the difference between a fall and a normal movement (walking or sitting). During a fall, the speed continuously increases until the sudden moment when the fall is finished. During walking or sitting down, the Doppler signal experiences a controlled movement. More precisely, while a person is sitting down the speed first gradually increases, and then decreases and stops smoothly. During a walk, instead, the speed is quite constant over time. Figure 3 and Figure 4 show the speed signal during a fall and a walk respectively. In the first case, it is clearly seen how the signal frequency (and thus the speed) increases with time and then abruptly stops when the ground is reached. In the second case, the frequency of the signal is quite constant over time. It has to be noted that in our lab experiment we used an inflating mattress when invoking falls. That is why, as can be seen in Figure 3, the signal does not stop suddenly but there is also the effect of the rebounds on the mattress. Moreover, in this preliminary phase, frontal falls are considered only. However, furniture was positioned in the room to mimic a real-life environment and metallic shelves were also present.

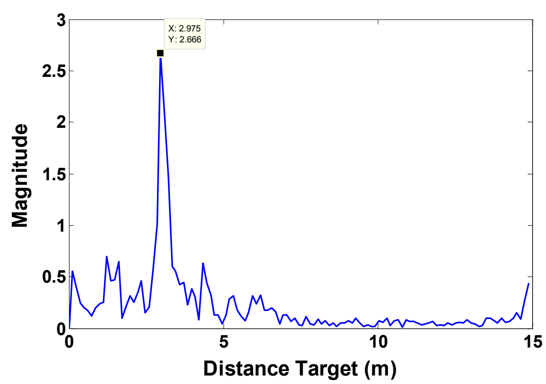

Fig. 2 – Range profile of a standing person with the radar fixed on the wall.

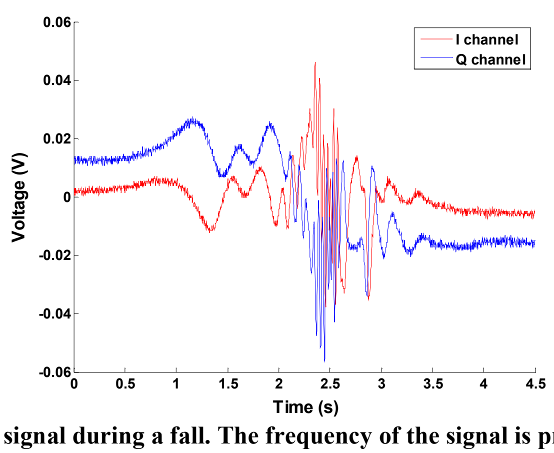

Fig. 3 – Speed signal during a fall. The frequency of the signal is proportional to the velocity of the person during the fall. The radar is fixed to the ceiling.

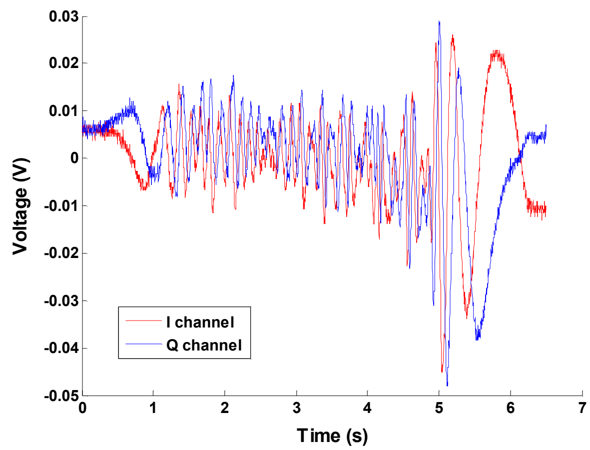

Fig. 4 – Speed signal during a walk. The frequency of the signal is proportional to the velocity of the person during the walk. The radar is fixed to the wall.

4 Wireless sensor network

A single radar sensor is insufficient for practical and real situations. In order to increase the accuracy of the system, and then to minimize the number of false positives, further research will be conducted to integrate multiple SFCW radars in a smart wireless sensor network. By combining the measured information (speed and absolute distance) from several sensors, a better estimate of the motion is obtained. Moreover, a single radar can detect absolute distance so by using multiple sensors it is possible to detect position (like in a GPS system). This, together with a better estimate of the speed, allows tracking the person. Four wireless communication technologies were considered and evaluated towards the best candidate for the Homecare WSN. Those are Bluetooth LE, Zigbee, WiFi and 802.15.4a UWB. This study considered parameters such as compatibility with radar devices, distance to be crossed, maximal RF power levels, power consumption, ease of synchronization, etc. Some characteristics of the above technologies are listed in table II. The most important consideration is that the wireless communication technology should not affect the contactless monitoring function and vice versa. The SFCW radar will be extended with the wireless communications module. Each sensor, or node, will transmit the information acquired to a base station. The task of the base station is to process the data as received by the various sensors in real time in order to detect a fall and to localize a person. A representative value is to detect the position of a person five times per second. It means that five bursts will be sent in a second. In between them, the frequency used for detecting speed should be transmitted and its relative baseband signal acquired. Considering both I and Q channels, 10-bit ADC, one sample for each DC level in a burst, and a proper number of samples for speed signal, the maximum data rate required for one sensor node is lower than 15 kbps. This assumes that the information is entirely processed in the base station. All the technologies are able to guarantee this data rate. Considering the distance to be crossed, both Bluetooth and UWB can cover theoretically 10 m and this value could not be suitable to cover a big room as opposed to Zigbee and WiFi. Considering the power consumption and the electromagnetic radiation, Zigbee and UWB represent the best candidates. The problems of the UWB lie in the difficulty of synchronization and in the technology maturity. Moreover, it presents an ultra-wideband nature and therefore it could interfere with the radar functionality. Considering the above characteristics, Zigbee has resulted to be currently the most suitable energy-efficient wireless technology for the considered application. The proper number and the optimal physical positioning of the sensors in the home environment is being investigated.

Table 2: Selected characteristics of wireless communication technologies

Characteristics	Bluetooth/Bluetooth LE	Zigbee	WiFi	UWB
IEEE standard	802.15.1	802.15.4	802.11b	802.15.4a
Frequency band and channels	2400 – 2483.5 MHz (79 channels)	2400 – 2438.5 MHz ISM band (16 channels)	2400 – 2483.5 MHz ISM band (14 overlapped channels)	3244 – 4742 MHz 5944 – 8236 MHz (9 channels)
Maximun data rate	3 Mbps (Enhanced Data Rate)	250 Kbps	2 Mbps (without High Data Rate/DSSS support)	27.24 Mbps
Nominal range for normal range devices	10 m	10-100 m	10-100 m	10 m
Electromagnetic radiation	118 dBμV/m	118 dBμV/m	118 dBμV/m	70 dBμV/m
Power consumption	Rx: 39.2 mW (2V voltage) Tx: 48 mW (CC2540 Bluetooth LE)	Rx: 33.3 mW (1.8V voltage) Tx: 46 mW (CC2520 Zigbee)	Rx: 295 mW (3.3V voltage) Tx: 425 mW (BCM4326 WiFi)	Tx: 0.65 mW – 1.4 mW
Ease of synchronization	Slightly difficult	Easy	Slightly easy	Difficult
Technology maturity	Mature	Very mature	Mature in other applications	Immature

5 Conclusion

An SFCW radar system has been developed which is capable of fall detection in an indoor environment. The system is inline with the growing need for home health care applications and supervision technology for elderly people living at home. A pure CW radar can measure the target's velocity without ambiguity, but is not able to determine absolute distances. The presented SFCW radar utilizes different frequencies as timing marks to realize a high resolution system providing the range resolution of wideband systems with the implementation advantages of narrowband systems. This involves a cost effective and an attractive technique to detect fall incidents and to localize people without any RFID tags. In this paper, for we give a proof of remote indoor fall detection by using a radar. This concept has been demonstrated by measurements. Moreover, to increase the accuracy of the system, and then to reduce the number of false positives, next research will be devoted to investigate a wireless sensor network in in-door environment. By determining and combining the information (absolute distances and speed of a target) from multiple sensors positioned in different places in the home, it is possible to distinguish a fall from a normal movement (i.e., walking or sitting down). For that reason, four wireless communication technologies were chosen and compared to identify the best candidate for the Homecare WSN. Zigbee has resulted currently to be the most suitable energy-efficient wireless technology for this application.

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References

[1] O. Boric-Lubecke and V.M. Lubecke, "Wireless house calls: using communications technology for health care and monitoring," *IEEE Microwave Magazine*, vol. 3, pp. 43-48, Sep. 2002.

[2] P. Haentjens, J. Magaziner, *et al.*, "Excess mortality after hip fracture among older women and men," *Annals of Internal Medicine*, vol. 152, pp. 380-390, 2010.

[3] S. R. Lord, C. Sherrington, and H. B. Menz, *Falls in Older People: Risk Factors and Strategies for Prevention*, Cambridge, U.K., Cambridge Univ. Press, 2007.

[4] R. J. Gurley, N. Lum, M. Sande, B. Lo, and M. H. Katz, "Persons found in their homes helpless or dead," *N Engl J Med.*, no. 334, pp. 1710-1716, 1996.
[5] C. G. Moran, R. T. Wenn, M. Sikand, and A. M. Taylor, "Early mortality after hip fracture: is delay before surgery important," *J. of Bone and Joint Surgery*, no. 87, pp. 483-489, 2005.
[6] M. Yu, S. M. Naqvi, and J. Chambers, "A robust fall detection system for elderly in a smart room," *International Conference on Acoustics Speech and Signal Processing,* pp. 1666 -1669, Dallas, USA, March 2010.
[7] Y. Zigel, D. Litvak, and I. Gannot, "A method for automatic fall detection of elderly people using floor vibrations and sound – Proof of concept on human mimicking doll falls," *Transactions on Biomedical Engineering,* vol. 56, no. 12, pp. 2858-2867, December 2009.