INTRODUCTION

Falls are one of the major causes of serious injuries or death among elderly people [1]. Data published by the National Safety Council show that falls on stairs are a leading cause of accidental death in the US, with 1197 (approximately 10%) of the 12,646 fall deaths in 1992 occurring on stairs [2, 3]. More than 78% of these individuals were aged 65 and older [2, 3]. It is indicative that the number of fall-related deaths is increasing which was stated in reports issued by the U.S. Department of Health and Human Services. In 2003, there were 18,044 fall-related deaths while in 2006 20,819 persons died due to unintentional falls. It is also shown that the age is a major factor in these statistics as fall-related fatalities rates per 100,000 persons increase almost exponentially with age (for persons aged 25-35 the rate is 55 while for persons aged 65-74 it is 507). Similar statistics can be found in other countries, i.e. in United Kingdom alone, approximately 20000 hospitalizations and 900 deaths occurred each year in those aged 65 and older due to falls on stairs or steps [4].

The key intrinsic factors for these occurrences are:

- age, fear of falls, polypharmacy, cognitive impairment, depression
- lower extremity weakness / lack of endurance
- problems with coordination, balance, sensation (including light touch, proprioception, vision, hearing, vestibular function
- pain

The current ways of preventing falls on stairs are usually orientated towards environment issues (e.g. handrails, non-slippery steps, good lighting, color contrast), promotion of exercising [5], improving the balance [6], providing passive assistance (e.g. ergonomic shoes, canes), prescribing glasses and hearing aids, and detecting falls after they occur [7]. To the extent of our knowledge, there are no active devices that could predict dangerous situations before they happen and warn a user in a “natural-like” manner.

In this research, we aim at improving the lives of elderly people by using miniaturized radar technologies in conjunction with signal processing algorithms and methods for immediate sensory feedback to provide a warning or additional awareness. By using these novel technologies as building blocks of a stand-alone device we want to change the way elderly people or people with disabilities interact with their surroundings in specific scenarios (such as stairs walking). In these scenarios, the main goal is to be able to predict a fall or similar incidents, where there is a serious risk of injury, and to inform the person so that she/he can make a corrective action and prevent the fall. Besides the immediate prevention of dangerous situations, the continuous usage of such assistive device will also increase mobility and confidence during walking, thus, decrease social inhibitions that result from fear of falling which is common among elderly people [6, 8]. In the proposed device work principle, the radar sensor is the main component that measures distances to surrounding objects with respect to the user’s foot trajectory. The developed algorithm will, based on the sensor data, predict if there is a risk of falling and the feedback module will communicate this information to the user via electrical stimulation delivered to the appropriate peripheral nerves located inside the leg so that the user can correct foot placement and thus avoid a fall.

Figure 1. Device work principle. Miniature mm-wave radars will be positioned on a person's shoes. Based on the surrounding objects and foot trajectory, the device will provide additional awareness or warnings to a user.
fall (Figure 1). As the mm-wave radars are the central element of the assistive device, this paper is focused on this emerging technology. The key features that separate this technology from similar measurement methods are small size (single IC), low power consumption (milliwatt), invariance to environmental conditions (direct bright light, dark, color, dust, moisture...), high accuracy (distance measuring of one or multiple objects with millimeter accuracy) and ability to sense object within “solid” angles.

METHODS

The studied system utilizes multiple state-of-the-art principles. These include mm-wave radar from Acconeer, Lund Sweden, wireless communication protocol, and a walking events classification algorithm based on machine learning techniques.

Equipment

The model of Acconeer mm-wave radar used in this study is the A111. The A111 radar sensor is a low power, high precision, pulsed short-range radar sensor with a footprint of only 29 mm² (5.5 mm x 5.2 mm x 0.88 mm). The radar sensor is delivered as a one-chip system in a package solution with embedded radio and antenna which means that no external parts are necessary. It operates at 60 GHz as a Pulsed Coherent Radar (PCR) with the measuring range 60-2000 mm and continuous update rate of up to 1500 Hz. The A111 radar sensor can detect multiple objects at close range with single measurements as well as continuous sweeps. For this study, the Continuous Sweep Update Rate was set to 100 Hz and the measurement range to 60 mm – 400 mm as these parameters match human walking dynamics and expected ranges between feet and neighboring objects. The minimal measurement distance was off-setted with the sensor placement, as shown in figure 2.

One of the advantages of the A111 is its compatibility with the Raspberry Pi. The model can be mounted onto a Pi and operated with the provided software development kit (SDK) from the manufacturer. This also enables communication between the Pi and a PC, allowing real-time visualization of the signals and data collection. The communication medium between the Raspberry Pi and the PC is based on a Wi-Fi protocol. It is implemented using the standard Python module. Python Scripts are written on both machines to construct the communication channel, where the Pi is mainly acting as the transmitter and the PC is mainly acting as the receiver.

Recording protocol

There are two main points related to signal recording that were considered within this feasibility study. These two points are the positioning of the Acconeer radar, and the walking scenarios.

The positioning of the radar was as shown in Figure 2. The radar was mounted on the shoe facing downwards. The PCB, which the radar is on, was parallel with the ground when standing. The major benefit for positioning the radar in this configuration is the increase in the radar’s effective range under the foot. Hence, increasing the amount of useful data captured by the radar.

There are three major scenarios considered when recording the data. The three scenarios are normal walking, placing foot over a single stair, and placing foot over two stairs. Figure 3 illustrates the last two scenarios.
Signal processing

The Acconeer mm-wave radar operates as a pulsed short-range radar sensor which means that it measures distances to all objects within its field of view. Based on time latencies between the transmitted pulse and received echoes, for each pulse the sensor forms vector of responses that coincide with the distances to the neighboring objects. In terms of walking, and specifically, stairs walking these reflection vectors have distinctive shapes that relate to different foot positions with respect to stairs or the floor. The typical responses are shown in figure 4. To detect three main foot placement conditions a relatively simple algorithm was derived. The first step of the algorithm is the estimation of measurement noise. It was calculated as the standard deviation of measurements between consecutive pulses. As the sensor responds with the vector of distances, the median value of all distances was selected as representative. Subsequently, the detection threshold was set to four times the estimated noise level to minimize false detections. Finally, the thresholded values of the signal were fed into the machine learning algorithm which detected key events related with stairs descending (hovering over one and two steps). For this purpose, a linear Support Vector Machine (SVM) classifier was selected.

RESULTS

The results of different walking scenarios are presented in figure 5. Figure 5a shows detected foot orientations with respect to stairs. In this test a subject is standing, then hovering over the next step, and finally pushing the foot forward so it exceeds the edge of the next step. It could be noted that there are distinct detection areas that correspond to the foot being on the step, while passing over next step and finally, exceeding it. The detected positions are robustly appearing during 10 repetitions during which subject moved its foot to the overshoot position. The distances of detection areas also fall inside stairs height ranges defined by The Stairway Manufacturers Association in 2006 Stair Building Code.

Another important issue that was addressed within this paper is if stair related event detection could also be detected during normal overground walking. For this reason, we applied the same detection method to signals recorded during self-paced walking. As it could be noted in figure 5b, there are only sporadic detections that fall in the stairs height range. Although these detection occurrences could be removed with simple duration constraints, a machine learning method was tested. Implementation of linear SVM classifier managed to discriminate properly.
recorded samples (hovering over steps vs overground walking) with less than 1% of false positives (true positive >99%).

DISCUSSION
The mm-wave radar setup and results presented in this paper are encouraging. There is a clear usage and setup scenario which is supported by the obtained results during crucial waking events related to stairs. As shown in figure 5a, the compact areas related to the foot being over next stair are easily distinguishable from the other walking events such as standing, overground walking and overshooting next stair. Furthermore, foot overshooting which dangerous stair walking event is again easily detected by the mm-wave radar. What is also important is that between discrete events related to stairs walking there is a continuous transition that could be used for early warnings even before the foot is placed improperly. And finally, the results presented in this paper reveal that there is no misclassification of crucial stair walking events during normal, self-paced overground walking (as shown in figure 5b).

The main advantage of the proposed system is the active component that provides real-time assistance during walking. Specifically, the use of state-of-the-art radar technology and signal processing algorithms will enable prediction of critical events that could lead to falling. As the mm-wave radar technology is relatively new, there are no devices that are focused on accurate and robust human-centered environment sensing. Furthermore, using the active feedback provided by the electrical stimulation, the device will also target additional awareness in the form of artificial sensing ("extra pair of eyes" and "artificial awareness of the feet positions"). Through this possibility, the device will be able to provide information regarding events within the cyclic walking sequence that serve as the cue for entering the next phase of walking. The examples of such functionalities are: the heel cleared the last step -> notification is provided to a user -> user can start lowering his/her foot, or, user approaches an obstacle (e.g. high rug) -> warning is provided -> user is stepping over obstacle -> user is notified that he/she exceeded the height of the obstacle -> user can continue forward movement. It is envisioned that after some time of familiarizing, a user will be able to reduce the use of visual feedback during walking which is associated with poor proprioception and fear of falling.

Work presented in this paper serves as the initial feasibility study which is focused on sensor placement and evaluation of initial algorithms for detection of crucial walking events. Future work related to this project will be oriented towards making of the database with elderly people walking in different scenarios, such as stairs walking, overground walking, uphill-downhill walking and avoiding flat and raised obstacles. This will be done to provide more relevant data for algorithm design and testing phases.

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REFERENCES