A Smart and Passive Floor-Vibration Based Fall Detector for Elderly

Majd Alwan[1], Prabhu Jude Rajendran[2], Steve Kell[1], David Mack[1], Siddharth Dalal[1], Matt Wolfe[1], Robin Felder[1]

[1]*Medical Automation Research Center (MARC),*
Department of Pathology,
[2]*Department of Electrical and Computer Engineering,*
University of Virginia,
PO Box 800403, Charlottesville VA 22908, USA
{Alwan, pjr5f, swk3f, dcm5a, dalal, raf7k}@virginia.edu and dacrimpa@hotmail.com (Matt Wolfe)

Abstract

Falls are very prevalent among the elderly. They are the second leading cause of unintentional-injury death for people of all ages and the leading cause of death for elders 79 years and older. Studies have shown that the medical outcome of a fall is largely dependent upon the response and rescue time. Hence, a highly accurate automatic fall detector is an important component of the living setting for older adult to expedite and improve the medical care provided to this population. Though there are several kinds of fall detectors currently available, they suffer from various drawbacks. Some of them are intrusive while others require the user to wear and activate the devices, and hence may fail in the event of user non-compliance. This paper describes the working principle and the design of a floor vibration-based fall detector that is completely passive and unobtrusive to the resident. The detector was designed to overcome some of the common drawbacks of the earlier fall detectors. The performance of the detector is evaluated by conducting controlled laboratory tests using anthropomorphic dummies. The results showed 100% fall detection rate with minimum potential for false alarms.

1. Introduction

Falls are very prevalent among the elderly. These adverse events are the second leading cause of unintentional-injury death for people of all ages and the leading cause of death for elders 79 years and older [1]. A five-year prospective study of an active ambulatory institutionalized population of adults over the age of 65 years revealed an annual fall rate of 668 incidents per 1000, with an increase in frequency for successive age groups above the age of 75 years. Forty-five per cent of all subjects suffered at least one fall during the study period [2]. The nature of falls can be broadly categorized as: falls that occur as a result of loss of consciousness and non-syncopal falls, which occur in full consciousness as a result of slipping or tripping. It has been observed in one of the fall studies that the risk of major injury was increased in falls associated with loss of consciousness, following the sudden drop in blood pressure (postural hypotension) upon attempting to stand or get out of bed for example, compared to nonsyncopal falls [3]. Studies have also shown that the medical outcome of a fall is largely dependent upon the response and rescue time. All these facts only emphasize the importance, if not the necessity, of reliable automatic fall detectors, that do not require human activation or compliance, to be deployed in the living setting of independent older adults. Autonomous fall event detection would improve health outcome prospects through faster caregiver response.

There are a number of fall detectors that are currently available and are being used in by older adults in different living settings; these include the following three general categories:

1. *User-Activated Fall/ Community Alarms:* These devices, generally, require the user to manually activate an alarm button, usually on a pendent or wrist watch device integrating a wireless transmitter, following the event of fall. Although such fall alarms are simple and low-cost (in terms of purchase price), they are not effective for falls associated with the loss of consciousness or if the subject was unable to activate the alarm due to trauma, pain, or other reasons. Manual activation may also fail in cases of elderly adults with dementia, as the user may forget to activate the device. Moreover, such devices relay on the premise that the user is wearing the device all the time such to activate them when needed. Nonetheless, users may take the device off, in the shower for example, and may not be wearing them when the fall occurred.

2. *Automatic Wearable Fall Detectors:* Various automatic fall detectors, which do not require manual activation, have been designed to overcome some of the aforementioned drawbacks [4], [5]. These devices generally use a combination of accelerometers and tilt sensors to automatically detect a fall event. However, these devices have some limitations of their own. They require the user to wear the device constantly, even during the night. Moreover, the potential users may

0-7803-9521-2/06/$20.00 ©2006 IEEE.

perceive the wearable device as a stigma labeling them as fallers among their peers [6].

3. *Camera Based Fall detectors:* These devices track the resident using cameras installed at vantage locations and detect an event of a fall based on image processing algorithms that are designed to identify unusual inactivity, which is more likely to follow an event of fall [7]. However, the resident may perceive such camera based monitoring technologies as intrusive. SIMBAD [8] uses a low-cost array of infrared detectors to capture low-resolution blurry image of the resident and then analyzes the subject's motion to detect a fall event. In spite of using a low quality imaging and on-site image processing, the residents experienced the feeling of "being-watched" based on their perception of the sensor.

The significance of fall detection in the elderly and the numerous drawbacks of the currently available fall detectors clearly call for an automatic, reliable, completely passive fall detectors that can be placed throughout the residence of independent older adults. This paper describes the working principles, and the design and of floor vibration based fall detector that is being developed at the University of Virginia. The floor vibration based fall detector is completely passive and unobtrusive, and hence can overcome most of the common drawbacks of currently available fall detectors. This paper builds on patent pending technology developed at the University of Virginia and previous research on monitoring floor vibrations to detect human gait and fall events [9], [10]. The fall detector's performance was evaluated by conducting controlled laboratory tests using anthropometric dummies. The results of these tests indicate that using the detector introduced in this paper, falls could be reliably detected, with minimum potential for false alarms.

2. Method

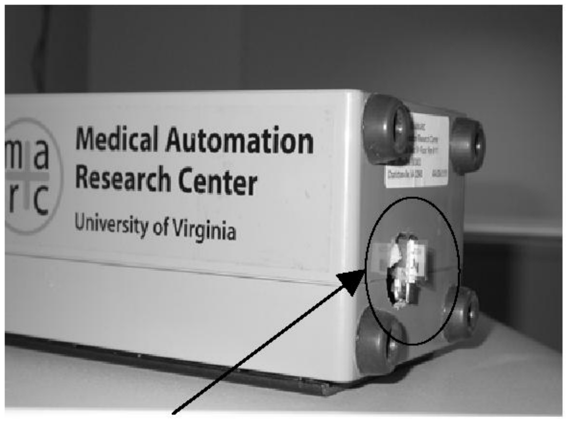
2.1 Working Principle and Design

It has been observed that human activities, like walking, running, can cause measurable vibrations on the floor [11]. It is quite clear that human falls will also cause a vibration pattern on the floor. When a human falls, the impacts of body part with the ground generate vibrations that are transmitted throughout the floor. The working principle of the floor vibration based fall detector is founded on the hypothesis that *it is possible to detect human falls by monitoring the vibration patterns in the floor*. The above hypothesis essentially implies that:

(i) The vibration signature of the floor generated by a fall of a human is significantly different from those generated by normal daily activities like walking, tapping etc.

(ii) The vibration signature of the floor generated by a human fall is significantly different from those generated by objects falling on the floor.

The floor vibration based fall detector, shown in Figure 1, uses a special piezoelectric sensor coupled to the floor surface by means of mass and spring arrangement, combined with battery-powered preprocessing electronics to evaluate the floor's vibration patterns and generate a binary fall signal, and a wireless transmitter that relays the fall alarm to a communication gateway. The complete detector set up weighs about 3.5 pounds, including batteries, and can be placed directly on the floor, typically one per large room.



Piezo Transducer

Figure 1. Floor Vibration Based Fall Detector laying on its side to show the transducer

Based on the experiments conducted, it was observed that there were significant differences in the patterns of vibrations induced on the floor by different activities. There was also a significant difference in the vibration pattern generated by a falling object as opposed to that generated by a falling anthropomorphic dummy, which in this case is representative of a human fall. This difference in the response of the floor to different excitation activities was effectively exploited to detect the falls with a higher degree of sensitivity and specificity (fewer false positives). The device detects a fall only when the vibration pattern (frequency, amplitude, duration, succession etc.) obtained from the floor over a small period of time matches the pattern induced when a person falls on the floor. The detector can then report the fall alert to the responder through an appropriate communications portal such as utilizing the telephone to send a message to a radio pager or to a cellular phone.

0-7803-9521-2/06/$20.00 ©2006 IEEE.

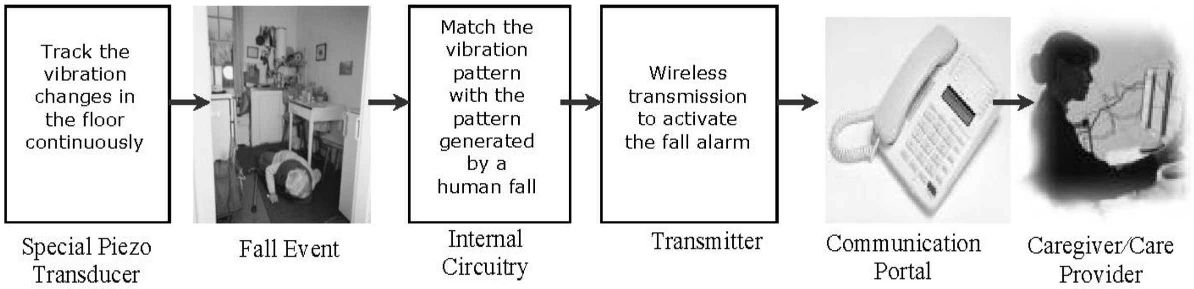


Figure 2. Schematic Representation of the Working Principle of the Floor Vibration Based Fall Detector

Figure 3. Sequence of Images Illustrating Falling while Trying to Get out of a Wheelchair

Figure 4. Sequence of Images Illustrating Tripping and Falling from an Upright Position

Figure 2 depicts a schematic representation of the various stages that the fall detector goes through to detect and then report a fall to the responder following a fall event.

2.2 Testing Methods

The performance of the detector was evaluated by conducting controlled laboratory tests. Human falls were simulated using anthropomorphic dummies, which have mass and mass distribution that are similar to those of humans and hence provide an excellent representation of the effect of a human's fall on the floor. The fall tests were conducted on mezzanine concrete floor and concrete slab floors. We used a Hybrid-III® crash test dummy molded in the seated position weighing 180 pounds, and a Rescue Randy®, a 6 ft. 1 in. tall dummy weighing 165 pounds. The Hybrid-III dummy was used to emulate the scenario of a person falling when attempting to get out from a chair/ wheelchair and the Rescue Randy was used to emulate tripping and falling from an upright position. Figures 3 and 4 depict a sequence of images illustrating the different stages of a fall on the Hybrid-III and Rescue Randy dummies respectively. The dummy falls were conducted at known distances from the sensor ranging from 2 feet to 20 feet. Experiments were repeated 3 times at each distance to ensure repeatability of the results.

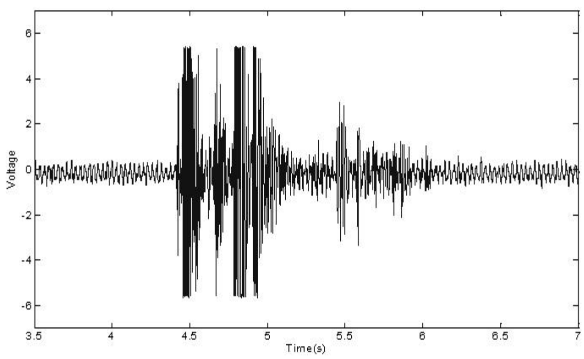


Figure 5: Pre-amplified signal from the piezo sensor showing the vibration pattern of the floor following the event of a Rescue Randy fall at a distance of 20 feet from the sensor, on Mezzanine concrete floor covered with linoleum.

The ability of the fall detector to distinguish a human fall from an object dropped within the detection range was evaluated by dropping two objects weighing 5 pounds and 15 pounds, which are representative of common objects in residential settings, at various distances covering the entire range of fall detection up to 20 feet. Figure 5 shows the vibration signal of the floor, as measured by the piezo sensor, for a Rescue Randy fall at a distance of 20 feet on mezzanine concrete floor. This vibration pattern is significantly different from the one that is produced by an object dropped as close as 2 feet from the sensor, shown in Figure 6.

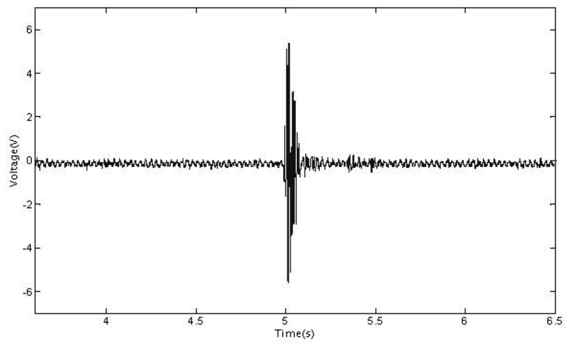


Figure 6: Pre-amplified signal from the piezo sensor showing the vibration pattern of the floor following a 15 lb object fall, at a distance of 2 feet from the sensor, on Mezzanine concrete floor covered with linoleum.

The fall tests, both for the dummies and objects, were repeated on different flooring treatments (carpet with and without foam padding) to evaluate the effect of floor treatments on the performance of the fall detector's performance. Finally, the fall detector was placed in a room, while the dummy was dropped in an adjacent room, with a wall separating the two rooms, to test the possibility of false alarms due to a fall in a neighboring apartment. This test was performed to determine the constraints that should be adhered to when installing the sensor in the field to limit the possibility of such false alarms. The dummy was dropped less than 2 ft. away from the wall, and the senor element was moved away from the wall in discrete steps until it no longer triggered for at least 3 successive falls.

3. Results

Based on the tests conducted, the fall detection range for the sensor was found to be 20 ft. in the case of mezzanine concrete floor covered with linoleum and 15 ft. on concrete slab floor. Dummy falls induced higher amplitude vibration signals on mezzanine concrete floors than on concrete slab floors at equivalent distances. Thus, the fall detector circuitry required different pre-processing thresholds for these two different floor types. This can be achieved by means of a simple toggle switch that selects threshold levels, and hence sensitivities, appropriate to the floor type where the device is installed. Utilizing these modifications in settings, the fall detection function produced reliable and repeatable performance on both mezzanine concrete and concrete slab floors.

A total of 70 dummy falls and 53 object drops were performed. The difference in the number of dummy and object trials is due to the fact that dummy falls were required to be performed for 2 different dummies at equivalent distances. The vibration patterns for a set of 20 Hybrid-III fall trials and 20 Object drop trials on mezzanine concrete floor were initially used as training set to tune the thresholds and amplification settings of the electronic circuitry and the later experiments were performed using the same circuit settings. We attained 100% detection rate of falling dummies and 0% detection rate of dropped objects having a weight of 15 lb. as close as 2 ft. away from the sensor. Two by two contingency table analysis and Fisher's exact test showed that the fall detector performance attained a 100% Sensitivity, with a 95% Confidence Interval (CI) of 94.87%-100%, and 100% Specificity, with a 95% CI of 93.28%-100%; the results were statistically significant at a P value of < 0.0001 (two-tailed). The performance was not significantly affected by the different floor treatments that we tested (linoleum, carpet, and carpet with foam padding). Thus, the different flooring treatments did not require any changes to the sensor mounting or the circuit sensitivity settings to maintain the detection ranges specified above for the tested variations.

The vibration signal transmittance tests showed that the fall detector should be placed no closer than 5 ft. to walls on mezzanine concrete floor , and no closer than 4 ft. on concrete slab floor, during the installation to minimize the chances of falsely triggering the fall detector as a result of a fall in a neighboring apartment.

4. Discussion

The results of the controlled laboratory tests clearly suggest that it is possible to reliably detect a human fall by passively monitoring the floor vibration patterns. Since this detector is not a wearable device, the resident need not remember to wear the detector every time he gets out of the bed. The detection range of around 15 feet, on concrete slab floors, is commensurate to relatively large room size in a residential setting. Hence, one detector per room should typically suffice for full fall monitoring coverage of a resident. Larger rooms can be monitored using multiple fall detectors that are spaced appropriately to cover the entire room space. The installation procedure for these detectors will only depend upon the floor dynamics, which can be measured by means of simple tests [12]. The installation is hence simple and does not require significant customization by specialist technical staff, as generally required in the case of image processing based fall detection methods. More importantly, monitoring floor vibrations is unobtrusive compared to other passive detection methods currently available. Thus, the user will not have the feeling of being "watched" or of having their privacy compromised.

5. Conclusions and Future Work

An automatic and cost-effective method of detecting human falls passively by monitoring the floor vibrations was discussed. Besides overcoming most of the common drawbacks of the currently available fall detectors, the results from the controlled laboratory tests for this detector were extremely encouraging. The results indicated that the described detector may well outperform other fall detectors in real-life applications. Controlled experiments conducted to test this fall detector showed that the detector had 100% true positives and 0% false alarms, compared to SIMBAD, the only other passive and non-obtrusive fall detector, which could only detect 35.7% of the actual falls in controlled laboratory tests [8].

A Future research direction will be to test the performance of this fall detector with human subjects in controlled setting and to conduct field trials with the potential user population.

6. Acknowledgements

The authors would like to thank the Center of Applied Biomechanics, University of Virginia, for providing the Hybrid-III dummy and Rescue Randy to perform the fall tests. This research was funded in part by the National Science Foundation (NSF award No. 0428420, PIs: Skubic, Alwan and Rantz).

7. References

[1] Hoskin AF., "Fatal falls: trends and characteristics", Stat Bull Metrop Insur Co. 1998 Apr-Jun; 79(2):10-5.

[2] C. I. Gryfe, A. Amies and M. J. Ashley., "A Longitudinal Study of Falls in an Elderly Population: I. Incidence and Morbidity", Age Ageing, 1977.

[3] Nevitt MC, Cummings SR, Hudes ES., "Risk factors for injurious falls: a prospective study.", J Gerontol. 1991 Sep; 46(5):M164-70.

[4] T. Degen, H. Jaeckel, M. Rufer, and S. Wyss, "Speedy: A fall detector in a wristwatch," 7th International Symposium on Wearable Computers (ISWC), White Plains, NY, Oct. 2003, pp. 184–189.

[5] Doughty K. Lewis R.; McIntosh A., "The design of a practical and reliable fall detector for community and institutional telecare", Journal of Telemedicine and Telecare, Volume 6, Supplement 1, 10 February 2000, pp. 150-154(5).

[6] Brownsell, S, Hawley, M., "Fall detectors: Do they work or reduce the fear of falling?", Housing, Care and Support, Feb 2004. Available on-line at (last accessed March 3, 2006): http://www.findarticles.com/p/articles/mi_qa4133/is_200402/ai_n9465084.

[7] Nait-Charif H. and Mckenna S., "Activity Summarisation and Fall Detection in a Supportive Home Environment", International Conference on Pattern Recognition 2004.

[8] A. Sixsmith and N. Johnson, "Smart sensor to detect the falls of the elderly," IEEE Pervasive Computing, vol. 3, no. 2, pp. 42–47, April-June 2004.

[9] Alwan M, Dalal S, Kell S, Felder R. "Derivation of Basic Human Gait Characteristics from Floor Vibrations", 2003 Summer Bioengineering Conference, June 25-29, Sonesta Beach Resort in Key Biscayne, Florida.

[10] Rajendran P, Alwan M., et al. "A Passive Floor-Vibration Based Fall Detector", 2006 International Conf on Aging, Disability and Independence, Feb 1-4, St.Petersburg, Florida.

[11] Allen, D.E. "Building Vibrations from Human Activities." Concrete International: Design and Construction, American Concrete Institute, Vol. 12, No. 6. 66-73.

[12] A. Blakeborough and M. S. Williams. "Measurement of floor vibrations using a heel drop test", Proceedings of the Institution of Civil Engineers, Structures & Buildings 156, November 2003 Issue SB4, Pages 367–371.